Food Plant Design

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Antonio López-Gómez
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Preface

Chemical engineering and food technology are subject areas closely related to food processing systems and food plant design. Food plant design, however, is often sporadic and inadequately addressed in food technology and engineering books. Some food data can be found in general chemical engineering books, but the data rarely include references to food processing systems and food plant design. Some food processing and plant design factors requiring specific treatment include natural variability of raw materials in quantity and quality, dependent on climate, growth, and biological conditions; food spoilage conditions during manufacturing and storage; and high safety levels required in end food products. In fact, these factors are very different from those usually addressed in chemical engineering. Some books have attempted to treat food engineering from this dual point of view (chemical engineering and food technology), but only a few have achieved a proper balance between the two. This kind of book usually gives more importance to one subject in particular, presenting only some aspects of the other, as a way of demonstrating the author's university education.

In this book, a well-thought-out balance is given to the engineering aspects of food processing and related factors. We discuss the design of the food processing system and the industrial food plant in a concrete, ordered form. This text is mainly aimed at pregraduate and postgraduate food engineers, design and project engineers, food engineering researchers and development centers, and food factory technicians. The book provides important data in graphic form and gives examples with characteristics that are treated only at a basic level. Up-to-date references expanding on the subject are also included.

When one is designing a food processing system for a food product, it seems logical to begin by specifying the particular food and the necessary raw matter, and then screening the various food processing equipment alternatives. Next, all possible equipment alternatives must be evaluated individually, choosing the one that best complies with the technical, hygienic, and economic restrictions in the food processing system design. This choice, which could be called the "optimum alternative," must be described last at a detailed engineering level to allow mechanical construction and erection.

The food processing system must be connected with necessary auxiliary systems (or utilities), and installed at an adequately rational, functional, and hygienic site for correct technical and hygienic operation. Food plant design is completely conditioned by the solution adopted for a particular food processing system. Thus, a food processing plant project will finally generate the development of an optimum engineered food processing system. The design will also include detailed information on (1) any civil works needed in the food processing rooms and buildings (areas for reception and storage of raw materials and packages, food processing, storage and shipment of processed products), and auxiliary system buildings (boiler rooms, engine rooms for refrigeration systems, etc.); and (2) a description of necessary auxiliary systems (steam, refrigeration, handling-materials equipment, and control systems).

The purpose of this book is to provide an adequate work procedure as well as to examine the techniques needed to solve the design problems of a food processing system and a food plant in making a defined food product.

In the first chapter, some interesting concepts are defined. In addition, the solution to food processing system and food plant design problems, in the context of overall optimization of an agro-industrial system and corresponding food chain, is outlined.

The modeling procedures for food processing systems and auxiliary systems, as well as a series of case studies, are presented in the second chapter, including the modeling of an entire food plant by means of artificial intelligence techniques. These tools are useful because they assist the design engineer in the screening and evaluation of different design and operation alternatives for the above systems.

Documentation and information handling, which should usually be done during the processing system and plant design, are analyzed in the third chapter, paying close attention to the rational use of raw matter and energy. Different levels of information and data regarding the food processing system and the food plant are analyzed, from product and raw matter studies to the detailed food plant project, which as a document is enough to build an entire food plant.

Synthesis techniques, as well as procedures to structure information and data on different food processing system alternatives, are outlined in Chapter 4. This chapter discusses the common usage of the basic modules method in synthesizing or generating different food processing system alternatives. The methods that are based on problem breakdown, as well as on mathematical programming, are also discussed. Different alternatives are analyzed from both a technical and an economical point of view in Chapter 5, where the difficulty in finding the optimum solution is discussed.

Experimentation in the pilot plant, of utmost importance in food factory optimization, is studied in Chapter 6. Here, its reliability as a source of technical data for the ultimate design and its use as an optimization technique for an existing food processing system are underlined. In the research and development of new products and processes, pilot plant experimentation frequently plays a decisive role.

Finally, all aspects of design are studied in Chapters 7, 8, and 9, taking into account the use of equipment while in contact with food. These chapters discuss the most suitable materials for construction of food processing equipment, and the design of processing systems and rooms from a hygienic point of view. Chapter 9 also addresses some considerations regarding the rational and functional design of food processing plants.

Antonio López-Gómez
Gustavo V. Barbosa-Cánovas

Authors

Antonio López-Gómez is currently full professor of food plant design and food process engineering, and director of the Food and Agricultural Engineering Department at the Polytechnic University of Cartagena, Spain. He is also the president of the Spanish Society of Refrigeration Science and Technology.

Prior to this, Prof. López-Gómez worked at the Polytechnic University of Catalonia, Spain, in the Food Technology Department. He next worked for CEMAGREF of Montpellier, France, Division of Food and Agricultural Machinery and at the Public University of Navarra, Spain, in the Food Technology Program.

More than 80 papers have been published by Prof. López-Gómez during his academic career, on subjects dealing primarily with food plant design, and food technology and engineering, in journals such as *Journal of Food Engineering, Drying Technology, International Journal of Refrigeration, Food Control, European Food Research and Technology,* and *Journal of Food Processing and Preservation.* In addition, he has presented more than 60 papers at food technology and engineering congresses and meetings in Spain, France, the Netherlands, Germany, Sweden, Ireland, Turkey, the United States, the Czech Republic, Australia, and Argentina.

In parallel with his academic career spanning from 1982 to 2004, Prof. López-Gómez has also worked as a food plant project and optimization engineer and has been involved with more than 150 food factories on design and optimization projects in Spain, France, Russia, Argentina, and Mexico.

Gustavo V. Barbosa-Cánovas received his B.S. in mechanical engineering at the University of Uruguay and his M.S. and Ph.D. in food engineering at the University of Massachusetts. He was an assistant professor of physics and mechanical engineering at the

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He is currently a professor of food engineering and director of the Center for Nonthermal Processing of Food (CNPF) at Washington State University. He teaches food process engineering design, dehydration of foods, food powder technology, and food rheology, and his current research activities are centered in the nonthermal and minimal processing of foods, high-pressure sterilization, and physical properties of foods. Prof. Barbosa-Cánovas is an Institute of Food Technologists (IFT) Fellow and a member of the Uruguayan Academy of Engineering, as well as a member of the International Academy of Food Science and Technology.

An active author and editor as well, Prof. Barbosa-Cánovas has written 14 books and edited 26 more, and is currently editor-in-chief of the CRC Press Food Preservation Series. In addition, he has published more than 100 refereed papers in top journals around the world. He is also an International Consultant for the United Nations Food and Agriculture Organization (FAO), and a consultant for several major food companies in the United States.

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Contents

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Economic and Technical Context of Food Plant Design

1.1 FOOD SCIENCE, TECHNOLOGY, AND ENGINEERING

1.1.1 Historical Evolution

Before the eighteenth century, the technology in the food industry was empirical, without the basis of scientific formation (Parisier, 1974; Peterson, 1968, 1975). In fact, science did not play a role in food technology until the nineteenth century, when biologists first interpreted fermentation and the role of yeast. In 1680, Antonie van Leeuwenhoek discovered yeast cells in beer but did not recognize them as living organisms, nor did he associate them with fermentation (Schlenk, 1997). In 1697, Georg Ernst Stahl suggested that fermentation was not a chemical process. One hundred years later, Antoine Lavoisier confirmed Stahl's point of view. In 1837, Theodor Schwann, F.T. Kutzing and C. Cagniard Latour observed the yeast multiplication mechanism, which was a biological phenomenon. Two years later, T. Schwann discovered the spore-forming capacity of yeast. In 1843, Jöns Jacob Berzelius and Justus Liebig theorized that fermentation was "the decomposition of an albuminoide." This theory was dominant until 1876, the year in which Louis Pasteur published his study on beer. In this work, Pasteur proved that yeast is a living organism. In 1890, Emil Fischer and Eduard Buchner proved the biochemical basis of fermentation, pointing out the enzyme production by yeast. With this discovery, fermentation technology advanced by means of scientific reasoning.

On the other hand, between 1795 and 1810 Nicholas Appert observed what he called “food rottenness,” although in a superficial way. He observed that food did not rot if it was heat-treated with certain intensity and if the bottles were hermetically sealed. The scientific principle of preservation by heat was completely unknown until the end of the century, when preservation technology was first introduced (Thorne, 1986).

Although food science was not very important in the initial development of preservation technology, something different happened with engineering. Hydraulic mills and windmills are two good examples. Here, engineering solved the problems associated with the power drive. Notwithstanding, the invention of the steam engine was not decisive in food engineering history. Although it did not have an important and a widespread application in the food industry, the steam engine was used in flour mills in early 1780 but without any spectacular increase in flour production because of the lack of transport and storage systems. Good distribution and supply systems were lacking in delivery of the finished products to consumers. The steam mills that were situated near the cities could only supply products to neighboring villages. But with the development of food technology and engineering during the second half of the eighteenth century, industrialization grew stronger. The development of flour mills is a good example of this phenomenon. Thus, the flour industry, a basic branch of the food industry, has existed for some time, and in some ways is a barometer or an indicator of the food industry’s progress in western countries because of the importance of bread in daily diets.

Before the eighteenth century, processing in mills was long, tedious, and slow. The endless screw conveyor developed by Oliver Evans (1785), an engineer from Philadelphia, was the first engineering advance to allow the elimination of hard labor. This conveyor was powered by a steam engine. The screw conveyor could move grains and flour through the mill in a horizontal fashion with much more efficiency than with manual labor. Evans also invented the bucket elevator, which could transport powdered products vertically. Using Evans's automatic system, the grain was elevated to the upper section of the mill and later distributed to the different grinding and processing equipment via gravity. This automatic process could have been the origin of the continuous process; it was soon expanded into actual food factories.

Richard Trevithick manufactured the first steam railway engine in 1804, half a century before the railway was well established and flourishing. Steamships began to be used for transport in 1814. Steam power was also tried in refrigeration installations — at the compressor — designed in the early 1830s.

The food was packed and preserved by placing it in contact with ice and storing it in a cellar. Subsequently, ice cooled the cellar, making the direct contact of food with ice unnecessary. Quick freezing of food appeared in the middle of the nineteenth century with Henry Benjamin, an Englishman who first patented this method, which involved submerging the food in a low temperature liquid. In 1861, Enoch Piper developed a freezing method for fish by placing the fish in direct contact with the surfaces of metallic panels containing a mixture of ice and salt inside. A freezing process that involved submerging the fish in brine was invented in 1911 by A. J. A. Ottesen, a Danish man who had developed the first commercially used quick-freezing method. The development of mechanical refrigeration was, without doubt, one of the greatest advances in the modernization of the food industry (Figure 1.1). Jacob Perkins patented the first vapor compression refrigeration system in 1834, while Ferdinand Carré of France developed the absorption refrigeration system in 1860. Other systems were developed later, but mechanical refrigeration did not gain any real importance until the twentieth century. This was the beginning of a revolution, because the extended use of refrigeration outside the food industry, even in consumers' homes, was becoming a reality.

In short, the food industry was not very mechanized in its early stages, since a firm concept of its current definition did not exist until different means of communication (by

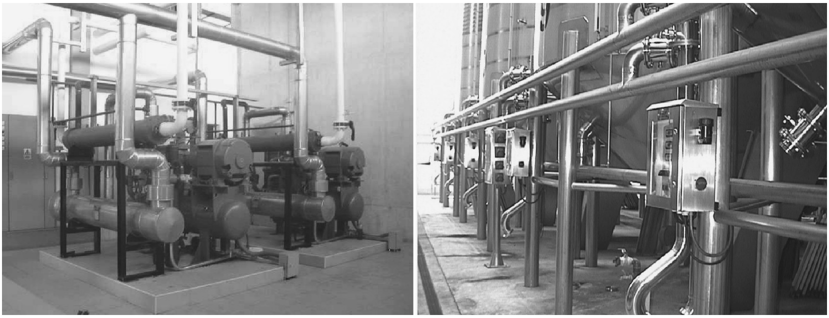

Figure 1.1 Compressors in a mechanical refrigeration system for water cooling in a juice factory (left), and controlled temperature fermentation tanks using cool water in a winery (right).

earth, sea, and air) and transport were developed, and before the mechanization of production in the industry as a whole. Thus, the food industry's development coincided with the industrial revolution, with the economic conversion of agricultural societies into industrial economies.

Some of the main developments in food engineering are compiled in the following examples, which indicate advances in materials handling, as well as in certain food processing systems.

Materials handling: About 30% of work in the food industry is managed by materials handling systems. These systems have largely been developed in the last 60 years, aided greatly by the chemical industry (in broad terms, the materials processing industry). This improvement began with Evans's endless screw conveyor, and in the last 50 years, the following have also been developed:

- Powdered product pneumatic transport
- Hydraulic transport through channels and pipes for nonliquid bulk products
- Other power-drive transport systems, such as belt conveyors, bucket elevators, etc. (Figure 1.2)
- Individualized handling of products, as in fruit placing and transport systems from one stage of the process to another (coring, mechanical peeling, cutting, etc.)

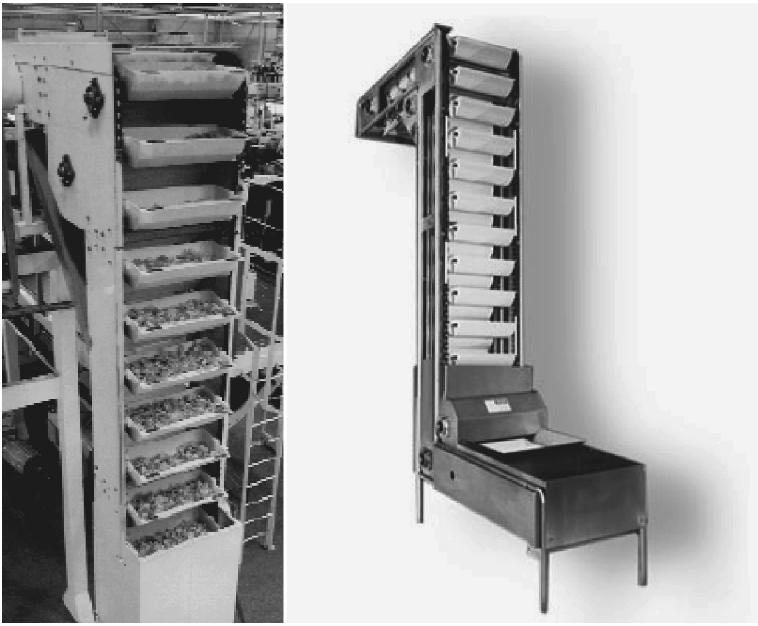

Figure 1.2 Bucket elevator in a potato chips processing line (courtesy of FMC Food Tech, Chicago, Ill.).

Selection, separation, classification, and cleaning operations: Removal of seed impurities with ventilators was practiced in the nineteenth century, and filtration in the eighteenth century for the sugar industry. In Europe, filters were first manufactured with cloth, which led to the manufacture of mesh or plate-and-frame filters, vacuum-rotary drum filters, and centrifugal filters.

Heat treatment operations: These are perhaps the most important of operations in the food industry. Denis Papin invented the retort in 1679, making it possible to cook foodstuff at temperatures higher than 100°C. Appert used this retort (a vessel with internal steam pressure), and Raymond Chevalier Appert was the first to use control systems in the retort, in 1852, but it was at the Exposition of London in 1857 when the J.H. Gamble Company demonstrated the retort method (patented by Stephen Goldner in 1841) that its use

Figure 1.3 FMC water spray retort (courtesy of FMC Food Tech, Chicago, Ill.).

became widely known. Previously, Angier Marsh Perkins (1850) had introduced steam tubes in ovens for baking bread, thus controlling the temperature and the process. Figure 1.3 shows a modern retort. The use of heat treatment at the industrial level permitted the development of the canning industry, which became a model for the food industry as a whole. Its reasonable use of design engineering, technology, and marketing factors, along with incoming scientific support, made it a viable industry. These factors made possible the diffusion of canned foods (vegetables, meat, and fish), resulting in mass consumption. Without doubt, this industry was the first to supply the "homemaker" with precooked food. Evaporation, as it is understood today, was first observed in the middle of the nineteenth century. In the U.S., Gail Borden (1856) discovered milk vacuum evaporation. Subsequently, a great industry was developed. In recent years, the evaporation-concentration of fruit and vegetable juices (Figure 1.4) has succeeded because of increasing consumption of juice, especially orange juice. Thanks to this process, food engineers have become interested in studying the physical properties of foods.

Figure 1.4 Evaporator for concentration of juices (courtesy of FMC Food Tech, Chicago, Ill.).

In the last 50 years, the quality and amount of food research have increased. A tight relationship between food science and food technology with benefits to both has also been established. The most important area in which research has advanced is in the study of food quality damage agents (microorganisms, enzymes, oxygen, and environmental agents like excessive heat or cold, and humidity).

Enzymes research has had a great technological influence. For instance, in powdered dehydrated eggs production, the addition of glucose oxydase to transform glucose into gluconic acid reduces the oxygen content needed to form hydrogen peroxide, which causes browning.

Research on microorganisms known to cause putrefaction in food has also resulted in advances in food technology. The influence of product moisture content (water activity), heat, cold, pH, ionizing radiation, etc., on microbial activity has been studied.

The development of new packages and packaging systems is also a significant field of research. Tin cans were developed sometime in the nineteenth century with the welding of both ends. But the truly decisive step was the setting up of tin cans in the automatic production line. This was highly efficient and has been a determinant for supplying foodstuff in large quantities ever since.

One of the biggest problems that researchers have encountered is in the establishment of precise heat treatment holding times. For this reason, procedures such as the general method (W.D. Bigelow, J.R. Esty, and C.C. Williams, in 1920) or formula method, to establish a mathematical relationship between time and temperature (C.O. Ball, in 1925), as well as a method using nomograms (F.C.W. Olson and H.P. Stevens, 1920), were developed.

Research has also approached subjects such as nonenzymatic browning, permanency of natural food color, texture of foodstuffs, and flavor and nutritional aspects. In effect, science has been a determinant in the food industry's expansion ever since the middle of the nineteenth century, and continues to address new problems such as the quality control of large volumes of products. This calls for knowledge of the product's composition, the nature of damage agents, and statistical analysis. Change in consumer consumption habits has been another important factor contributing to the development and expansion of the food industry. These changes are due to clever advertisement campaigns (using all communication media) and to the promotion of different eating facilities (e.g., bars and restaurants). Without doubt, the daily time constraint of a typical workday has lessened the desire to cook at home, promoting the use of fast foods (prepared and precooked).

In short, before the mid-1800s, the advances made in engineering were more a determinant in the food industry's development than science alone, permitting changes in dated, inefficient, and difficult work. At present, the food engineer handles (on a research level) the problems related to the design and optimization of food processing systems, attempting to solve certain unit operations and processes not yet mechanized and/or in a developmental stage.

1.1.2 The Design Engineer in Food Engineering

The increased size of and the need to optimize a food factory's production structures have created a real and potential demand for qualified technicians with university training. The food engineer, as well as other professionals, has traditionally solved the problems of structural change in the food industry. However, there is a certain technological level (i.e., in process design, process optimization, automation, research, and development of new technologies, etc.) of problems in the food industry that appear to apply more specifically to the food engineer.

The functions of a food engineer (who is trained specifically to solve engineering problems in the food industry) are

- Technical management of production
- Design of processing systems
- Design of food processing plants
- Research and development of processes and products
- Management of product distribution to the consumer

The design engineer's overall objective in the food industry is to provide the tools needed to integrate a food processing system design with a corresponding processing plant, and to produce the desired products with minimum cost in equipment, energy, human labor, etc. In effect, to develop, synthesize, and optimize a given process according to the resources and problems in each particular case, suitable methodology is required in its design, which involves alternatives generation techniques and corresponding evaluation methods (Giral, et al., 1979).

The different yet practicable alternatives of a process are generated through various process synthesis techniques. These alternatives, usually a small number of possibilities, must be evaluated in order to meet the most favorable process solution. For this reason, suitable techniques for analyzing the alternatives must be used, taking both design economics and hygienic design criteria into consideration.

1.2 SOCIOECONOMIC AND TECHNICAL CONTEXT

Concepts that apply to (1) the agro-industrial system and food chain and (2) the food processing system, auxiliary systems (or utilities), and food processing plant will be discussed next.

1.2.1 Agro-Industrial System and the Food Chain

According to Austin (1981), the agro-industrial system can be defined as a system encompassing all persons, companies, and institutions involved in activities concerning agricultural and fishing production, processing or manufacturing, transport, storage, financing, commercialization, and regulation of food products.

The term arouses interest because analysis of this system helps in the overall design and execution of agro-industrial projects, since it examines three main food factory activities: gathering of raw matter, processing or transformation, and commercialization of final products. The importance of analyzing this system is clearly reflected in the following example, in Austin's words (1981): "...a government of an Occidental African country adopted an agro-industrial development strategy in order to maximize the added value of the agro-industrial products in the country. This country had been exporting cotton seeds for a long time; for this reason, the government accepted the idea of building of a cotton seeds oil extraction plant since it agreed with the strategy of developing the added value. The plant was built but the maximum process capacity was bigger than the available cotton seeds. So, a program aimed to increase the cotton production became necessary. This crop increasing led to the construction of a textile plant. At that time the cotton crop did increase, and in a considerable way, but it seemed that either the risk that the row of cotton had was too high, or there were too little benefits. The farmers kept on *rowing* substance farming giving them priority in harvest time. Consequently, there was a lack of labor for the cotton harvesting so large quantities of the mentioned crop were left in the fields. The cotton oil extraction factory and the textile plant functioned below its real process capacity. This led to import cotton thread. In

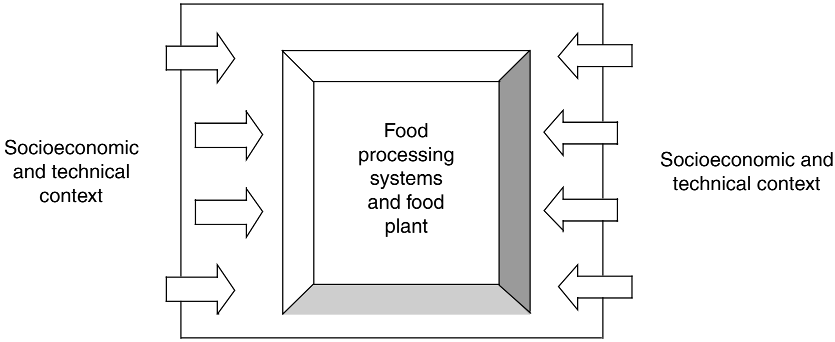

Figure 1.5 The socioeconomic and technical context exerts certain pressure on food processing systems and on corresponding food plant designs and operations.

addition to this, the cotton seed oil production was bigger than the maximum that the local refinery could absorb, so they were forced to export unrefined oil. In a similar way, the country lacked an internal market for the cotton seed residual because the feed industries weren't in the adequate development level to allow absorbing this secondary product. It had to be sent to the international market in a very low price at the time that the country imported expensive products as protein sources, for animal feeding. This example reveals all the handicaps that a limited point of view of the agro-industrial projects can bring..."

Therefore, all aspects referring to (1) raw matter, (2) products made in the food plant, (3) process technology and engineering, and (4) auxiliary systems engineering must be taken into account in the design of a food processing system and corresponding food plant. In fact, the success of a food plant depends on coherence between its design and the socioeconomic and technical context in which the food plant is submerged (Figure 1.5).

An interesting concept, the "food chain," represents the above-mentioned socioeconomic and technical context. According to Filka (1988), a typical food chain is vertically divided into four elements:

1. Agriculture and cattle production
2. Food processing (industry)
3. Distribution (retailers)
4. Consumption (consumers)

The food chain is closely linked to the agro-industrial system since the main function of both is to supply food to the population, thus meeting consumer demand and, at the same time, conducting an economic activity. This economic activity must also reach a maximum in global profit.

The successive loss that is possible in each step of the food chain can decrease global profit. Losses in mass are usually eliminated as wastes. In developed countries, 20% of this food loss results from agricultural production, 15% from processing, 5% from distribution, and 60% from consumption; 80–90% of overall production is used by the consumer. However, in developing countries, only 20–80% of overall food production is really used by the consumer (Filka, 1986, 1988). This means the food chain is not optimized in developing countries, in view of the fact that there are too many losses. According to Filka (1986), optimization of the food chain can be achieved if every step is optimized. It is in this overall approach that the optimization and design of a food processing plant should be included, as shown in Figure 1.6. This figure shows that food plant optimization is achieved through the design and operation optimization of food equipment and the processing system.

For example, food loss in the consumption sector could be reduced by modifying a product's properties during processing and packing, and similarly, losses in the agricultural and processing sectors by modifying the requirements for properties of raw matter. In fact, according to Filka (1988), to improve only the efficiency of the processing part in the chain may not be the best investment. This author proposes a procedure for mathematically modeling a food chain, to describe analytically the relationships between the individual chain elements and the inputs and outputs. In this manner, each chain element can be described by the following equations:

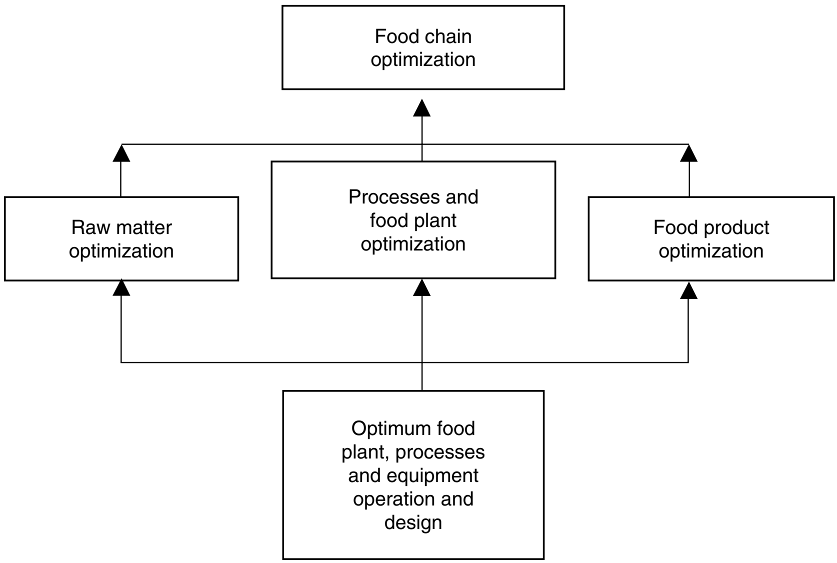

Figure 1.6 Food plant processing optimization involves food chain optimization, and vice versa.

- For cumulative investment requirements:

$$CI = \sum_{n=1}^{N} \left(M_n i_n \right) \tag{1.1}$$

- For cumulative mass loss:

$$CL = \sum_{n=1}^{N} \left(M_n l_n \right) \tag{1.2}$$

- For cumulative energy loss:

$$CW = \sum_{n=1}^{N} w_n \left(M_{n-1} q_{n-1} + M_n e_n \right) \tag{1.3}$$

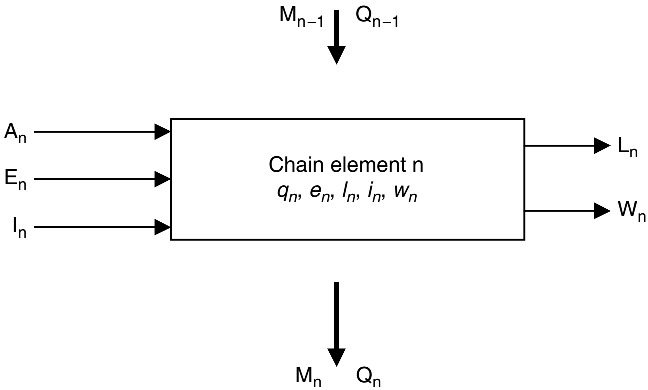

Figure 1.7 Food chain element inputs and outputs.

The different parameters are indicated in Figure 1.7, where A_n (in kg) represents the auxiliary materials and ingredients, E_n (in J) the energy inputs, I_n the investment depreciation and wages (in monetary units), L_n the mass loss (in kg), M_n and Q_n the mass and energy content of raw material or product (in kg and J, respectively), W_n the waste energy (in J), and e_n, i_n, l_n, q_n, w_n the fractional expressions of corresponding variables.

In cumulative mass loss, the loss of nutrients can be included. So, for every food chain element optimization the criteria should be defined as the maximum efficient and economic use of the following:

- Raw materials and nutrients
- Energy
- Money

In this way, the loss of mass, energy, and money will be minimal at the end of the completed food chain and within the boundaries, "from farm to table" (Filka, 1988).

1.2.2 Food Processing Systems, Auxiliary Systems, and Food Plants

The food processing system is an engineering system that transforms raw materials into food products ready for consumption by means of a series of unit operations. A processing system can also be defined as an aggregation or assemblage of equipment linked by some form of interaction or interdependence (Farrall, 1979). Either way, the processing equipment constitutes the processing system. Food processing equipment "manufactures" and transforms the raw materials, as well as configures the type of process engineering (or process system engineering) involved. Engineering puts into practice the process technology. In other words, process technology is related to how food products are manufactured, whereas process engineering is the physical support behind this technology.

Equipment in the processing system is interconnected by means of transport or the materials handling systems: belt conveyors, screw conveyors, hydraulic transport channels, pipes, and liquids pumping equipment, etc. A supply of electric energy, hot water or steam, cold water or cold air, and so forth is also needed for equipment operation. Additionally, all processing systems require devices to control and correct possible deviations in the established process conditions. In this way, the auxiliary systems service the food processing system, facilitating its proper operation. Good design of auxiliary systems is critical for the commercial success of a food processing plant. The materials handling systems, the energy handling systems, and the process control systems are all included in the auxiliary systems. The materials handling system includes:

1. Solids handling equipment:
   - Pneumatic transport installations
   - Mechanical transport installations (belt conveyors, screw conveyors, bucket elevators, etc.) (Figure 1.2)
   - Hydraulic transport installations
   - Installations for storage of solids
2. Liquids handling equipment:
   - Water treatment installations for steam generation and other uses (Figure 1.8)
   - Installations for storage and supply of water for both the process and steam generation

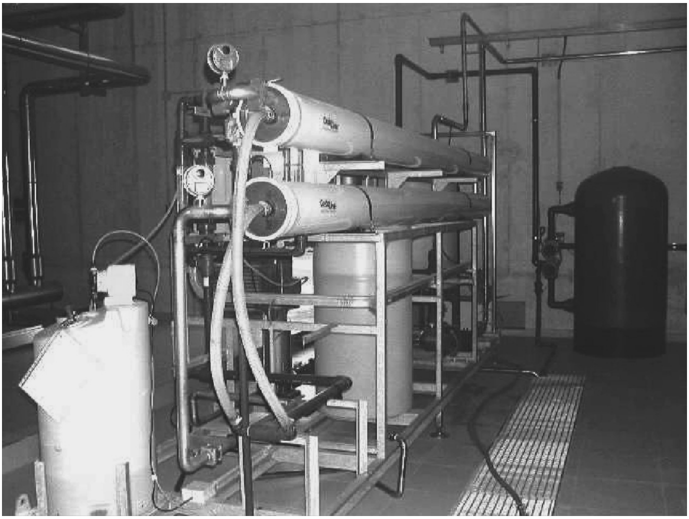

Figure 1.8 A water treatment installation by reverse osmosis in a food processing plant.

- Pumping and storage equipment for liquid foodstuff (Figure 1.9)

3. Handling of gas equipment:
   - Installations for generation and supply of compressed air
   - Installations for pressing, storage and distribution of non-combustible gases (e.g., CO_2 in beer factories or N_2 used as an inert atmosphere) (Figure 1.10)

4. Energy handling systems:

   - Installations for reception, storage and supply of combustibles (solid, liquid or gas) (Figure 1.11)
   - Steam generation and distribution installations, including the condensation return system (Figure 1.12)
   - Generation and distribution of combustion gases installations (e.g., in air heating, drying fruit by means of propane combustion gases)

Figure 1.9 System for transporting crushed grapes into fermentation tanks.

Figure 1.10 Installation for supply of nitrogen during juice bulk storage.

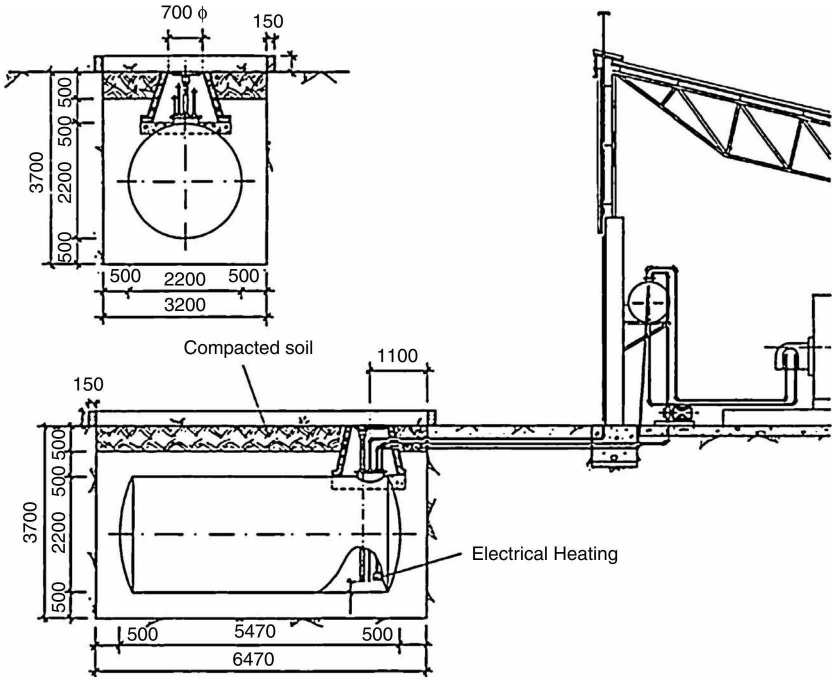

Figure 1.11 Installation of storage to supply fuel in a food by-products factory.

- Thermal fluids generation and distribution installations (e.g., hot water or overheated water for heating operations)
- Energy recovery installations (e.g., heat exchangers: air/air or liquid/liquid)
- Refrigeration installations for cooling of air, gases, solids, and liquids
- Installations for distribution and return of cold water during process (Figure 1.13)

Electrical installations could involve the energy handling system at a process plant level, which would include (1) connection to the main electrical line and transformer, and (2) power and lighting supply installations in the food processing plant.

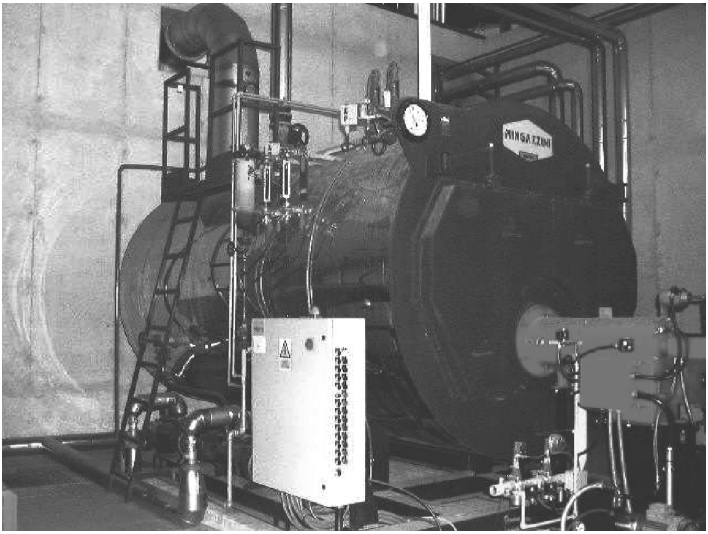

Figure 1.12 A steam generator in a food factory.

Thus, control systems that can ensure the processing system runs under desirable conditions will include all of the automatic control installations (Figure 1.14 and Figure 1.15).

In auxiliary systems, the following could also be considered (including in materials handling systems):

- Wastewater treatment installations (Figure 1.16)
- Safety systems, such as firewater installations
- Automatic cleaning systems (clean-in-place [CIP] systems)

Processing systems as well as auxiliary systems are placed in a logical manner in different buildings of the processing plant, wherein proper working conditions (comfort, hygiene, reliability, and safety) are also established. Therefore, the food processing plant or food plant comprises as a whole the food processing systems, auxiliary systems, and buildings (Figure 1.17 and Figure 1.18).

For example, an FMC® peach processing line (or system) in a corresponding peach plant is presented in Figure 1.17, in which the different processing plant operations are described here:

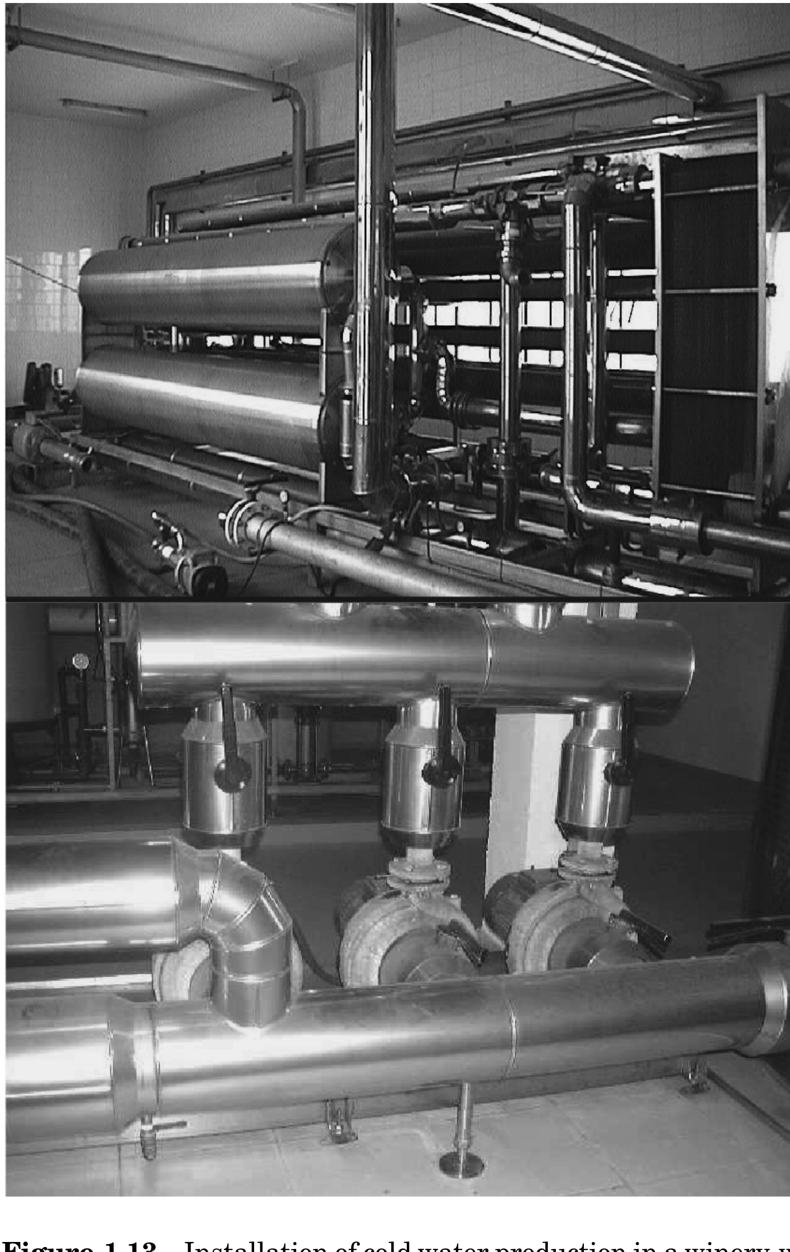

Figure 1.13 Installation of cold water production in a winery, with scraped surface heat exchanger and plate heat exchanger (top), and cold water pumping system in a juice factory (bottom).

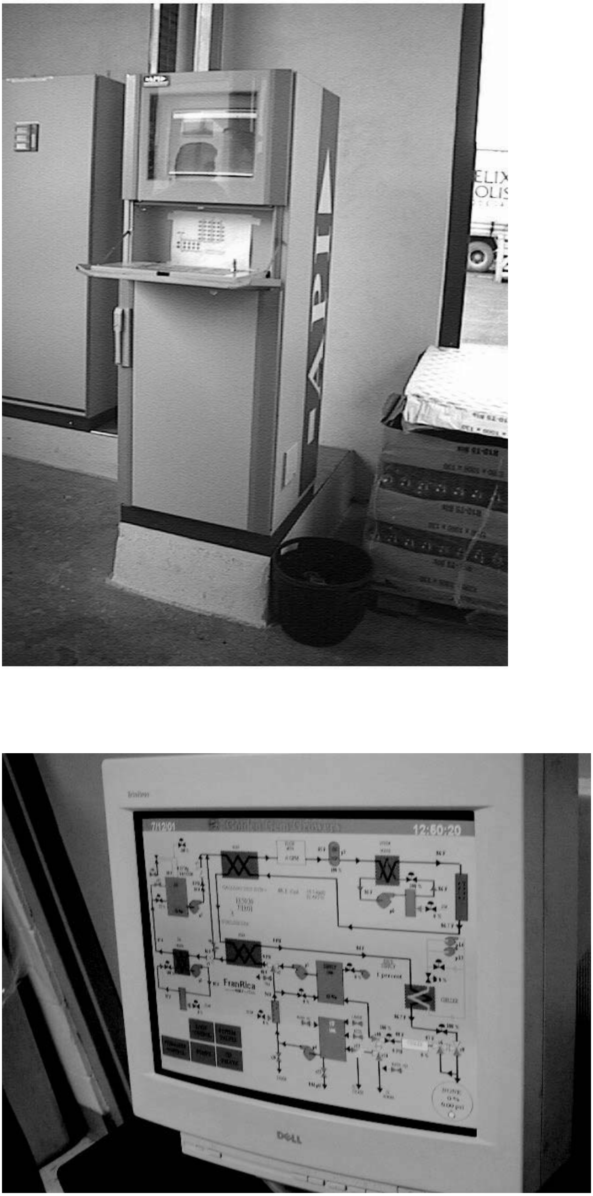

Figure 1.14 Wine-making control system (top), and juice bulk storage control system (bottom).

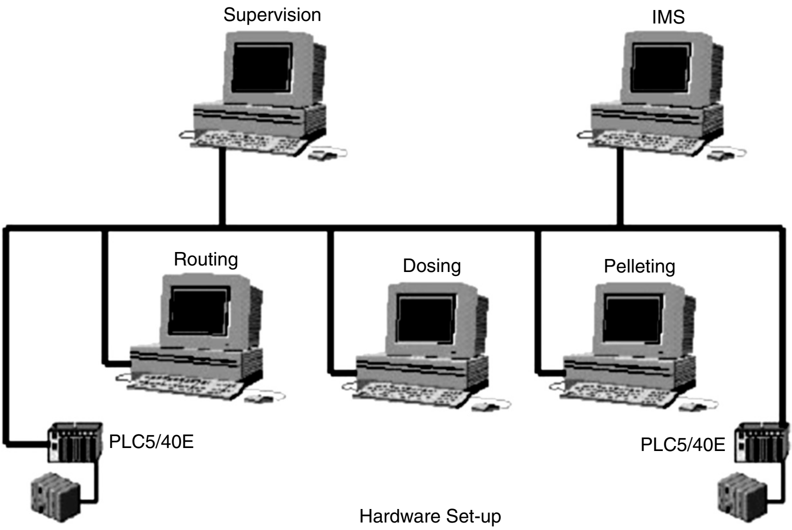

Figure 1.15 Feed manufacturing control system (courtesy of Norvidan Overseas, from www.norvidan.dk).

Figure 1.16 The wastewater treatment installation in the Arla Foods dairy factory (www.grundfos.com/dosing).

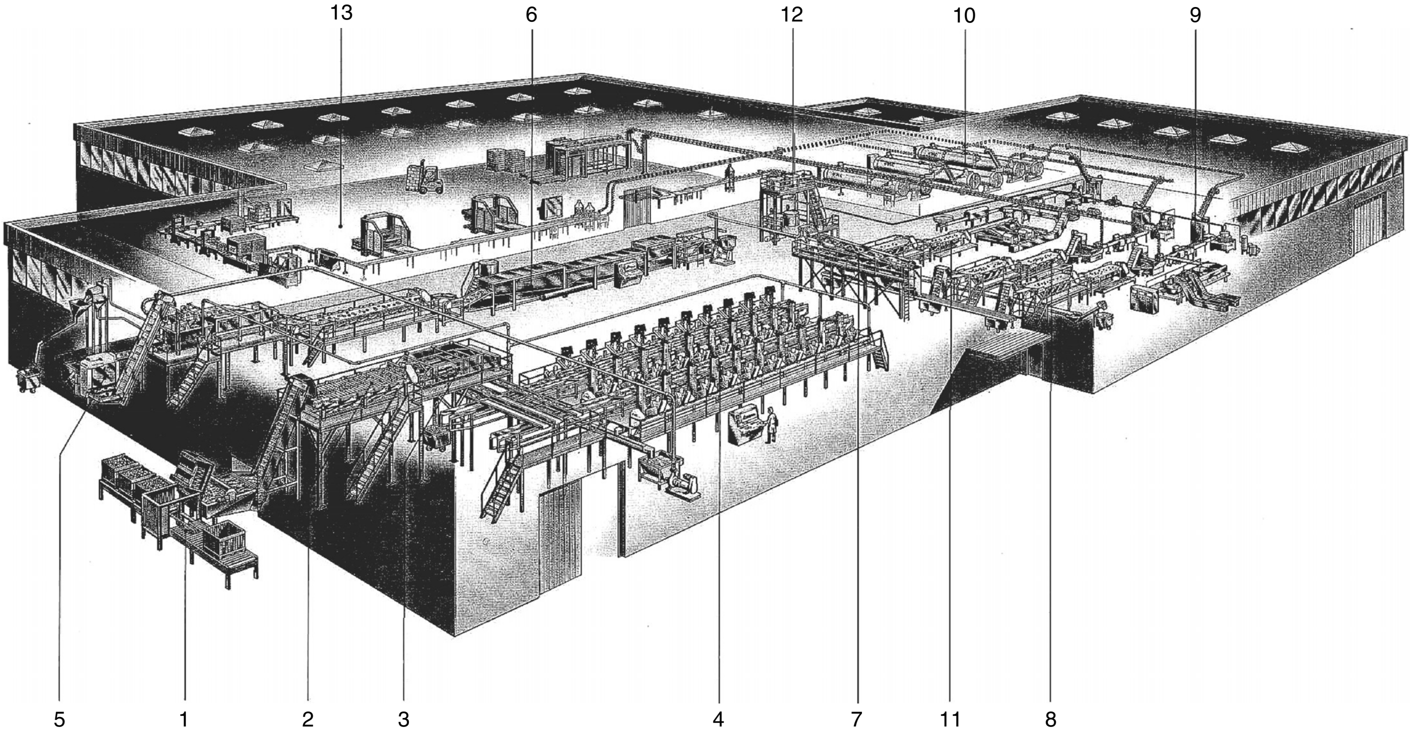

Figure 1.17 A peach processing line and corresponding processing plant (courtesy of FMC Food Tech, Chicago, Ill.).

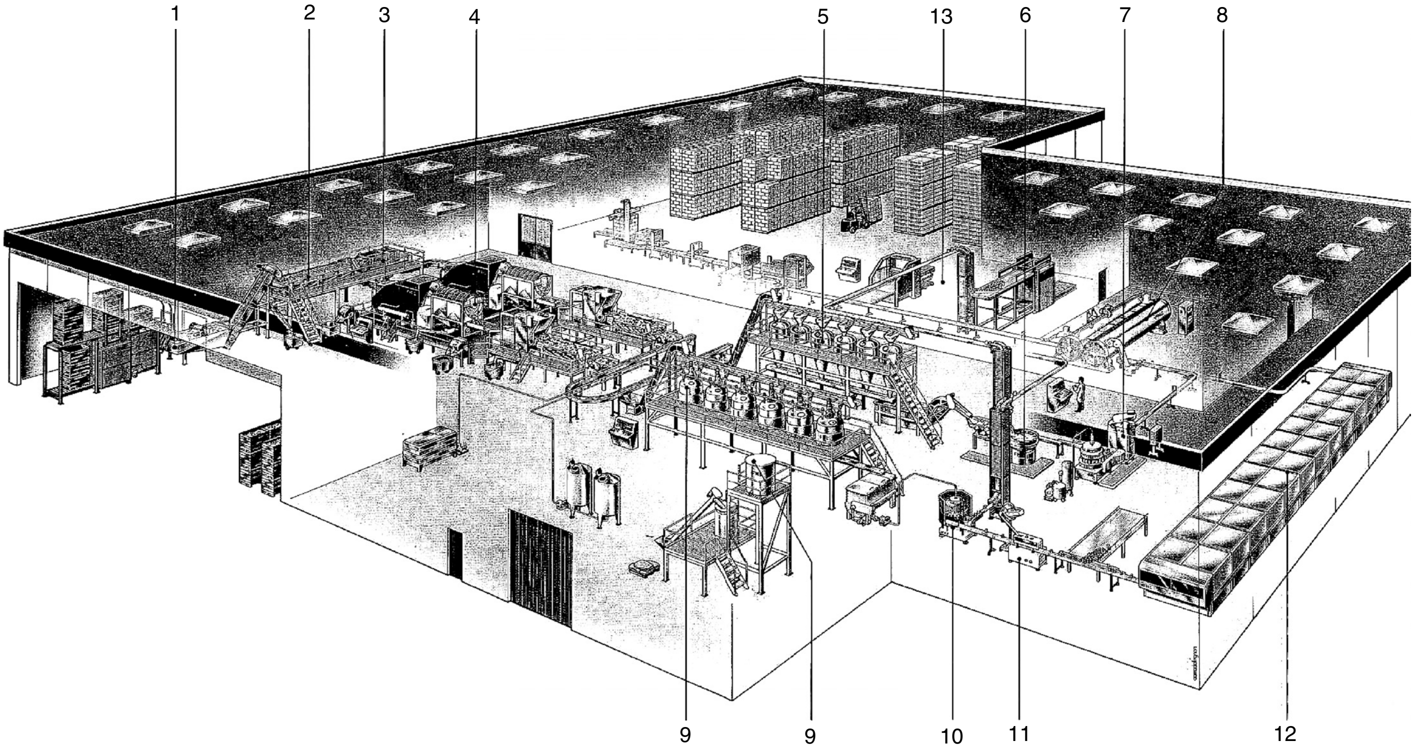

Figure 1.18 An apple processing line and corresponding processing plant (courtesy of FMC Food Tech, Chicago, Ill.).

1. *Receiving-dumping*. Upon arrival at the cannery, the bins are unloaded by forklift trucks (a component of the materials handling system) and stacked in holding areas. Bin dumpers (materials handling system) empty the bins into a water-filled tank, which cushions the fall of the product. An appropriate elevator (materials handling system) removes the product from the water, while freshwater spray washes the product before discharge (the washing machine is processing type equipment).
2. *Inspection*. A properly designed sorting belt allows inspection of the product before being processed. Unwholesome and immature fruits are removed at this point.
3. *Sizing and distribution*. Peaches are conveyed to a mechanical sizer (an equipment component of the peach processing system or line), which eliminates fruits too small and then separates the balance of the product into a number of different diameters according to pitting operation setup. Different grades are discharged onto a distributing belt (merry-go-round) and conveyed to the pitters.
4. *Pitting*. Whole peaches are delivered from the merry-go-round to the pitter through a feeder, and then transferred to the aligning section. Orientation begins immediately and continues until the peach is transferred to the pitting station. At this stage, the pit is oriented on the same vertical and horizontal center lines of the twist mechanism. The pit is held between two blades, while a pneumatic activated diaphragm envelops each half of the fruit, which rotates in less than one-half turns in opposite directions (counter-twisted). After the pitting cycle is completed, the cleanly pitted halves and the pit are discharged into a fluming system below the machines.
5. *Repitting*. The flume discharges the product into a vibrating pit separator, allowing the loose pits to fall through a perforated screen. A cup-up turnover orients all halves onto an inspection belt with the pit cavity up so that fruits containing pit fragments can

be removed and conveyed to the FMC repitters for final pit removal.

6. *Peeling*. This operation requires a peeler (processing equipment). In this case, the fruit peel is removed using an FMC lye peeler. The halved fruits are oriented with the pit cavity down by a cup-down turnover, transferred into a chemical application section, held by steam, washed, and rinsed. Here, the skin disintegrates and is washed out without harming the flesh.
7. *Size grading of halves*. The peeled peach halves are pumped into an FMC shaker sizer (processing equipment). Perforated screens set in descending steps separate the halves into four diameter sizes, plus an oversize one. The four grades are conveyed to the sorting area while the oversized fruit is delivered to the slicing line.
8. *Sorting and filling*. Inspection of the fruit prior to filling is completed on the halves while in cup-up and cup-down positions on a properly designed sorting belt. Inspectors sort the halves for uniform colors and defects. The product suitable for canning is automatically transferred into cans by an FMC halves filler fed through a vibrating bed.
9. *Syruping and closing*. The filled cans are fed into an FMC prevacuumizing syruper. The syruper is set for a specific can size and grade of syrup. The cans and contents are completely vacuumized and then filled with syrup to a predetermined headspace. The syruper is synchronized with a closing machine. The closer directs a jet steam across the top of the can to remove air from the headspace before sealing the can lid onto the can. This operation provides a final vacuum in the can when the steam condenses. The closed cans now proceed to the pasteurization and cooling equipment.
10. *Pasteurization and cooling*. FMC continuous rotary cookers are extensively used for applications requiring some automation and high thermal efficiency. The

seamed cans enter the pasteurizer through a feed device, which delivers the cans to the revolving reel in the cooker. The reel, working in conjunction with the stationary spiral, carries the cans through the cooking steam. The continuous spiral motion through the cylinder ensures an even processing of every can. At the end of the cooking process, the cans are fed via transfer mechanism into the cooler unit, where a similar process slowly cools the cans under pressure.

11. *Slice canning*. Halves size-graded from oversized fruit and fruit that fails to make graded halves are normally destined for slicing. These fruits are fed into a cup-down turnover, then onto a single filling belt, and through a slicer. A set of rotary knives cut the peaches in half into the desired number of segments. The slices are next inspected for blemishes and other defects. Upon completion of inspection, the slices are conveyed to the FMC volumetric filler for filling to a prescribed weight. Vacuum syruping, closing, sterilizing, and cooling operations are performed as described for peach halves.
12. *Syrup preparation plant*. Syrup is prepared in jacketed kettles and then transferred to the holding tank located in the upper part of the platform. The hot syrup is next conveyed by gravity to the syrupers by means of sanitary piping connections.
13. *Packaging and warehousing*. Following the sterilization process, the finished canned product is handled in various ways. The cans may be conveyed directly to packaging lines for labeling, packed in fiber cartons, sealed by compression, and stacked on shipping pallets. Cases can then either be shipped immediately or stored in the warehouse. Alternatively, the cans may be conveyed to a palletizing machine where they are stacked in layers and unlabeled on a warehouse pallet. This method, referred to as bright stacking, allows the canner to delay the labeling operation. The palletizing machine can be used as a depalletizing unit during the labeling operation in off-season;

the bright stacked pallet is mechanically depalletized and the cans are labeled and packaged as described above.

Figure 1.18 shows another example of an apple processing plant, consisting of the (1) receiving and dumping installation, (2) inspection system, (3) mechanical sizer, (4) peeling, coring and slicing systems, (5) deaerating plant, (6) product filling system, (7) syruping and closing systems, (8) can pasteurization and cooling systems, (9) compote preparation installation, (10) jar filling system, (11) jar closing system, (12) jar pasteurization and cooling system, and (13) packaging and warehousing systems.

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2

Mathematical Modeling of Food Processing Systems and Food Plant Simulation

2.1 TRANSFER PHENOMENA AND PROPERTY BALANCE

2.1.1 Transfer Phenomena

The physical state of a body is absolutely defined when the following characteristics are established:

- Quantity of matter and composition
- Total energy (internal, electric, magnetic, potential, kinetic, etc.)
- Components of the velocity at which the body is circulating

The changes that take place during a unit operation in raw matter or an intermediate product are

- Changes in mass or composition (phase separation, blending, transformation by biochemical reactions, etc.)

- Changes in level or quality of the energy in the product (cooling, vaporization, heating, pressure increasing, etc.)
- Changes in motion conditions (increasing velocity or changing direction, etc.)

In addition, changes taking place in a system must be in accordance with the following conservation laws (Welty et al., 1997):

- Law of conservation of mass
- Law of conservation of energy
- Law of conservation of momentum

Generally, the changes that occur in a system, body, or product during a unit operation can be carried out by means of the mass, energy, and momentum transfer phenomena. In fact, when a system is not in a state of equilibrium, it is inclined to achieve it; as the system approaches equilibrium, such transfer phenomena properties will take place. Mass, energy, and momentum are designated as properties of transfer phenomena since they are considered properties of the system.

So, when there is a temperature difference between two points in a system, the heat transfer phenomenon takes place, from a point of greater temperature to a point of lower temperature. This transfer takes place until a state of equilibrium is reached, where all points in the system are at the same temperature.

As an example, the heat transfer phenomenon is shown during the cooling of fruit in cold storage in Figure 2.1. Temperature of the fruit arriving from the field is 25°C, while the air in the cold chamber is 0.5°C. The heat transfer phenomenon takes place within the fruit (in this case, the fruit is the system) because the skin, the exterior part of the system, is in contact with the air temperature (0.5°C) and the internal points of the fruit (25°C). The heat is transferred from the internal points of greater temperature (Ti) to the skin points of lower temperature (Te) until all points, external and internal, are at the cold chamber air temperature (0.5°C). In this situation, the fruit — the system — is at a state of equilibrium

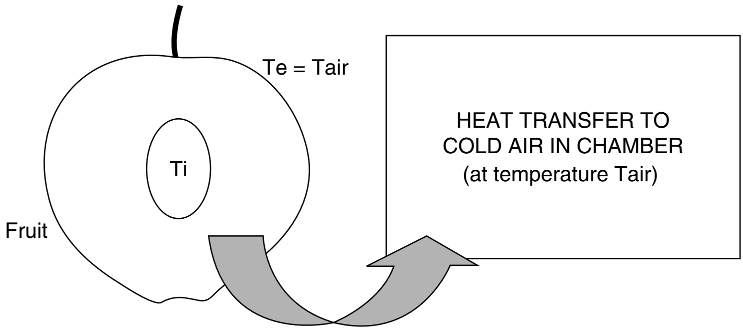


Figure 2.1 Heat transfer from the fruit to the cold air.

with respect to temperature. This equilibrium situation changes, however, because the cold chamber air temperature will increase over time due to heat entering through the walls. Then, as the air temperature becomes greater than 0.5°C, heat transfer occurs again from the air to the fruit, which is colder than the air in the chamber. When the air temperature is too high (e.g., 1°C), the evaporator of the refrigeration system is switched on to cool the chamber air until an air temperature of 0.5°C is reached. Now, since the air temperature is lower than the fruit temperature (close to 1°C), heat transfer takes place again from the internal to the external points of the fruit, and from here to the air, until a new equilibrium state is reached.

Heat transfer density within a solid body is given by Fourier's equation:

$$\vec{q} = -k \cdot \vec{\nabla} T \tag{2.1}$$

where q is the heat transfer density (J/s.m^2), k is the conductivity coefficient (J/s.m°C), and ∇T is the gradient of temperature between the different points of the solid (°C/m). From this equation, heat is transferred from points in the solid at greater temperature to respective points at lower temperatures.

When there is a velocity difference between two points in a fluid (Figure 2.2), a momentum transfer phenomenon

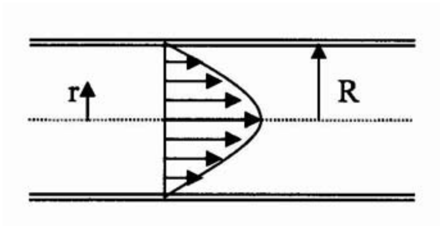


Figure 2.2 A velocity profile in a liquid circulating at laminar regime in a cylindrical tube.

takes place, from points at greater velocity to points at lower velocity. This transfer phenomenon takes place until the equilibrium state is reached, where all points are at the same velocity.

Fgure 2.2 shows the velocity profile of a liquid circulating at laminar regime in a cylindrical tube. The system (the fluid) is not at equilibrium because there is a velocity difference between the points in the fluid located at different distances r from the tube center (with $r \leq R$).

In this case, Newton's equation for a Newtonian liquid circulating in laminar flow between two parallel planes is given by

$$\tau_{yx} = -\mu \cdot \frac{dv_x}{dy} \tag{2.2}$$

where τ is the shear stress (Pa), μ is the viscosity of the liquid (Pa.s), and dv/dy is the shear rate or velocity gradient (s^{-1}) between the different points in the fluid. This expression shows the relationship between the deformation of the fluid (given by the velocity gradient) and the cause of this deformation, the shear stress.

In the same manner, when there is a difference in concentration between the points of a system, the mass transfer phenomenon takes place, from points at greater concentration to points at lower concentration, until all points are at the same concentration. This is the equilibrium state of the system.

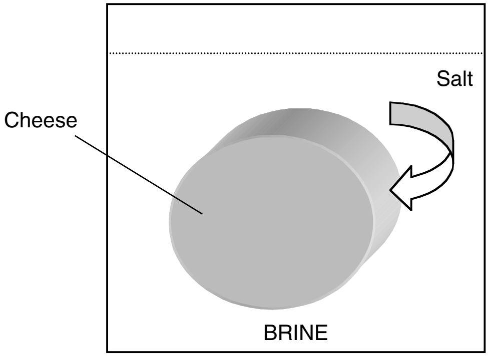


Figure 2.3 Brine salting of cheese curd.

For example, during brine salting of cheese curd (Figure 2.3), salt penetration takes place transferring from the brine to the internal parts of the cheese. Salt transfer phenomenon occurs because the concentration of salt in the brine (and in the external points of the cheese in contact with the brine) is greater than in the internal points of the cheese. There is a situation of nonequilibrium with respect to the salt concentration within the system of the cheese. This salt transfer takes place until all points of the system have the same salt concentration, which will be approximately the salt concentration of the brine.

Mass transfer density is given by Fick's equation:

$$\vec{\eta} = -D \cdot \vec{\nabla} \rho \tag{2.3}$$

where η is the mass transfer density (kg/s.m^2), D is the coefficient of diffusion (m^2/s), and $\nabla\rho$ is the gradient of concentration (kg/m^3.m).

From the above laws of Fourier, Newton, and Fick, it is deduced that the property transfer rate is directly proportional to the property gradient. The greater the property gradient, the greater the transfer rate — that is, the greater the temperature difference, the greater the heat transfer rate; and the higher the velocity gradient in a Newtonian fluid, the higher the momentum transfer rate; and the greater the concentration difference, the greater the mass transfer rate.

On the other hand, property transfers (of mass, energy, and momentum) can take place by means of two mechanisms: molecular and turbulent transport.

Molecular transport is based on the interaction between individual molecules or the motion of such. This is the case, for example, of heat transfer through a stationary solid material (the wall of a tank, the insulated wall of a cold chamber, etc.).

Turbulent transport is based on the motion of large groups or clusters of molecules, which transport mass, energy, and momentum at the same time. There is also interaction between groups or clusters of molecules. The mechanism of turbulent transport is evidenced only in fluids, while molecular transport takes place in solids and fluids.

2.1.2 Macroscopic Balances and Physical Properties

2.1.2.1 Mass Balance

Given an open system, there are T mass inlet and outlet flow streams, with S mass components in each stream, as shown in Figure 2.4.

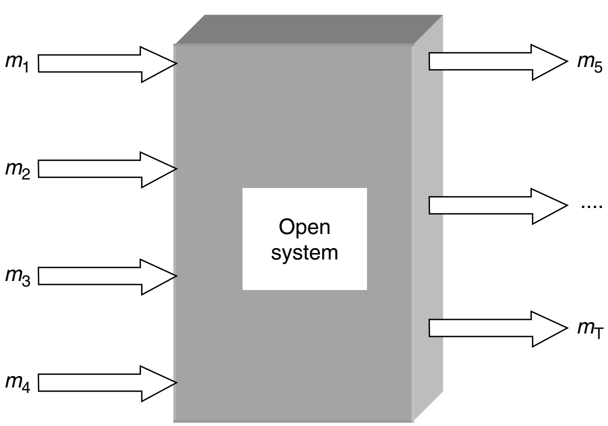


Figure 2.4 An open system with mass inlet and outlet streams.

The mass macroscopic balance applied to this system is given by the relationship

$$\left\{\begin{array}{c}\text{Rate of mass}\\ \text{accumulation in}\\ \text{the system}\end{array}\right\}=\left\{\begin{array}{c}\text{Net rate of}\\ \text{mass entering}\\ \text{the system}\end{array}\right\}+\left\{\begin{array}{c}\text{Rate of mass}\\ \text{generation in}\\ \text{the system}\end{array}\right\}$$

When this balance is applied for only one component, *j,* as indicated above, this relationship takes the following form:

$$\frac{dn_j}{dt}=\sum_{m=1}^{T}\dot{m}_{m,j}+R_j \qquad \left(j=1,2,\ldots,S\right) \tag{2.4}$$

where dn_j/dt represents the variation with time of the mass quantity of component j in the system (n_j), that is, the accumulation term; $\dot{m}_{m,j}$ represents the mass rate of component j, which moves in or out of the system via stream m, considering T streams in or out. Finally, Rj is the quantity of component j generated per unit of time in the system.

In the case of steady-state systems, such as process equipment working continuously (heat exchangers, freezers, refrigeration systems, etc.), this mass balance can be simplified to where there is only one inlet for mass flow, this one corresponding to the product (or refrigerant in the case of a refrigeration system). When the inlet mass flow is equal to the outlet mass flow, there is no accumulation of refrigerant in the elements of the refrigeration system. The equipment will be in steady state, without a mass generation term, the equation for which (with only one component) follows:

$$\sum_{m=1}^{T}\dot{m}_m=0 \tag{2.5}$$

2.1.2.2 Energy Balance

Usually, knowledge of the mass macroscopic balance — for example, the system's thermal behavior — is not enough. It would be useful to know the temperature of each stream, the amount of thermal energy that is exchanged in particular equipment, and similar information. Thus, it becomes necessary to apply an energy macroscopic balance to the system.

The different kinds of energy that take part in the energy macroscopic balance are (Costa et al., 1994)

- Internal energy (U_i)
- Potential energy (ϕ)
- Kinetic energy (K)
- Heat (Q)
- Work (W)

The first three kinds of energy are state functions, while heat and work depend on thermodynamic processes occurring as mass flows along the system. Heat and work are types of energy exchanged between the system and the surroundings through the walls of the system, and these energies are not associated with mass flows. Usually, internal energy, heat, and work are considered in the energy macroscopic balance around different food processing equipment and elements of the refrigeration system, while variations in the potential and kinetic energies are negligible.

Internal energy (U_i) is the sum of the energies of the particles that constitute a substance. These particles (atoms, molecules, ions, etc.) are in continuous motion (rotation, vibration, and translation), and the total internal energy of the system is the sum of energies of these particles due to their motions. The value of the internal energy is a function of the amount of matter, specific heat, and temperature of the system. Thus, for a mass n of a substance, the internal energy is given by the following equation:

$$U_i = \int_n \hat{c}_v \cdot T \cdot dn \tag{2.6}$$

where $\hat{c}_v$ is the specific heat at constant volume and T is the temperature.

The heat term (Q) is the heat exchanged between the system and the surroundings, and depends on the difference in temperatures between both sides of the exchange surface.

The heat transfer per unit of time between the system and the surroundings is given by this equation:

$$\dot{Q} = A \cdot U \cdot \Delta T \tag{2.7}$$

where U is the overall coefficient of heat transfer (J/m^2·°C·s), A the exchange surface (m^2), and ΔT is the difference in temperatures between the system and the surroundings (°C).

Work (W) can be mechanical, thermal, or electrical. In this case the mechanical work of compression is the integral of the product of a force F and distance (x). For fluids compressed within a closed system, work is given by the following equation:

$$W = \int_x F \cdot dx = \int_x p \cdot S \cdot dx = \int_V p \cdot dV \tag{2.8}$$

When an open system is represented by a block (Figure 2.4), with mass flows taken in and out, the energy macroscopic balance is given by the expression

$$\left\{ \begin{matrix} \text{Rate of accumulation} \\ \text{of} \\ \text{energy} \end{matrix} \right\} = \left\{ \begin{matrix} \text{Net rate of} \\ \text{energy entering} \\ \text{system} \end{matrix} \right\}$$

Since only energy forms that are state functions can be accumulated in the system (internal, kinetic, and potential energy), the above accumulation term is given by

$$\left\{ \begin{matrix} \text{Rate of accumulation} \\ \text{of energy} \end{matrix} \right\} = \frac{d}{dt}\left(U_i + K + \Phi\right) \tag{2.9}$$

Within the energy net rate term, there are two kinds of energy: energy associated with the in and out mass rates, and energy exchanged with the surroundings of the system:

$$\left\{ \begin{matrix} \text{Net rate of} \\ \text{energy entering} \\ \text{system} \end{matrix} \right\} = \begin{matrix} \sum_m \hat{U}_{i,m} \cdot \dot{m}_m + \sum_m \hat{K}_m \cdot \dot{m}_m + \\ \sum_m \hat{\Phi}_m \cdot \dot{m}_m + \sum_m p_m \cdot S_m \cdot v_m \end{matrix} \tag{2.10}$$

where

- $\hat{U}_{i,m}$ = Internal energy per unit of mass of the stream m
- $\hat{K}_m$ = Kinetics energy per unit of mass of the stream m
- $\hat{\phi}_m$ = Potential energy per unit of mass of the stream m
- p_m = Pressure of the stream m, at inlet of the system
- S_m = Crossing section of the stream m, at inlet of the system
- v_m = Average velocity in the stream m

The product $S_m \cdot v_m$ is the volume rate, which is the same as $\dot{m}_m \cdot \hat{V}_m$. The enthalpy per unit of mass is given by

$$\hat{H}_m = \hat{U}_m + p_m \cdot \hat{v}_m \tag{2.11}$$

Thus, the overall energy balance is the following:

$$\frac{d}{dt}\left(U_i + K + \Phi\right) = \sum_m \left(\hat{H} + \hat{K} + \hat{\Phi}\right)_m \cdot \dot{m}_m + \dot{Q} + \dot{W} \tag{2.12}$$

This expression of the energy macroscopic balance is difficult to use, however, because absolute values of enthalpy and kinetic, internal, and potential energies are used. It is necessary, therefore, to transform this expression into one written in relative values. These reference values can be defined by means of temperature for the enthalpy H^*, a distance above the ground, or another reference point, for the potential energy Φ^*, and a coordinates system for the kinetic energy K^*.

The expression for the overall energy balance with these reference values is

$$\begin{gathered}\frac{d}{dt}\left(U_i - H^* + K - K^* + \Phi - \Phi^*\right) = \\ \sum_m \left(\hat{H} - \hat{H}^* + \hat{K} - \hat{K}^* + \hat{\Phi} - \hat{\Phi}^*\right)_m \cdot \dot{m}_m + \dot{Q} + \dot{W} + \frac{d\left(\rho \cdot V\right)}{dt}\end{gathered} \tag{2.13}$$

The variation in internal energy can be written as

$$\frac{dU_i}{dt} = \frac{dH}{dt} - \frac{d\left(p \cdot V\right)}{dt} \tag{2.14}$$

Then the expression for the macroscopic energy balance will be

$$\frac{d}{dt}\left(U_i - H^* + K - K^* + \Phi - \Phi^*\right) = \sum_m \left(\hat{H} - \hat{H}^* + \hat{K} - \hat{K}^* + \hat{\Phi} - \hat{\Phi}^*\right)_m \cdot \dot{m}_m + \dot{Q} + \dot{W} \tag{2.15}$$

This general equation can be simplified. For example, in macroscopic energy balances applied to food processing systems, the possible variations in kinetic and potential energies are negligible. In this case, Equation 2.15 will be transformed as follows:

$$\frac{d}{dt}\left(H - H^*\right) = \sum_m \left(\hat{H} - \hat{H}^*\right)_m \cdot \dot{m}_m + \dot{Q} + \dot{W} + \frac{d\left(p \cdot V\right)}{dt} \tag{2.16}$$

When there is heat generation in the system, and the system works at constant pressure and volume, the energy balance is given by the equation

$$\frac{d}{dt}\left(H - H^*\right) = \sum_m \left(\hat{H} - \hat{H}^*\right)_m \cdot \dot{m}_m + \dot{Q} + \sum_j R_j \Delta\hat{H}_j^* \tag{2.17}$$

where ΔH is the reaction enthalpy of food processing operations like fermentation (in making alcoholic drinks such as wine, beer, and cider), barley germination (in malting plants), and cold storage of fruits and vegetables (where respiration of fruits and vegetables is a process that generates heat).

If the system is in steady state and there is no heat generation because it is working continuously and the biochemical reactions are negligible (e.g., as occurs in continuous heat exchangers or concentration systems by evaporation), the Equation 2.17 is transformed as

$$0 = \sum_m \left(\hat{H} - \hat{H}^*\right)_m \cdot m_m + \dot{Q} \tag{2.18}$$

where Q is the heat exchanged with the surroundings through the walls of the system. Generally, if the system is insulated, the Q value is negligible with respect to the enthalpy entering and leaving the system associated with the mass flow of the different mass streams. In this case, Equation 2.18 is reduced to

$$0 = \sum_{m} \left(\hat{H} - \hat{H}^*\right)_m \cdot \dot{m}_m \tag{2.19}$$

2.1.2.3 Momentum Balance

In operations with changes in momentum, as occurs in fluid transport through tubes or in other unit operations, there are problems that cannot be solved by means of applying mass and energy conservation laws only. For example, the calculation of falling velocity of a solid spherical particle within a fluid (sedimentation operation) cannot be completed using only mass and energy balances. It is necessary to apply the momentum balance.

A system with mass n increases the velocity and, in this manner, the momentum ($\vec{P}$) given by the equation:

$$n \cdot \vec{v} = \vec{P} \tag{2.20}$$

if, and only if, a force acts on this system. In this case, the momentum change and the force acting on the system are related by means of the following expression:

$$\vec{F} = \frac{d(n \cdot \vec{v})}{dt} \tag{2.21}$$

In an open system, the momentum balance or the expression of the momentum conservation law will be a force balance, and it is given by

$$\begin{Bmatrix} \text{Rate of accumulation} \\ \text{of momentum in the} \\ \text{system} \end{Bmatrix} = \begin{Bmatrix} \text{Net rate of} \\ \text{momentum entering} \\ \text{the system} \end{Bmatrix} + \begin{Bmatrix} \text{Sum of forces} \\ \text{acting on the system} \end{Bmatrix}$$

It is interesting to note that in fluids circulation (fluid dynamics) the system is the fluid portion, without considering the container (e.g., the tube within which the fluid circulates). But with the problem of particles falling within a fluid, the system is the particle and the fluid the surroundings.

The momentum accumulation term is

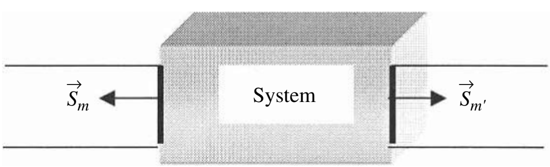
$$\frac{d(n \cdot \vec{v})}{dt} = \frac{d(\vec{P})}{dt} \tag{2.22}$$

The mass flow entering through each stream, m, is $\dot{m}_m$ (a quantity of mass per unit of time, in kg/s). Then, if v_m is the mean velocity of the mass stream m, and there are T streams (crossing T inlet and outlet sections), the net rate of momentum entering the system is given by the equation

$$\sum_{m=1}^{T} \dot{m}_m \cdot \vec{v}_m \tag{2.23}$$

where the momentum given out is negative and the momentum taken in is positive.

The force acting on cross section m (of stream m) due to pressure p_m is



and the force acting on cross section m' (of stream m' at the outlet) due to pressure $p_{m'}$ is

$$+p_{m'} \cdot \vec{S}_{m'} \tag{2.24}$$

In this manner, the net force due to pressure acting on the system is given by

$$-\left(p_m \cdot \vec{S}_m - p_{m'} \cdot \vec{S}_{m'}\right) \tag{2.25}$$

The negative sign means the force taken into the system is negative, while the force given out is positive because the surface vector is oriented out of the system. In the system with T streams (with T inlet/outlet cross sections), the forces acting on the inlet/outlet cross sections are

$$-\sum_{m=1}^{T} p_m \cdot \vec{S}_m \tag{2.26}$$

When the system has a mass n, the gravity force ($\vec{g}$) is

$$n \cdot \vec{g} \tag{2.27}$$

The force from the system acting on the surroundings has a negative sign; it also is the force resulting from the momentum balance. This force is manifested as pressure of the fluid on the tube and friction on the tube walls. In this manner, the momentum macroscopic balance is given by the equation

$$\frac{d(n \cdot \vec{v})}{dt} = \sum_{m=1}^{T} \dot{m}_m \cdot \vec{v}_m - \sum_{m=1}^{T} p_m \cdot \vec{S}_m + n \cdot \vec{g} - \vec{F} \tag{2.28}$$

As this balance has vectorial character, it must be solved with respect to a system of coordinates. As an example, this momentum balance can be applied to study the gravity sedimentation operation of solid particles within a food fluid (like the clarification of grape juice in white wine-making). In this case (Figure 2.5), the solid particle, with mass n and density ρ, is considered as a sphere suspended within a fluid with density ρ_f. The macroscopic balance of forces is given by Equation 2.29:

$$\frac{d(\vec{P})}{dt} = n \cdot \vec{g} - \vec{F} \tag{2.29}$$

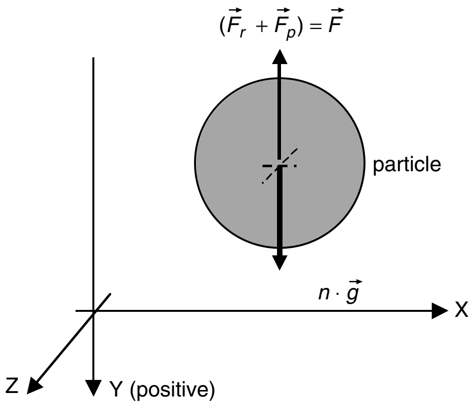


Figure 2.5 A solid particle within grape juice.

where force F is the sum of friction force F_r and the reaction force of the system (the particle) to the exterior pressure F_p (the particle is considered a solid that cannot be deformed). This force, due to exterior pressure, is given by Archimedes's principle (the ascendant force executed by the fluid on a solid immerged within is equal to the weight of the fluid displaced by the solid), and expressed as

$$\begin{aligned} \vec{E} &= \int_S p \cdot d\vec{S} = -\rho_f \cdot V \cdot \vec{g} = -\vec{F}_p \\ \vec{E} &= -\vec{F}_p \end{aligned} \tag{2.30}$$

where V is the particle volume and p the exterior pressure. In this manner, the momentum balance is

$$\begin{aligned} \frac{d\vec{P}}{dt} &= n\vec{g} - \left(\vec{F}_p + \vec{F}_r\right) \\ \frac{d\vec{P}}{dt} &= \rho_s V\vec{g} - \rho_f V\vec{g} - \vec{F}_r = \left(\rho_s - \rho_f\right) V\vec{g} - \vec{F}_r \end{aligned} \tag{2.31}$$

and, as all forces have the same direction (on the Y axis), Equation 2.31 can be expressed as

$$\frac{dP}{dt} = \left(\rho_s - \rho_f\right)Vg - F_r \tag{2.32}$$

Experimentally, it is stated that the friction force is a function of kinetic energy of the particle per unit of mass ($v^2/2$), on the area A (projected by the particle on a plane perpendicular to the direction of the motion of the falling particle) and the density of the fluid:

$$F_r = C_D A \rho_f \frac{v^2}{2} \tag{2.33}$$

where C_D is a friction coefficient, which is a function of the motion conditions of the fluid. If it is considered that $A/V = 3/(2d_p)$ and $P = nv = \rho_s Vv$, Equation 2.33 can be written as

$$\begin{aligned} \frac{d(\rho_s Vv)}{dt} &= \left(\rho_s - \rho_f\right)Vg - C_D A \rho_f \frac{v^2}{2} \\ \frac{dv}{dt} &= \frac{\left(\rho_s - \rho_f\right)}{\rho_s} g - \frac{3}{4} C_D \left(\frac{\rho_f}{\rho_s}\right)\frac{v^2}{d_p} \end{aligned} \tag{2.34}$$

where v is the falling velocity of the particle and d_p is the particle diameter. From this equation, at the initial instant $v = 0$ and $F_r = 0$, the particle will start to ascend or descend (depending on whether $\rho_s<\rho_f$ or $\rho_s>\rho_f$). In this manner, the greater the particle velocity, the greater the force F_r becomes, until the value of F_r is equal to $(\rho_s - \rho_f)Vg$, the same moment at which the particle momentum is not altered and $dP/dt = 0$, when steady state is reached.

The limit velocity is reached, which is given by the equation

$$\begin{aligned} 0 &= \left(\frac{\rho_s - \rho_f}{\rho_s}\right) g - \frac{3}{4} C_D \left(\frac{\rho_f}{\rho_s}\right)\frac{v^2}{d_p} \\ v_s &= \left[\frac{4}{3}\frac{g}{C_D}\left(\frac{\rho_s - \rho_f}{\rho_f}\right)d_p\right]^{\frac{1}{2}} \end{aligned} \tag{2.35}$$

2.1.2.4 Physical Properties

To solve the mass, energy, and momentum balances in a food processing plant, it is necessary to know the physical properties of each substance acting in the system being studied, as listed here:

- Air (acting in food processing operations, such as drying, cold storage, freezing by cold air, germination ventilated with cold air, etc.; and in auxiliary systems, such as refrigeration systems, pneumatic transport systems, etc.)
- Water, as liquid or steam (in food processing operations such as cooling by water, heating by hot water, sterilization with steam, blanching with hot water, washing, etc.; and in auxiliary systems such as refrigeration systems, steam generation, distribution installations, etc.)
- Refrigerant fluids, such as those used in refrigeration systems (R-22, NH3, R-134a, etc.), used in most cooling and freezing processes in food factories
- Packaging materials (in cold storage, in thermal treatments with liquid or solid packed food, in packages such as glass bottles, plastic bottles or boxes, wood boxes, plastic film applied to the product, etc.)
- Food (liquid or solid, such as fruits, vegetables, liquid milk and milk products, meats and meat products, juices, etc.)
- Cleaning and sanitation chemicals used in CIP systems
- Construction materials of food processing equipment (such as stainless steel, rubbers, elastomers, and thermal insulation materials), floors, walls, and ceilings

It is also necessary to know the following physical properties:

- Density and specific gravity of solids: solid density, bulk density, liquid density, gases and vapor density, density of aerated products (overrun)

- Surface properties: surface tension, surface activity, interfacial tension, detergency, foaming, wettability
- Thermodynamic and thermal properties: specific heat, specific enthalpy, specific enthalpy of reaction, and latent heat for solids, liquids, gases, and vapors

Good books are available that deal with the physical properties of foods as well as those physical properties and principles involved in food processing operations, from which these properties can be obtained (Lewis, 1990; Jowitt et al., 1983; Mohsenin, 1980; Heldman and Lund, 1992; Heldman and Singh, 1981; Hayes, 1987; Peleg and Bagley, 1983; Perry et al., 1992; Rao and Rizvi, 1986; Singh and Medina, 1988; Toledo, 1994).

2.1.3 Microscopic Balances and Transfer Phenomena

The macroscopic balances described earlier result from the application of conservation laws to systems considered as black boxes. In this way, the relationships between entering and exiting property flows are obtained, also explaining the generation and accumulation of properties taking place within the system. It is actually not possible to know what occurs at each point in the system by means of these macroscopic balances.

For example, the system can be a batch dryer for walnuts (Figure 2.6). In this case, the walnut deep bed is located in a silo with a perforated floor, through which the hot air enters to dry the walnut.

Here, by means of macroscopic balances, the temperature and relative humidity of hot air at the inlet and outlet can be calculated. It is also possible to calculate the average moisture content of the dried walnut once the mass flow of dry air is known, as well as its moisture content and temperature at the dryer inlet and outlet, and the time interval that the hot air has been passed through. However, it is not possible to calculate the walnut's moisture content and temperature at each point within the dryer, or similarly, the relative humidity and temperature of hot air within the deep walnut bed in the silo dryer. In fact, the temperature of the hot air and the

Figure 2.6 Batch dryer for walnuts.

walnut changes as the layer rises in the silo dryer: the air temperature decreases and the moisture content and relative humidity of the air increases. At the same time, the higher the walnut layer becomes, the higher the moisture content.

To calculate the moisture content of the cereal at each point in the bed, it is necessary to apply microscopic balances of mass and energy to the system. As a result, the system is considered as a box filled with mechanisms, not as a black box.

2.1.3.1 Microscopic Mass Balance: Fick's Laws

To obtain microscopic balances, microscopic description parameters are used:

- Partial mass density ρ_j for the component j (kg/m^3), which is a function at locations (x, y, z) within the system and for time (t)
- Mass flow density n_j for the component j (kg/m^2.s), which is the mass quantity (kg) crossing over a unit of surface (m^2) in the system per unit of time (s), calculated as follows:

$$n_j = \rho_j \cdot v_j \tag{2.36}$$

- Velocity of the component j at each point v_j (m/s) in the system

It is considered a system immobile in space without displacements and with volume V and surface S. Thus, the mass balance for component j can be written as follows:

$$\begin{Bmatrix} \text{Rate of accumulation} \\ \text{of mass component } j \\ \text{in the system} \end{Bmatrix} = \begin{Bmatrix} \text{Net flow rate of mass} \\ \text{component } j \text{ entering} \\ \text{the system} \end{Bmatrix} + \begin{Bmatrix} \text{Generation of mass} \\ \text{component } j \text{ per unit of} \\ \text{time in the system} \end{Bmatrix}$$

The mass quantity of component j within the system is expressed as

$$\int_V \rho_j dV \tag{2.37}$$

where dV is a differential of volume for the system (m^3). Thus, the accumulation term in the above mass balance expression is

$$\frac{d}{dt}\int_V \rho_j dV \tag{2.38}$$

which represents the change in the time of mass of j component in the system; this is an accumulation term for mass balance expressed microscopically.

If the mass enters through the system's surface, and it is considered as a surface element dS, then the mass quantity entering the dS is

$$-\vec{n}_j \cdot d\vec{S} \tag{2.39}$$

When the mass flow leaves the system, the above scalar product must be positive. Therefore, the net mass flow rate of component j entering the system is

$$-\int_S \vec{n} d\vec{S} \tag{2.40}$$

On the other hand, if the mass generation of component j per unit of time and unit of volume is r_j, then the total mass of component j (Rj) in the system is

$$R_j = \int_V r_j dV \tag{2.41}$$

Thus, mass balance for component j can be written as follows:

$$\frac{d}{dt}\int_V \rho_j dV = -\int_S \vec{n}_j d\vec{S} + \int_V r_j dV \tag{2.42}$$

This expression can be converted to systems without biochemical reactions, by applying the Gauss-Ostrogradskii and Leibnitz principles:

$$\int_V \frac{\partial}{\partial t}\rho_j dV = -\int_V \left(\vec{\nabla}\vec{n}_j\right) dV \tag{2.43}$$

From this expression, the continuity equation for the j component becomes

$$\frac{\partial \rho_j}{\partial t} + \vec{\nabla}\vec{n}_j = 0 \tag{2.44}$$

which is the microscopic mass balance for the j component. The overall microscopic mass balance is the sum of S microscopic balances for S components.

$$\sum_{j=1}^{S}\frac{\partial \rho_j}{\partial t} + \sum_{j=1}^{S}\vec{\nabla}\vec{n}_j = 0 \tag{2.45}$$

If it is taken into account that

$$\sum_{j=1}^{S}\rho_j = \rho \tag{2.46}$$

and
$$\sum_{j=1}^{S} \vec{n}_j = \rho \cdot \vec{v} \tag{2.47}$$

then
$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \rho \vec{v} = 0 \tag{2.48}$$

where ρ is the overall density and v is the average velocity for all mass points entering the system.

In Equation 2.48, if the gradient vector is in rectangular coordinates:

$$\vec{\nabla} = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k} \tag{2.49}$$

then the equation of continuity is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}\left(\rho v_x\right) + \frac{\partial}{\partial y}\left(\rho v_y\right) + \frac{\partial}{\partial z}\left(\rho v_z\right) = 0 \tag{2.50}$$

In an immobile material, the heat and mass transfer phenomena mainly occur through the molecular transport mechanism; the turbulent transport mechanism is negligible. For this kind of material, the partial mass density or mass concentration of component j at a determined point and moment is

$$\rho_j = \rho_j\left(x, y, z, t\right) \tag{2.51}$$

The constant concentration surfaces in immobile material are given by this equation:

$$\rho_j\left(x, y, z, t\right) = constant \tag{2.52}$$

such that the concentration difference between two immediate surfaces is $d\rho_j$, a value infinitely small. The First Law of Fick is given as follows:

$$\vec{n}_j = -D_j \vec{\nabla} \rho_j \tag{2.53}$$

where D_j is the coefficient of diffusion. From this equation, the mass flow density vector is a function of the gradient vector of concentration. Thus, when a concentration gradient in the system exists, there is a mass flow density from points with greater concentration to zones with lower concentration, in contrast to the gradient vector (oriented from lower to greater concentration). Diffusion of mass occurs in a direction normal to constant concentration surfaces. With rectangular coordinates, and for cases in which the coefficient of diffusion is constant and equal at all points in the system, the mass flow density vector is given by

$$\vec{n}_j = -D_j \left(\frac{\partial \rho_j}{\partial x} \vec{i} + \frac{\partial \rho_j}{\partial y} \vec{j} + \frac{\partial \rho_j}{\partial z} \vec{k} \right) \tag{2.54}$$

From the continuity equation or microscopic mass balance, plus the above expression, the Second Law of Fick is obtained:

$$\frac{\partial \rho_j}{\partial t} = -\vec{\nabla} \vec{n}_j = -\vec{\nabla}\left(-D_j \vec{\nabla} \rho_j\right) = D_j \nabla^2 \rho_j \tag{2.55}$$

which is for rectangular coordinates and cases in which the coefficient of diffusion is constant and equal for all points of the system:

$$\frac{\partial \rho}{\partial t} = D_j \left(\frac{\partial^2 \rho_j}{\partial x^2} + \frac{\partial^2 \rho_j}{\partial y^2} + \frac{\partial^2 \rho_j}{\partial z^2} \right) \tag{2.56}$$

2.1.3.2 Momentum Balance: Newton's Law

By means of momentum microscopic balance, it is possible to know the velocity profile for the different points of a fluid circulating through a tube or within a particles bed.

The procedure to obtain the momentum microscopic balance is similar to one used for mass microscopic balance. The system is considered to have volume V and is enclosed in surface S. Therefore, the momentum is given by

$$\left\{\begin{array}{l}\text{Rate of accumulation}\\\text{of momentum}\\\text{in the system}\end{array}\right\} = \left\{\begin{array}{l}\text{Net flow rate of}\\\text{momentum}\\\text{entering the system}\\\text{through mass flow}\end{array}\right\}$$

$$+\left\{\begin{array}{l}\text{Net flow rate of}\\\text{momentum entering}\\\text{the system by}\\\text{molecular flow}\end{array}\right\} + \left\{\begin{array}{l}\text{Sum of}\\\text{exterior}\\\text{forces}\end{array}\right\}$$

where each representative term in brackets has a unit of force (N). The momentum per volume unit is given by this expression:

$$\rho \cdot \vec{v} \tag{2.57}$$

and the momentum of volume differential element dV by

$$\rho \vec{v} dV \tag{2.58}$$

From here, the momentum of a system with volume V is given by

$$\int_V \rho \vec{v} dV \tag{2.59}$$

and the momentum change in time for this system is

$$\frac{d}{dt} \int_V \rho \vec{v} dV \tag{2.60}$$

Given the mass flow density $\rho\vec{v}$, if considered as surface element $d\vec{S}$, the mass flow crossing this will be

$$\rho \vec{v} \cdot d\vec{S} \tag{2.61}$$

and the momentum flow rate crossing the surface element $d\vec{S}$ will be

$$\left(\rho\vec{v}\cdot d\vec{S}\right)\cdot\vec{v} \tag{2.62}$$

and crossing all of surface S in the system results in

$$-\int_S\left(\rho\vec{v}\vec{v}\right)\cdot d\vec{S} = -\int_V\vec{\nabla}\cdot\left(\rho\vec{v}\vec{v}\right)\cdot dV \tag{2.63}$$

If the molecular flow of momentum through the unit surface is $\vec{T}_m$, the molecular flow of momentum through all of surface S is expressed as

$$-\int_S\vec{T}_m dS \tag{2.64}$$

Regarding external forces, if $\rho\vec{g}$ is the force per volume unit due to gravity, the force acting on volume V is expressed as

$$\int_V\rho\vec{g}dV \tag{2.65}$$

On the other hand, the force due to pressure (p) acting on a differential element of surface is $-pd\vec{S}$, and the total pressure force acting on surface S of the system is

$$-\int_S pd\vec{S} = -\int_V\vec{\nabla}pdV \tag{2.66}$$

Thus, the expression for microscopic momentum balance becomes

$$\frac{d}{dt}\int_V\rho\vec{v}dV = -\int_V\vec{\nabla}\cdot\left(\rho\vec{v}\vec{v}\right)dV - \int_S\vec{T}_m dS + \int_V\rho\vec{g}dV - \int_V\vec{\nabla}pdV \tag{2.67}$$

2.1.3.2.1 Newton's Law

Consider an experimental situation in which a fluid is located between two parallel and horizontal planes, with area A, and

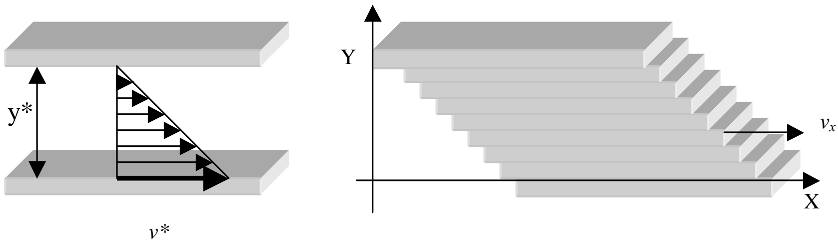


Figure 2.7 Fluid deformation with displacement of the different fluid layers.

at a distance with very little y^*. If the inferior plane begins moving with a constant velocity v^*, and the other superior plane remains immobile, it is observed that the fluid layer in contact with the moving plane is moved (gains momentum), and the remaining layers (ones in contact with the others) are put into motion at lower velocities since the layers are at a greater distance from the moving inferior plane. After a few minutes, a steady state is reached with a linear distribution of velocities. This is manifested as fluid deformation with displacement of the different fluid layers, one on top of the other, as shown in Figure 2.7.

With the velocity at direction X, v_x changes in a linear manner with distance y given by

$$v_x = v^* - by \tag{2.68}$$

where b is the slope of the linear distribution of velocities. To maintain the above condition in a steady state, it is necessary to apply continual force on the plane in direction X. This force F (N) is called shear force, and τ_{yx} (shear stress, N/m^2) is given as follows:

$$\tau_{yx} = \frac{F}{A} \tag{2.69}$$

where A is the area (m^2) on which force F is applied. In this example, the shear stress is the agent causing the velocity's gradient along axis Y. It is found experimentally for Newtonian fluids that slope b is directly proportional to the shear stress, which is expressed as follows:

$$b = \left(\frac{dv_x}{dy} \right) = -\frac{1}{\mu} \cdot \tau_{yx} \tag{2.70}$$

that is,

$$\tau_{yx} = -\mu \cdot \left(\frac{dv_x}{dy} \right) \tag{2.71}$$

This is Newton's Law, where the proportionality constant μ (kg/m.s, or Pa.s) is equal to the viscosity of the fluid and $\left(dv_x/dy\right)$ is the velocity's gradient or shear rate (s^{-1}). This shear rate is also given by parameter $\dot{\gamma}$.

Referring back to the concept of molecular flow density (of momentum or viscous flow), it is known that molecular flow is related to shear stress via the following equation:

$$\vec{T}_m = \left[u_x \; u_y \; u_z \right] \cdot \begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix} = \vec{u} \cdot \vec{\vec{\tau}} \tag{2.72}$$

where the nine components of shear stress tensor are the shear stresses coming from the shear forces actuating in *x, y, z* directions and forming velocity gradients along directions *x, y, z*.

In this manner, the motion equation or general expression for momentum microscopic balance is given by

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) = -\vec{\nabla} \cdot \left(\rho \vec{v} \vec{v}\right) - \vec{\nabla} \cdot \vec{\vec{\tau}} - \vec{\nabla} p + \rho \vec{g} \tag{2.73}$$

If conservation laws and transfer rate equations are applied to the study of fluid flow through cylindrical tubes, it is possible to determine the relationship between flow and pressure drop of a fluid circulating within a tube, taking into account the viscosity of the fluid and tube diameter. Consider a Newtonian and incompressible fluid circulating in a laminar

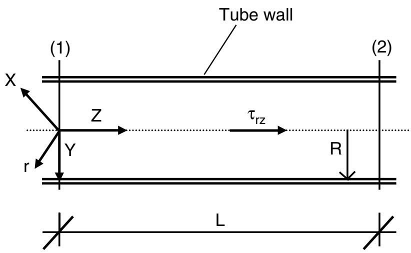


Figure 2.8 Newtonian and incompressible fluid circulating within a cylindrical tube (left); tube network in a juice factory (right).

regime that is in a steady-state within a cylindrical tube, as Figure 2.8 shows.

If the total pressure at (1) and (2) is $P = p + \rho g h$, the shear stress is given by the equation

$$\tau_{rz} = \left(\frac{P_1 - P_2}{2L} \right) \cdot r \tag{2.74}$$

where it is manifested that the shear stress increases linearly from the tube center to the tube wall. In Equation 2.74, a close relationship can be seen between the pressure drop of a fluid circulating within a tube and the shear stress.

The velocities profile within the tube is calculated as

$$v_z = \frac{\left(P_1 - P_2\right) \cdot R^2}{4\mu L} \left[1 - \left(\frac{r}{R} \right)^2 \right] \tag{2.75}$$

which is a parabola. The maximum velocity is at the tube center and is calculated as

$$\left(v_z\right)_{\max} = \frac{\left(P_1 - P_2\right) \cdot R^2}{4\mu L} \tag{2.76}$$

and the mean velocity is given by the equation

$$\left(v_z\right)_{\text{mean}} = \frac{\int_S v_z dS}{\int_S dS} = \frac{\left(P_1 - P_2\right) \cdot R^2}{8\mu L} \tag{2.77}$$

which is half the maximum velocity. The velocity is at maximum when the shear stress is zero (at the tube center), and this velocity is zero at the wall when the shear stress is at maximum.

From the above equation, the volumetric flow of fluid circulating within the tube is obtained:

$$\dot{V} = \left(v_z\right)_{\max} \cdot S = \frac{\pi\left(P_1 - P_2\right) \cdot R^4}{8\mu L} \tag{2.78}$$

which is the Hagen-Poiseuille equation for Newtonian liquid fluids.

On the other hand, the shear force at the tube wall is given by the following equation:

$$F_z = \left(2\pi RL\right) \cdot \left(\frac{P_1 - P_2}{2L}\right) \cdot R \tag{2.79}$$

2.1.3.3 Energy Balance: Fourier's Law

By means of an energy microscopic balance, it is possible to know at any given moment the temperature evolution during thermal processing of every point within a food product mass. This is interesting since a food product can lose its quality if the processing temperature is excessive, as occurs during blanching and sterilization.

When it is considered an open system with volume V and is enclosed in surface S, the conservation law of energy establishes that

$$\left\{\begin{array}{l}\text{Rate of energy}\\ \text{accumulation}\\ \text{in the system}\end{array}\right\} = \left\{\begin{array}{l}\text{Net flow rate}\\ \text{of energy entering}\\ \text{the system}\end{array}\right\}$$

If it is only accumulated internal energy, kinetic energy, and potential energy in the system, and the energy contained in volume V is

$$\int_V \rho \cdot \left(\hat{U} + \hat{K} + \hat{\Phi}\right) \cdot dV \tag{2.80}$$

then the accumulation can be expressed as

$$\frac{d}{dt}\int_V \rho \cdot \left(\hat{U} + \hat{K} + \hat{\Phi}\right) \cdot dV = \frac{d}{dt}\int_V \rho \cdot \hat{E} \cdot dV \tag{2.81}$$

where $\hat{E}$ is the total energy per mass unit in volume dV. Equation 2.81 also can be written as

$$\int_V \frac{\partial}{\partial t} \rho \hat{E} \cdot dV \tag{2.82}$$

Concerning the net flow rate of energy entering the system, there are three types of entry procedures: energy entering via mass flow, energy due to surface forces, and energy entering via molecular flow.

Through the differential surface $d\vec{S}$ of the system, if $\vec{v}$ is the velocity of the fluid taken in, the mass flow entering is given as follows:

$$-\rho \cdot \vec{v} \cdot d\vec{S} \tag{2.83}$$

and the mass flow has energy $\hat{E}$. Then, the net flow rate of internal, kinetic and potential energy taken in is

$$\int_S \rho \cdot \vec{v} \cdot d\vec{S} \cdot \hat{E} = \int_V -\vec{\nabla} \cdot \left(\rho \cdot \hat{E} \cdot \vec{v}\right) \cdot dV \tag{2.84}$$

Through the differential surface $d\vec{S}$, the intake of energy due to pressure is $-p \cdot \vec{v} \cdot d\vec{S}$, and the energy due to viscous forces is $-\left(\vec{\vec{\tau}} \cdot \vec{v}\right) \cdot d\vec{S}$. Then, the total energy taken into the system due to the action of viscous forces is

$$-\int_S \left(p \cdot \vec{v} + \vec{\vec{\tau}} \cdot \vec{v}\right) \cdot d\vec{S} = -\int_V \vec{\nabla}\left(p \cdot \vec{v} + \vec{\vec{\tau}} \cdot \vec{v}\right) \cdot dV \tag{2.85}$$

If $\vec{q}$ is the energy flow density by conduction (molecular transport of energy) on the differential surface $d\vec{S}$, the net flow rate of energy taken in via molecular transport is obtained as follows:

$$-\int_S \vec{q} \cdot d\vec{S} = -\int_V \left(\vec{\nabla}\vec{q}\right) \cdot dV \tag{2.86}$$

In sum, the net flow rate is given by the expression

$$\int_V -\vec{\nabla} \cdot \left(\rho \cdot \hat{E} \cdot \vec{v} + p \cdot \vec{v} + \vec{\vec{\tau}} \cdot \vec{v} + \vec{q}\right) \cdot dV \tag{2.87}$$

which must be equal to the accumulation term:

$$\int_V \frac{\partial}{\partial t} \rho \cdot \hat{E} \cdot dV \tag{2.88}$$

In this manner, the energy microscopic balance is calculated:

$$\frac{\partial}{\partial t}\left(\rho\hat{E}\right) = -\vec{\nabla}\left(\rho\hat{E}\vec{v} + p\vec{v} + \vec{\vec{\tau}}\vec{v} + \vec{q}\right) \tag{2.89}$$

2.1.3.3.1 Fourier's Law

Similar to the study on mass transfer (Fick's Law), if a solid is heated by means of a flame, surfaces at constant temperature are formed, described as follows:

$$T = T\left(x, y, z, t\right) \tag{2.90}$$

Thus, the gradient vector of T, $\vec{\nabla}T$, will be perpendicular to these constant temperature surfaces, and there is a sense of going from a lower to a higher temperature.

Fourier's Law states that heat flow density $\vec{q}$ (by molecular transport or conduction) is directly proportional to the temperature gradient:

$$\vec{q} = -k \cdot \vec{\nabla} T \tag{2.91}$$

But heat flows from higher temperature points to lower temperature points.

The coefficient k in Fourier's Law (Equation 2.91) is called thermal conductivity, and its units are W/(m.K). Its value depends on the material type and the physical state.

2.1.3.3.2 Heat Transfer in Solids at Steady State

In solids at steady state, and without chemical reaction, the energy microscopic balance is reduced to the expression

$$\vec{\nabla}\vec{q} = 0 \tag{2.92}$$

When thermal conductivity is constant, that is, the material is isotropic, and it is not dependent on temperature (within a determined temperature interval), the application of Fourier's Law leads to this equation (in rectangular coordinates):

$$\nabla^2 T = 0 = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \tag{2.93}$$

From this equation, the following expressions result for a plane layer (see Figure 2.9).

As the temperature is a function only of X,

$$T = T_0 + \frac{T_1 - T_0}{e} \tag{2.94}$$

If A is the area of the plane layer, the rate of heat flow through is given by

$$\dot{Q} = q_x \cdot A = -k \cdot A \cdot \frac{dT}{dx} = -k \cdot A \cdot \frac{T_1 - T_0}{e} \tag{2.95}$$

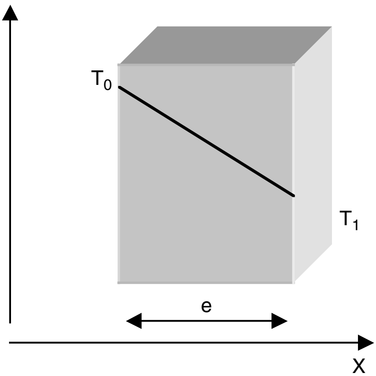


Figure 2.9 Temperature profile for a plane layer (left), as it occurs in a wall panel (right).

If the plane layer is a compound with N layers, and k_i is the thermal conductivity of the material for each layer *i,* and the interface temperatures are T_{i-1} and T_i, the thickness is e_i, and the layer is located at x_i, then:

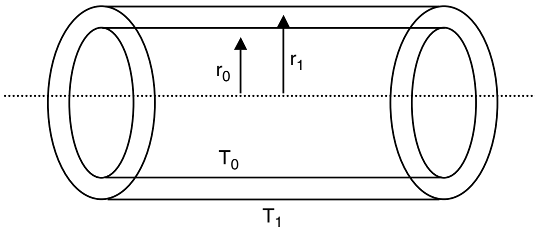
$$T\left(x_i\right) = T_{i-1} + \frac{T_i - T_{i-1}}{e_i} \cdot x_i \tag{2.96}$$

The heat flow rate through the compound layer is

$$\dot{Q} = \frac{T_0 - T_N}{\sum_{i=1}^{N} \frac{e_i}{k_i \cdot A}} \tag{2.97}$$

In a cylindrical layer (see Figure 2.10):

$$T = T_0 - \left(T_0 - T_1\right) \cdot \frac{\ln\left(\frac{r}{r_0}\right)}{\ln\left(\frac{r_1}{r_0}\right)} \tag{2.98}$$



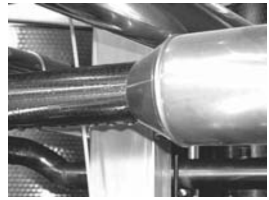


Figure 2.10 Cylindrical layer (left), as in the pipe insulation (right).

$$\dot{Q} = \frac{T_0 - T_1}{\dfrac{e}{k \cdot A_{ml}}} \tag{2.99}$$

where $e = r_1 - r_0$ is the thickness and A_{ml} is the logarithmic mean area of the internal and external cylindrical surfaces:

$$A_{ml} = \frac{A_{ext} - A_{int}}{\ln \dfrac{A_{ext}}{A_{int}}} = 2\pi L \cdot \frac{r_{ext} - r_{int}}{\ln \dfrac{r_{ext}}{r_{int}}} = 2\pi L \cdot r_{ml} \tag{2.100}$$

If the cylindrical layer is a compound, with N layers, and k_i is the thermal conductivity of the material, for each cylindrical layer i, and the thickness of each is e_i, the heat flow rate through the compound cylindrical layer is

$$\dot{Q} = \frac{T_0 - T_N}{\displaystyle\sum_{i=1}^{N} \frac{e_i}{k_i \cdot A_{mli}}} \tag{2.101}$$

When the cylindrical layer radius is great and the thickness is small, the equations for the cylindrical layer tend to be equal to those for the plane layer.

2.1.3.3.3 Heat Transfer in Solids at Unsteady State

In vegetable canning, for example, in the thermal processing stage, knowing the amount of time needed to reach a determined temperature in the can's center is fundamental to obtaining quality goods and to assuring consumer health safety. To calculate this time, or the thermal conditions at different points in the solid after thermal processing, it is necessary to take into account the unsteady state of this process.

In this case, the solution to the energy microscopic balance is more complex, because temperature is a function of both position and time.

Consider, for example, a solid body at temperature T_0 initially, which is submerged in a fluid bath at temperature T_e. If T_e is greater than T_0, the solid will increase in temperature to reach temperature T_e, after a certain length of time.

From the onset, the temperature at each point of the solid will increase with time; then the state of the solid will become unsteady, as stated above. In this case, the energy microscopic balance is given by the equation

$$\frac{\partial}{\partial t}\left(\rho \cdot \hat{c}_p \cdot T\right) = -\vec{\nabla} \cdot \vec{q} \tag{2.102}$$

Applying Fourier's Law and assuming that ρ, $\hat{c}_p$ and k are constants, the following equation results:

$$\frac{\partial T}{\partial t} = \alpha \cdot \nabla^2 T \tag{2.103}$$

where

$$\alpha = \frac{k}{\rho \cdot \hat{c}_p} \tag{2.104}$$

which is thermal diffusivity.

2.2 TRANSFER PROPERTIES: VISCOSITY, CONDUCTIVITY, AND DIFFUSIVITY

2.2.1 Viscosity

Several important factors need to be taken into consideration in the design of food processing plants in order to ensure the

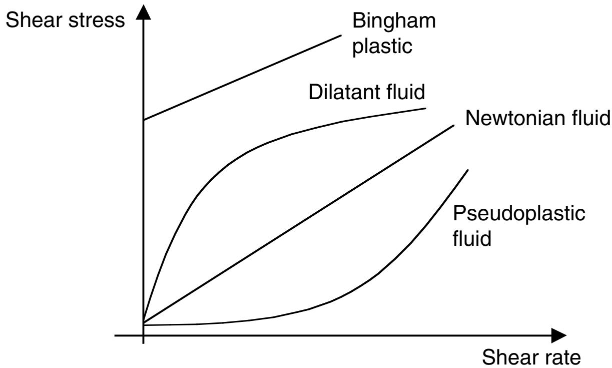


Figure 2.11 Shear stress-shear rate graphics.

quality of final products. One factor would be the question of rheology (Bylund, 1995).

For fluids known as Newtonian fluids, there is a linear relationship between the shear stress and the shear rate or velocity gradient. These fluids have a constant viscosity dependent on temperature but that are independent of the applied shear rate. A Newtonian fluid can therefore be defined by a single viscosity value at a specified temperature. Data for fluids are often presented in the form of shear stress-shear rate graphics (Figure 2.11), plotted in either a linear or a log-log form. Such plots are called rheograms (Lewis, 1990; Bylund, 1995).

Most gases and simple fluids exhibit Newtonian behavior at the shear rates normally encountered. Gases have the lowest viscosity values. Simple fluids such as water, dilute solutions, and organic solvents are considered low-viscosity fluids. Vegetable oils, pure sucrose solutions (e.g., fruit juices), and low-concentration liquids in general (e.g., whole milk and skim milk) may for practical purposes be characterized as Newtonian fluids. It should be noted that the viscosity increases as the solids concentration increases, so that during certain unit operations, such as evaporation, the viscosity will increase and the behavior will be non-Newtonian (Lewis, 1990; Bylund, 1995).

Materials that cannot be defined by a single viscosity value at a specified temperature are called non-Newtonian fluids (Newton's Law is not applicable). The viscosity of these materials must always be stated together with a corresponding temperature and shear rate, as in the case of fluids (Bylund, 1995):

- *Plastic flow behavior*: Significant force must be applied before the material starts to flow like a liquid (often referred to as the ketchup effect). Once the yield stress is exceeded, the liquid can flow like a Newtonian liquid and be described as a Bingham plastic liquid (Figure 2.11), or it can flow like a shear thinning liquid and be described as a viscoplastic liquid. Typical plastic fluids are quarg, tomato paste, and certain ketchups and greases.
- *Shear thinning flow behavior*: The viscosity of these fluids (also called pseudoplastic fluids, as shown in Figure 2.11) decreases with increasing shear rate. The reason for shear thinning flow behavior is that an increased shear rate will deform and/or rearrange particles, resulting in lower flow resistance. Typical examples of these kinds of fluids are cream and juice concentrates.
- *Shear thickening flow behavior*: The viscosity of these fluids (also called dilatant fluids, as shown in Figure 2.11) increases with increasing shear rate. This type of flow behavior is generally found among suspensions of very high concentration, as in concentrated starch suspensions.

The generalized power law equation is applicable to plastic as well as shear thinning and shear thickening fluids, as follows:

$$\tau_{yx} - \tau_0 = K \cdot \left(\frac{dv_x}{dy} \right)^n \tag{2.105}$$

where τ is the shear stress (Pa), τ_0 is the yield stress (Pa, which is zero for shear thinning and shear thickening fluids),

K is the consistency coefficient (Pa·s^n), and n is the flow behavior index (dimensionless). For Newtonian fluids K is equal to μ and $n = 1$.

The main benefit of using the generalized power law equation is its applicability to a large number of non-Newtonian fluids over a wide range of shear rates (or circulating velocities) in pressure drop and heat transfer calculations (Bylund, 1995). For example, the relationship between flow rate and pressure drop in circular ducts is given by

$$\Delta p = \left(\frac{3n+1}{n}\right)^n \left(\frac{\dot{V}}{\pi R^3}\right)^n \frac{2LK}{R} \tag{2.106}$$

where V is the flow rate (m^3/s), R is the duct radius (m), Δp is the pressure drop (Pa), L is the tube length (m), n is the flow behavior index, and K is the consistency coefficient.

2.2.2 Thermal Conductivity

Thermal conductivity provides a means of quantifying the heat transfer properties of a solid material. Under steady-state conditions, the rate of heat transfer (Q) along a piece of solid material will depend upon the cross-sectional area of the surface (A), the temperature gradient, and the thermal conductivity of the material (k), as Fourier's Law states:

$$\dot{Q} = -k \cdot A \cdot \frac{T_1 - T_0}{e} \tag{2.107}$$

Most foods are poor conductors of heat, and therefore heat transfer processes in which conduction is the predominant mechanism are slow. In fact, the thermal conductivity of a food is influenced by its composition, in a manner similar to specific heat: water exerts a major influence (Lewis, 1990). The thermal conductivities of various components given by Miles et al. (1983) follow:

- k_a (air) = 0.025 W/m·K
- k_p (protein) = 0.20 W/m·K
- k_c (carbohydrate) = 0.245 W/m·K

- k_s (solids) = 0.26 W/m·K
- k_f (fat) = 0.18 W/m·K
- k_w (water) = 0.6 W/m·K
- k_i (ice) = 2.24 W/m·K

Thus, for n-components food, using the parallel model, the thermal conductivity is given by (Lewis, 1990)

$$k = V_1k_1 + V_2k_2 + V_3k_3 + \ldots + V_nk_n = \sum_{i=1}^{n} V_ik_i \tag{2.108}$$

where V_i is the volume fraction of each component (water, air, etc.), and k_i is the thermal conductivity of each component.

2.2.3 Diffusivity

Diffusion is the spreading out of a material into its surroundings. The two major types encountered are molecular diffusion and eddy, or turbulent, diffusion. Molecular diffusion can be defined as the transport of matter on a molecular scale through a stagnant fluid or, if the fluid is in laminar flow, in a direction perpendicular to the main flow. In contrast, turbulent diffusivity is concerned with mass transfer processes involving bulk fluid motion (Lewis, 1990).

For diffusion in gases and vapors, the concentration term in Fick's Law can be replaced by partial pressure, using the relationship for an ideal gas (Lewis, 1990):

$$C_{gas} = \frac{p_{gas}}{RT} \tag{2.109}$$

where C_{gas} is the molar concentration of the gas, p_{gas} is the partial pressure of the gas, R is the gas constant, and T is the absolute temperature. Therefore, the molar diffusion transfer rate is given by

$$N_{gas} = \frac{D}{RT}\Delta p_{gas} \tag{2.110}$$

where D is the diffusion coefficient or diffusivity.

Diffusion in a solid matrix is more complex than diffusion in a liquid or gas because, although the product may appear to be diffusing within the solid matrix, it may actually be diffusing through liquid contained within the matrix or through the gas phase in a porous solid. Therefore, the diffusivities in solids are poorly known (Lewis, 1990).

Fick's Second Law of Diffusion can be used to solve unsteady-state mass transfer problems. It describes how concentration changes with time t and position in the food. Methods of solving this equation are similar to those for unsteady-state heat transfer problems and have been discussed for certain shapes, such as an infinite slab, infinite cylinder, and a sphere (Loncin and Merson, 1979), for example, in modeling food drying processes (López et al., 1997):

- Infinite slab:

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2}{4} X^2 \right] \tag{2.111}$$

- Infinite cylinder:

$$\frac{M - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{1}{\beta_n{}^2} \exp\left[-\frac{\beta_n{}^2}{4} X^2 \right] \tag{2.112}$$

- Sphere:

$$\frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\frac{n^2 \pi^2}{9} X^2 \right] \tag{2.113}$$

where M is the moisture content at any time, M_e is the moisture content at equilibrium, M_0 is the initial moisture content of the product, and $(\beta n)^2$ is the root of Bessel Function of first type and zero order. X^2 is given by

$$X^2 = \frac{A}{V} D_{eff} \cdot t \tag{2.114}$$

where A is the transfer area (m^2), V is the volume of the product, D_{eff} is the effective diffusivity (m^2/s), and t is the time (s).

To evaluate the evolution of product moisture during the drying process, and considering, for example, the sphere geometry (with radius r) of the product, in Equation 2.113 only the first term ($n = 1$) is used because the remaining terms are considered negligible. In this manner,

$$\frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \exp\left(-\frac{D_{eff}}{r^2} \cdot t \right) \tag{2.115}$$

From this expression, D_{eff} is obtained for different drying air conditions, for example, if the drying is carried out by hot air.

2.3 HEAT TRANSFER IN FLUIDS

Heat transfer in fluids occurs naturally and mainly by convection, which is the typical heat transfer mechanism in fluids. However, if the fluid is in repose initially and a temperature gradient is generated, the conduction heat transfer mechanism is also present, but a motion in the fluid originates from the density variations in the fluid (flotation forces taking place). The greater the viscosity of a fluid becomes, the greater the friction, and the greater the resistance of the fluid to the motion.

The convection mechanism can be natural or forced, depending on the forces acting on the fluid. In the first case, only the flotation forces are present, due to the fluid density differences generated by the temperature gradients. In the second case (forced convection), the motion of the fluid is generated by external forces or agents (pumps, agitators, etc.).

2.3.1 Individual Coefficients of Heat Transfer by Convection

When a fluid is circulating within a cylindrical tube, the amount of heat passing from the tube wall to the fluid (or from the fluid to the wall) depends on the contact area and the temperature difference between the wall and the fluid $\left(T_w - T_f\right)$. In fact, if $d\dot{Q}$ is the heat flow rate through the contact area dA, wall-fluid, the individual coefficient of heat transfer by convection h is defined by the equation

$$d\dot{Q} = h \cdot dA \cdot \left(T_w - T_f\right) \tag{2.116}$$

This coefficient depends on the physical and dynamical properties of the fluid, and its determination is done by means of experimentation and the use of dimensional analysis. This approach results in an equation that relates the heat transfer coefficient to other physical properties of the fluid. These equations are found in the bibliography, and are generally different for natural convection and forced convection.

2.3.2 Heat Transfer Coefficients in Newtonian Fluids

For Newtonian fluids, with constant density, viscosity, conductivity, and specific heat, it has been shown experimentally that coefficient h is a function of the following:

- Mean velocity of the fluid, v
- Viscosity of the fluid, μ
- Thermal conductivity of the fluid, k
- Density of the fluid, ρ
- Specific heat of the fluid, $\hat{c}_p$
- Temperature differences between the wall and the fluid, $\left(T_w - T_f\right)$
- Heat transfer area, which for cylindrical tubes is a function of diameter D and length L

By means of dimensional analysis, the following equation is obtained:

$$\frac{h \cdot D}{k} = f\left[\frac{v \cdot D \cdot \rho}{\mu}, \frac{\hat{c}_p \cdot \mu}{k}, \frac{\mu \cdot v^2}{k\left(T_w - T_f\right)}, \frac{L}{D}\right] \tag{2.117}$$

that is,

$$Nu = f\left(\mathrm{Re}, \mathrm{Pr}, Br, L/D\right) \tag{2.118}$$

where Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number, and Br is the Brinkman number, which is expressed as follows:

$$Br = \frac{\mu \cdot v^2}{k\left(T_w - T_f\right)} \tag{2.119}$$

For forced convection, and Newtonian fluids circulating in cylindrical tubes, without phase changes, the following equations can be used:

- Laminar regime ($Re < 2100$):

$$Nu = 1.86 \cdot \left(\mathrm{Re} \cdot \mathrm{Pr} \cdot \frac{D}{L} \right)^{1/3} \tag{2.120}$$

When the product ($\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L$) < 100, the following expression (Singh and Heldman, 1984) is also valid:

$$Nu = 3.66 + \frac{0.085 \cdot \left(\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L \right)}{1 + 0.045 \cdot (\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L)^{0.66}} \left(\frac{\mu_f}{\mu_w} \right)^{0.14} \tag{2.121}$$

and, if ($\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L$) > 100:

$$Nu = 1.86 \cdot \left(\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L \right)^{0.33} \left(\frac{\mu_f}{\mu_w} \right)^{0.14} \tag{2.122}$$

where all properties are evaluated for the mean temperature conditions of the fluid, and μ_w is evaluated for the tube wall temperature.

- Turbulent regime ($Re > 10\,000$ and $L/D > 10$):

$$Nu = 0.026 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{1/3} \tag{2.123}$$

For natural convection, the following is obtained via dimensional analysis:

$$Nu = f\left(\mathrm{Pr}, Gr \right) \tag{2.124}$$

where Gr is the Grashof number:

$$Gr = \frac{D^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \left(T_w - T_f \right)}{\mu^2} \tag{2.125}$$

where g is the gravity acceleration, 9.8 m/s^2, and β is the thermal coefficient of volumetric expansion (for an ideal gas,

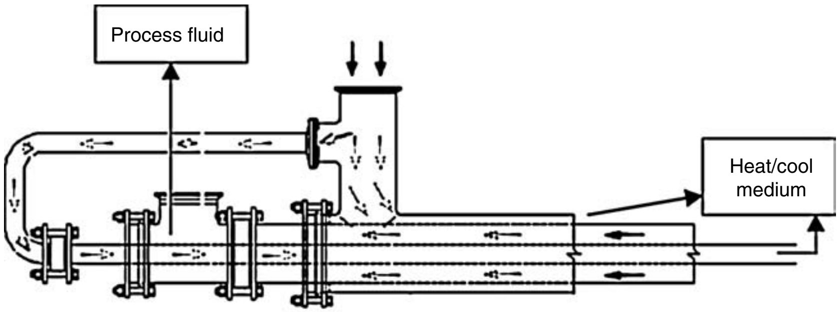


Figure 2.12 Triple-tube heat exchanger (courtesy of Genemco Machinery and Equipment, www.genemco.com).

β is the inverse of absolute temperature and valid for Newtonian fluids).

The following can be obtained experimentally:

$$Nu = 0.525 \cdot \left(\Pr \cdot Gr\right)^{1/4} \tag{2.126}$$

for $(\Pr \cdot Gr) > 10^4$ and $\Pr > 0.6$.

In the case of different heat exchangers used in food plants, the heat transfer coefficient h is evaluated using correlations found in the bibliography. As examples, different cases are evaluated in the following:

- Triple-tube heat exchangers, where the food product circulates within the annular space (Figure 2.12):

$$Nu = \left(\frac{D_2}{D_1}\right)^{0.8} \cdot \left(Gz\right)^{0.45} \cdot \left(Gr\right)^{0.05} \tag{2.127}$$

where Gz is the Graetz number (Gz = Re.Pr.D/L), Gr is the Grashof number, and D_1 and D_2 are the diameters of the annular space.

- Heat transfer coefficient in a stirred tank with plane blades:

In the case of an agitator with six blades, and the ratio = height of liquid/tank diameter is 1 and the ratio = impeller diameter/tank diameter is 1/3, it is possible to use the following expression:

$$Nu = C \cdot (\mathrm{Re})^{0.67} \cdot (\mathrm{Pr})^{0.33} \cdot \left(\frac{\mu}{\mu}\right)^{0.14} \tag{2.128}$$

where C is 0.54 for Re < 400, and C is 0.74 for Re > 400. The Re number is

$$\mathrm{Re} = \frac{\rho D^2 N}{\mu} \tag{2.129}$$

where N is the number of revolutions per second.

2.3.3 Heat Transfer Coefficients in Non-Newtonian Fluids

Evaluation of the heat transfer coefficient in non-Newtonian fluids can be conducted using the expressions given for Newtonian fluids, but by using the delta function (Toledo, 1994):

$$\text{Delta function } = \Delta^{0.33} = \frac{Nu_{non-Newtonian}}{Nu_{Newtonian}} \tag{2.130}$$

where $Nu_{non\text{-}Newtonian}$ is the Nusselt number evaluated for the non-Newtonian fluid, and $Nu_{Newtonian}$ is the Nusselt number evaluated for the Newtonian fluid.

In this manner, if Nu for a Newtonian fluid is given by

$$Nu = 1.75 \cdot (Gz)^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{2.131}$$

then, for a non-Newtonian fluid, it follows that

$$Nu_{non-Newtonian} = 1.75 \cdot \Delta^{0.33} \cdot (Gz)^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{2.132}$$

For n (flow behavior index) > 0.4, and for all values of Gz, the delta function is

$$\Delta^{0.33} = \left[\frac{3n+1}{4n}\right]^{0.33} \tag{2.133}$$

If $n < 0.4$, then it follows that

$$\begin{aligned}
\Delta^{0.33} &= -0.24n + 1.18 \quad \text{for } Gz = 5 \text{ and } 0 < n < 0.4 \\
\Delta^{0.33} &= -0.60n + 1.30 \quad \text{for } Gz = 10 \text{ and } 0 < n < 0.4 \\
\Delta^{0.33} &= -0.72n + 1.40 \quad \text{for } Gz = 15 \text{ and } 0 < n < 0.4 \\
\Delta^{0.33} &= -0.35n + 1.57 \quad \text{for } Gz = 25 \text{ and } 0 < n < 0.4
\end{aligned} \tag{2.134}$$

Another way to evaluate the heat transfer coefficient h for non-Newtonian fluids is from the equations obtained for Newtonian fluids, but by using the equivalent viscosity of non-Newtonian fluids.

The Reynolds number for a non-Newtonian fluid, and for a mean flow velocity $\bar{v}$, is given by

$$\mathrm{Re} = \frac{8(\bar{v})^{2-n} R^n \rho}{K\left(3+\frac{1}{n}\right)^n} \tag{2.135}$$

While for a Newtonian fluid, Re is equal to $\rho\bar{v}D/\mu$, the value of an equivalent viscosity for a non-Newtonian fluid is

$$\mu = \frac{D\bar{v}\rho}{8(\bar{v})^{2-n} R^n \rho \Big/ \left[K\left(3+\frac{1}{n}\right)^n\right]} = \frac{K}{4}\left(\frac{3n+1}{n}\right)^n (R)^{1-n} (\bar{v})^{n-1} \tag{2.136}$$

At the wall, the viscosity is

$$\mu_w = K\left(\frac{2\bar{v}}{D}\right)^{n-1}\left[\frac{3n+1}{n}\right]^{n-1} \tag{2.137}$$

In this manner, by substituting in the corresponding Nusselt expression of μ and μ_w for the non-Newtonian fluid, it is possible to evaluate the heat transfer coefficient for non-Newtonian fluids.

For example, if the Nusselt number for a Newtonian fluid is given by the equation

$$Nu = 1.615 \cdot \left[\mathrm{Re} \cdot \mathrm{Pr} \cdot \frac{D}{L} \right]^{0.33} \left(\frac{\mu}{\mu_w} \right)^{0.14} \tag{2.138}$$

and if

$$\begin{aligned} \mathrm{Re} &= \frac{D\bar{v}\rho}{\mu} = \frac{D\bar{v}\rho}{\frac{K}{4}\left(\frac{3n+1}{n}\right)^{n} (R)^{1-n} (\bar{v})^{n-1}} \\ \mathrm{Pr} &= \frac{\hat{c}_p \cdot \mu}{k} = \frac{\hat{c}_p \cdot \frac{K}{4}\left(\frac{3n+1}{n}\right)^{n} (R)^{1-n} (\bar{v})^{n-1}}{k} \end{aligned} \tag{2.139}$$

then, simplification will yield the following:

$$Nu = 1.615 \left[\frac{3n+1}{4n} \right]^{0.33} \left[\frac{D^2 v \rho \hat{c}_p}{kL} \right]^{0.33} \left[\frac{\mu}{\mu_w} \right]^{0.14} \tag{2.140}$$

where μ and μ_w are evaluated from the above expressions.

2.4 MATHEMATICAL MODEL OF A UNIT OPERATION: HOT AIR DRYING

World production of malt averages approximately 15 million tons per year, the European Union being the greatest producer (around 5 million tons), followed by the U.S. (nearly 3.2 million tons). In malt production, energy consumption plays an important role in the total processing cost. This cost oscillates between 25% and 30%, depending on the equipment used and the size of the malting plant. In 1992, in France and the U.K., consumption of energy in the most energy efficient malting plants was 1.5 GJ/t and 3.3 GJ/t, respectively. From this example, it would appear that 80–90% corresponded to the green malt drying process (Jolibeet, 1987; BCEOM, 1992).

In the study of deep-layer cereals drying, several mathematical models that allow drying operation simulations have been used. However, the results have not been directly applicable to malt drying or to those results obtained in barley drying. The main reasons that general mathematical models for barley and cereals are not valid for malt drying are (Lopez, 1994):

- Malt is dried at high temperatures (50–100°C), while barley is dried at low temperatures, around 40°C (Colliver et al., 1983).
- The initial moisture content of malt is high, but final content is low. In barley drying, the initial moisture content is no greater than 20–25%, and final content is around 12%.
- The endosperm cellular walls degrade during the malting process. Therefore, the chemical composition and microstructure differ in both barley grain and malt grain.
- The final transformed malt product must be of adequate quality (e.g., proper color and flavor).

For these reasons, drying models for barley or cereals in general are not directly applicable to deep-layer malt drying, so it is necessary to develop a specific model (O'Callaghan et al., 1971).

Although a few studies on malt drying have already been carried out, the malting factories have spent a lot of money in the last few years on energy saving techniques, such as

- Heat recovery from outlet drying air, by means of cross-flow air-air heat exchangers
- Heat pumps to recover the condensation latent heat of water vapor in outlet drying air, a technique mainly used in France (Halipre, 1986)
- Automatic control systems for malt drying process (controlling drying air temperature program, air recirculation, and airflow rate in drying air fans)

Although significant energy savings have been achieved with these techniques (e.g., energy savings of 25–30% with air-air heat exchangers), it is important to keep in mind that heat recovery and process control effectiveness depend on theoretical knowledge of the drying process in particular, as well as on availability of the mathematical model (Gumasekaran, 1986).

The deep-layer malt drying mathematical model can be used to develop and test advanced control systems, to increase the energy efficiency of the malting process, and to analyze the operating conditions of existing drying installations.

In this study, a mathematical model is presented based on the development of four partial differential equations established around the drying bed layers with differential thickness (Sharp, 1982):

- Water balance equation
- Heat balance equation
- Heat transfer rate equation
- Moisture transfer rate equation within the grain, which constitutes the drying rate equation

In the study, the bed was divided into elementary layers (Figure 2.13), with a differential thickness (δz) and area of 1

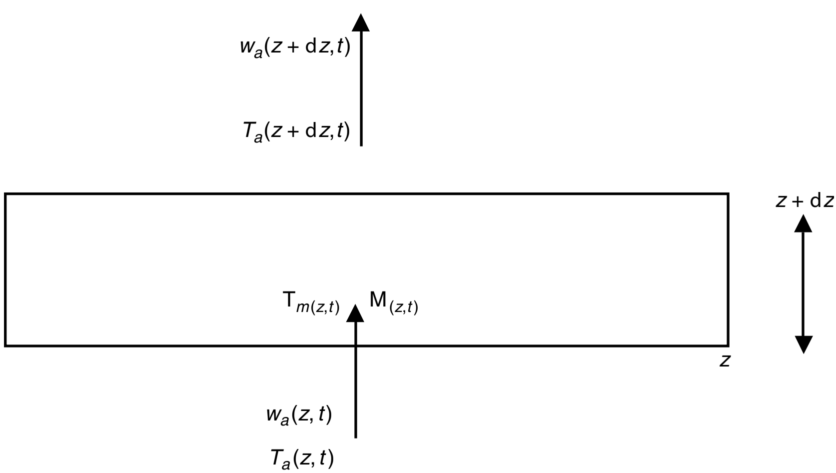


Figure 2.13 Elementary layers with differential thickness.

m^2. The physical changes occurring in these layers during differential time δt were thus analyzed (Sharp, 1982; Cenkowski et al., 1993; Parti, 1991; Patil, 1987).

The water (or moisture) and heat balance equations, as well as the matter (water) and heat transfer rate equations, are established around this elementary layer. Therefore,

(1) Water (or moisture) balance equation:

$$\begin{Bmatrix}\text{Air moisture content change}\\ \text{through elementary layer}\end{Bmatrix}=\begin{Bmatrix}\text{Water mass}\\ \text{leaving the grain}\end{Bmatrix}-\begin{Bmatrix}\text{Moisture change in}\\ \text{the air within the layer}\end{Bmatrix}$$

Creating a balance in the elementary layer:

$$\begin{aligned}&G\delta t\left[w_a\left(z+\delta z,t\right)-w_a\left(z,t\right)\right]=\\&-\frac{\partial M}{\partial t}\delta t\rho_g\delta z-\varepsilon\rho_a\delta z\left[w_a\left(z,t+\delta t\right)-w_a\left(z,t\right)\right]\end{aligned}\tag{2.141}$$

Thus, limited by ($\delta t\to 0$ and $\delta z\to 0$):

$$G\frac{\partial w_a}{\partial z}=-\rho_g\frac{\partial M}{\partial t}-\varepsilon\rho_a\frac{\partial w_a}{\partial t}\tag{2.142}$$

(2) Heat balance equation:

$$\begin{Bmatrix}\text{Enthalpy change rate}\\ \text{in the grain and the air}\\ \text{within the elementary}\\ \text{layer}\end{Bmatrix}=\begin{Bmatrix}\text{Heat flow rate}\\ \text{associated with}\\ \text{inlet air flow rate}\\ \text{through the layer}\end{Bmatrix}-\begin{Bmatrix}\text{Heat flow rate}\\ \text{associated with}\\ \text{outlet air flow rate}\\ \text{from the layer}\end{Bmatrix}$$

$$-\begin{Bmatrix}\text{Heat flow rate}\\ \text{associated with}\\ \text{outlet water flow rate}\\ \text{from the layer}\end{Bmatrix}+\begin{Bmatrix}\text{Inlet heat flow rate}\\ \text{to elementary layer}\\ \text{and not associated with}\\ \text{mass flow rate}\end{Bmatrix}$$

Therefore,

$$\frac{\partial}{\partial t}\left[\rho_g \delta z\left(C_g + C_w M\right)T_g + \rho_a \varepsilon \delta z\left(C_a + C_w \cdot w_a\right)T_a\right]$$
$$= G\left(C_a + C_v w_a\right)\left[T_a\left(z,t\right) - T_a\left(z+\delta z,t\right)\right] \tag{2.143}$$
$$+ \frac{\partial M}{\partial t}\rho_g \delta z\left[C_w T_g + L_g + C_v\left(T_a - T_g\right)\right] + h\cdot 2\left(1+\delta z\right)\cdot\left(T_a - T_g\right)$$

The transferred heat not associated with the matter flow rate into the elementary layer (from direction perpendicular to airflow) can be overlooked, so that $h\cdot 2\left(1+\delta z\right)\left(T_a - T_g\right) = 0$. And since $\partial T_a/\partial t = 0$ and $\partial w_a/\partial t = 0$ for the time differential (δt), then

$$\frac{\partial}{\partial t}\left[\rho_g \delta z\left(C_g + C_w M\right)T_g\right] = G\left(C_a + C_v w_a\right)\left[T_a\left(z,t\right) - T_a\left(z+\delta z,t\right)\right]$$
$$+ \frac{\partial M}{\partial t}\rho_g \delta z\left[C_w T_g + L_g + C_v\left(T_a - T_g\right)\right] \tag{2.144}$$

The results of the above equation:

$$\rho_g \frac{\partial}{\partial t}\left[\left(C_g + C_w M\right)T_g\right] = -G\left(C_a + C_v w_a\right)\frac{\partial T_a}{\partial z}$$
$$+ \frac{\partial M}{\partial t}\rho_g\left[C_w T_g + L_g + C_v (T_a - T_g)\right] \tag{2.145}$$

and

$$\frac{\partial T_g}{\partial t} \approx 0 \Rightarrow \rho_g \frac{\partial M}{\partial t}\left[C_v\left(T_a - T_g\right) + L_g\right] = G\left(C_a + C_v w_a\right)\frac{\partial T_a}{\partial t} \tag{2.146}$$

(3) Equation for heat transfer rate between hot air passing through the elementary layer and grain contained in the layer:

$$\left\{\begin{array}{l}\text{Heat transferred from the}\\ \text{the air to the grain by}\\ \text{convection in time } dt\end{array}\right\} = \left\{\begin{array}{l}\text{Grain enthalpy}\\ \text{change in time}\\ dt\end{array}\right\}$$

$$+\left\{\begin{array}{l}\text{Required heat to}\\ \text{vaporize the moisture leaving}\\ \text{the grain in time } dt\end{array}\right\}$$

$$+\left\{\begin{array}{l}\text{Required heat to increase the}\\ \text{vapor temperature to}\\ \text{air temperature}\end{array}\right\}$$

Therefore,

$$\begin{aligned} h_c A_g \rho_g \delta z \left(T_a - T_g\right)\delta t = \rho_g \delta z \left(C_g + C_w M\right)\left[T_g\left(z, t+\delta t\right) - T_g\left(z,t\right)\right] \\ - \frac{\partial M}{\partial t}\delta t \rho_g \delta z \left(L_g + C_v T_a\right) \end{aligned} \tag{2.147}$$

And if $h_c A_g = h_{cv}$ is considered and δz and ρ_g are suppressed (at the limit, $\delta t \to 0$),

$$h_{cv}\left(T_a - T_g\right) = \left(C_g + C_w M\right)\frac{\partial T_g}{\partial t} - \frac{\partial M}{\partial t}\left(L_g + C_v T_a\right) \tag{2.148}$$

(4) Equation for matter transfer rate within grain. Drying rate equation:

To solve the mathematical model of deep-layer malt drying, it is necessary to find equations that describe the thin-layer drying curves of the product for different drying air conditions.

During the falling drying rate period, the Fick's Second Law of Diffusion has been used by several authors (Ramaswany et al., 1982; Mowlah et al., 1982) to obtain the drying rate equation. Assuming a constant diffusion coefficient, the equation for one diffusion direction only in partial derivatives would be

$$\frac{\partial M}{\partial t} = D_{eff} \cdot \left(\frac{\partial^2 M}{\partial r^2} + \frac{C}{r} \cdot \frac{\partial M}{\partial r} \right) \tag{2.149}$$

where $C = cte$, which is 2 in spherical geometry. Normally, the initial and boundary conditions are

$$M(r,0) = M_o \text{ , at } t = 0$$

$$M(r_o,t) = M_e \text{ , at } r = r_o \text{ (on surface)}$$

$$M(0,t) = \textit{finite value}\text{, at } r = 0 \text{ (at center)}$$

Assuming an even distribution of initial moisture (without external resistance), the analytical solution to Fick's law for a sphere (Crank, 1956; Brooker et al., 1974) would be

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \cdot \sum_{n-1}^{\infty} \frac{1}{\pi^2} \cdot exp\left(-\frac{D_{eff}}{r^2} \cdot t \right) \tag{2.150}$$

where
D_{eff} = effective diffusivity (m^2/s)
r = sphere radius (m)

For long drying periods, and for undimensional moisture $\left[(M - M_e)/(M_o - M_e) \right]$ smaller than 0.6, only the first term (n=1) in Equation 2.150 can be used to obtain the drying rate. Thus, the equation becomes

$$\frac{M - M_e}{M_o - M_e} = a \cdot exp(-k \cdot t) \tag{2.151}$$

From this expression, it is possible to obtain the effective diffusivity coefficient (D_{eff}) since $k = D_{eff}/r^2$. The influence of temperature (T) on this coefficient (D_{eff}) can be established by means of the Arrhenius equation:

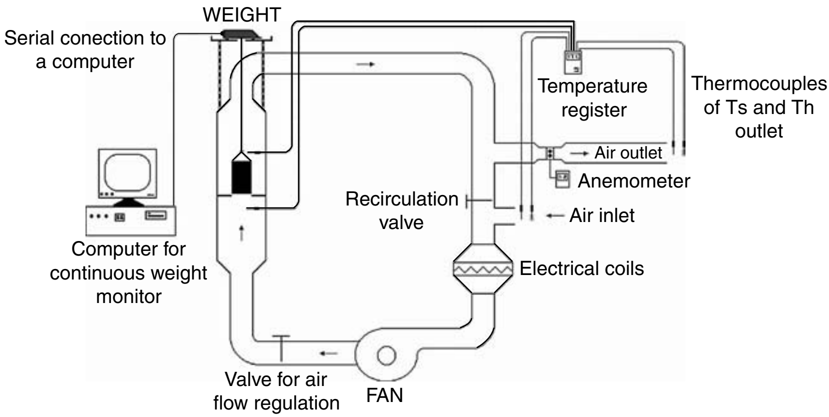


Figure 2.14 A drying pilot plant (adapted from López et al., 1997).

$$D_{eff} = D_o e^{-\frac{E_a}{RT}} \tag{2.152}$$

From this equation, the corresponding activation energy E_a and the constant D_o can be obtained (Rizvi, 1986, López et al., 1995a).

A drying rate equation, in which $a = 1$, has been proposed for wheat, rice, and barley (Simmonds et al., 1953; O'Callaghan, 1954; Hall and Rodríguez-Aris, 1958; Boyce, 1966; Kachru et al., 1971; Watson and Bhargava, 1974; Noomhorm and Verma, 1986), known as the simple exponential equation.

To determine drying constants, experiments with thin-layer malt drying (Wang, 1979; Bala and Woods, 1992) at different temperatures (30, 40, 50, 60, 70, 80, and 90°C) have been made according to several air relative humidities, while keeping the drying air rate constant (0.25 m/s). The schematic diagram of the pilot drying plant used is shown in Figure 2.14 (Morey and Huithen, 1984; López et al., 1997).

2.4.1 Equations for General Model

In the *water balance* equation (Equation 2.142), the finite differences solution has been considered (Bala and Woods, 1984; Lopez et al. 1995b, 1997; Rouet et al., 1979):

$$\Delta w_a = -\rho_m \cdot \frac{\Delta z}{G} \cdot \left(\frac{\Delta M}{\Delta t} \right) \tag{2.153}$$

In the *drying rate* equation (Equation 2.151), the simple exponential equation has been considered (Ingram, 1976):

$$M_{(t+\Delta t)} = M_{(t)} \cdot e^{-k \cdot \Delta t} + M_e \cdot \left(1 - e^{-k \cdot \Delta t}\right) \tag{2.154}$$

To solve the *energy balance* at the elemental layer (Equation 2.146) and the *heat transfer rate* (Equation 2.148), a modified Nellist model (Nellist, 1974) has been used. To simplify their solution, the following assumptions have been established:

- No heat loss or gain exists in directions perpendicular to the airflow across the malt bed.
- Heat loss or gain by conduction within the drying bed is worthless.
- Water, water vapor, and air specific heat are constant during drying process.
- Water vaporization latent heat in malt grain relies on the grain's moisture.
- Bed contraction and bulk density of the malt in dry basis rely on the malt's moisture content.
- Partial derivatives of T_a and w_a according to time are worthless.

This mathematical model, as explained by Nellist (1974) and applied to rye-grass seed drying, directly expresses in finite differences, with some simplifications, the heat balance and heat transfer rate equations (Equation 2.146 and Equation 2.148) in every elemental layer, obtaining values for ΔT_a and ΔT_m.

2.4.2 Equations from This Model

(1) Heat balance equation

{Air enthalpy change} = {Malt grain enthalpy change}

Air enthalpy change:

$$G \cdot \Delta t \cdot \begin{bmatrix} \left(C_a \cdot T_a + C_v \cdot w_a \cdot T_a + L_a \cdot w_a\right) - \\ \left(C_a \cdot \left(T_a + \Delta T_a\right) + C_v \cdot \left(w_a + \Delta w_a\right) \right. \\ \left. \cdot \left(T_a + \Delta T_a\right) + L_a \cdot \left(w_a + \Delta w_a\right) \right) \end{bmatrix} \tag{2.155}$$

Malt grain enthalpy change:

$$\rho_m \cdot \Delta z \cdot \begin{bmatrix} T_m \cdot \left(C_m + C_w \cdot M\right) \\ -\left(T_m + \Delta T_m\right) \cdot \left(C_m + C_w \cdot \left(M + \Delta M\right)\right) \end{bmatrix} \tag{2.156}$$

Substituting $\Delta w_a = -\rho_m \cdot \Delta z / G \cdot \left(\Delta M / \Delta t\right)$ and combining Equation 2.155 and Equation 2.156, the air temperature change value in the elemental layer is

$$\Delta T_a = \frac{\dfrac{\rho_m \cdot \Delta z}{G \cdot \Delta t} \cdot \begin{bmatrix} \Delta M \cdot \left(C_v \cdot T_a + L_a - C_w \cdot T_m\right) \\ -\Delta T_m \cdot \left(C_a + C_w \cdot \left(M + \Delta M\right)\right) \end{bmatrix}}{C_a + C_v \cdot \left(w_a - \rho_m \cdot \dfrac{\Delta z}{G} \cdot \dfrac{\partial M}{\Delta t} \right)} \tag{2.157}$$

(2) Heat transfer rate equation

{Heat transferred between air and grain} = {change in grain sensitive heat} + {(evaporated water enthalpy – water enthalpy before evaporating)}

Heat transfer rate between air and grain:

$$h_{cv} \cdot \Delta z \cdot \left[\left(T_a + \tfrac{1}{2} \cdot T_a\right) - \left(T_m + \tfrac{1}{2} \cdot T_m\right)\right] \cdot \Delta t \tag{2.158}$$

Grain heat variation sensitivity:

$$\rho_m \cdot \Delta z \cdot \Delta T_m \cdot \left(C_m + C_w \cdot M\right) \tag{2.159}$$

Evaporated water enthalpy variation for interval and layer considerations:

$$\rho_m \cdot \Delta z \cdot (-\Delta M) \cdot (L_m + C_v \cdot T_a - C_w \cdot T_m) \tag{2.160}$$

Thus, the malt grain temperature variation is expressed as

$$\Delta T_m = \frac{A + \rho_m \cdot \dfrac{\Delta M}{\Delta t} \cdot \left[\dfrac{2 \cdot Y}{h_{cv}} + \dfrac{\Delta z}{G \cdot E} \cdot F \right]}{1 + \dfrac{\rho_m}{\Delta t} \cdot \left[\dfrac{2 \cdot B}{h_{cv}} + \dfrac{\Delta z}{G \cdot E} \cdot (B + C_w \cdot \Delta M) \right]} \tag{2.161}$$

where

$$A = 2 \cdot (T_a + T_m) \qquad B = C_m + C_w \cdot M$$

$$E = C_a + C_v \cdot \left(w_a - \frac{\rho_m \cdot \Delta z}{G} \cdot \frac{\Delta M}{\Delta t} \right) \qquad F = C_v \cdot T_a + L_a - C_w \cdot T_m$$

$$Y = L_m + C_v \cdot T_a - C_w \cdot T_m \tag{2.162}$$

The malt's physical properties are needed to solve the mathematical model of the deep-layer malt drying process. The following has been used to determine the physical properties:

- Malt-specific heat (Bala and Woods, 1984):

$$C_m = 1.651 + 0{,}004116 \cdot M \tag{2.163}$$

- Latent heat of malt water evaporation (Bala and Woods, 1984):

$$L_m = L_a \cdot \left[1 + 0.5904 \cdot \exp(-0.1367 \cdot M) \right] \tag{2.164}$$

- Heat transfer coefficient by convection (Bala and Woods, 1984):

$$h_{cv} = 49.32 \cdot 10^3 \cdot G^{0.6} \tag{2.165}$$

The malt bed contraction coefficient during the drying process has been determined experimentally at the industrial level. The heights of both the superior and inferior parts of every superficial wave in the malt bed were measured throughout the drying box. Adjustment of experimental data yielded the following equation:

$$s = 25.2086 \cdot \left[1 - \exp\left(-0.04238 \cdot \left(M_0 - M\right)\right)\right] \tag{2.166}$$

Determination of malt desorption isotherms has been carried out experimentally using the static gravimetric method, with sulfuric acid solutions at different concentrations (Molnar, 1987). In order to model the malt desorption isotherms, the data was adjusted to the GAB model (Van der Verg, 1984):

$$M_e = \frac{A \cdot B \cdot C \cdot a_w}{\left(1 - C \cdot a_w\right) \cdot \left[1 + \left(B - 1\right) \cdot C \cdot a_w\right]} \tag{2.167}$$

The equations used to calculate the humid air properties (Singh and Heldman, 1984):

- Air moisture content:

$$w_a = 0.622 \cdot \frac{HR \cdot P_s}{p - HR \cdot P_s} \tag{2.168}$$

- Saturated water-vapor pressure at air temperature:
  If $T < 60°C$

$$P_s = \frac{\exp\left(14.293 - \dfrac{5291}{T_a + 273.15}\right)}{3.2917 - 0.01527 \cdot \left(T_a + 273.15\right) + 2.54 \cdot 10^{-5} \cdot \left(T_a + 273{,}15\right)^2}$$

  If $T > 60°C$

$$P_s = \exp\left(13.5921 - \frac{5064.72}{T_a + 273.15}\right) \tag{2.169}$$

- Air enthalpy:

$$i_a = C_a \cdot T_a + w_a \cdot \left(L_a + C_v \cdot T_a\right) \tag{2.170}$$

- Latent heat of water vaporization:

$$L_a = 2500.6 - 2.3643956 \cdot T_a \tag{2.171}$$

2.4.3 Results of Experiment

Using the GAB equation to model the malt desorption isotherms, the temperature dependence equations for the parameters were

$$A = 0.01183 \cdot \exp\left(\frac{469.017}{T}\right) \qquad R^2 = 0.8085 \tag{2.172}$$

$$B = \exp\left(\frac{943.854}{T}\right) \qquad R^2 = 0.9951$$

$$C = \exp\left(-\frac{28.639}{T}\right) \qquad R^2 = 0.9922$$

The drying constants in the simple exponential equation, for different drying temperatures, and the effective diffusivity, are

$$k = \frac{D_{eff}}{r^2} \qquad r = 5\ mm.$$

$$D_{eff} = 0.41036 \cdot \exp\left[-\frac{5108.4454}{(T_a + 273.15)}\right] \qquad R^2 = 0.9793 \tag{2.173}$$

To establish the malt drying general model in the deep-layer mode, a simulation algorithm has been developed, which determines the solution sequence for different equations of the model, and which is explained in López et al. (1997).

The above mathematical model and the simulation algorithm developed can predict

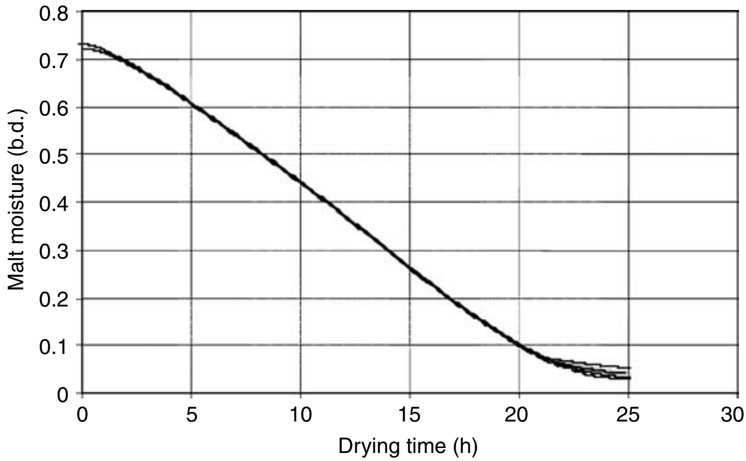


Figure 2.15 Evolution of malt moisture content during drying (adapted from López et al., 1997).

- Evolution of average moisture content in entire malt bed during drying process, for a predetermined incoming drying air condition (Figure 2.15)
- Evolution of drying air temperature at several drying bed depths
- Drying air RH evolution with drying time and position in drying bed
- Evolution of drying air moisture content with drying time and position in drying bed (Figure 2.16)
- Evolution of malt temperature with drying time and position in drying bed (Figure 2.17)
- Evolution of malt moisture content with drying time and position in drying bed, for predetermined drying air conditions

This model has been validated at an industrial level in drying boxes measuring 1.20 m in initial bed depth. Its predictions clearly fit the observed values for RH and temperature evolution of the outlet drying air, malt moisture content during the drying process, and several heights within the drying bed (López et al., 1997).

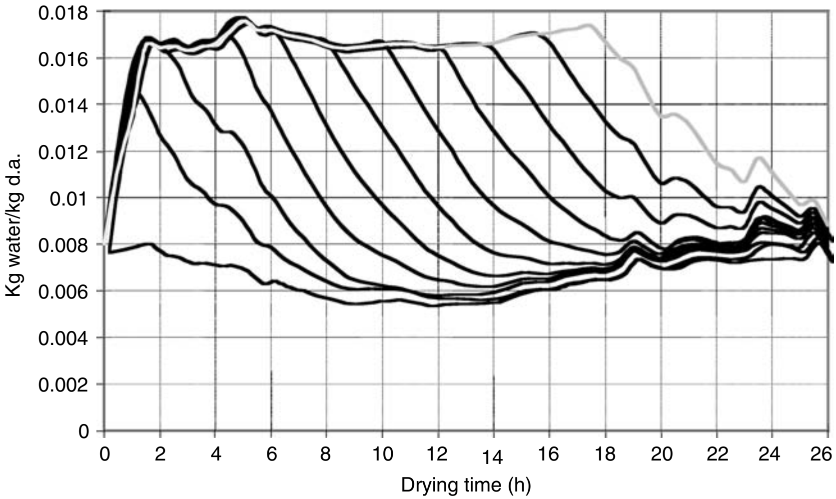


Figure 2.16 Evolution of drying air moisture content during drying (adapted from López et al., 1997).

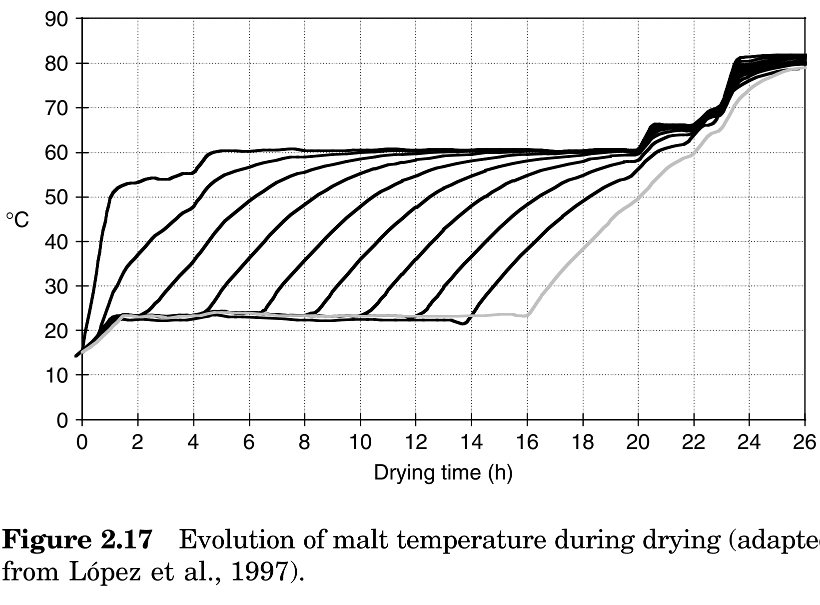


Figure 2.17 Evolution of malt temperature during drying (adapted from López et al., 1997).

Once the mathematical model has been solved and validated, several change possibilities in drying conditions can be analyzed, in order to decrease energy consumption and drying time. Thus, several air-recirculation programs have been analyzed, with different percentages of air and recirculation periods. With this computer model, the instantaneous consumption of thermal energy expended in air drying (according to type of air recirculation) can be calculated. The maximal energy savings in studied cases would be 5.39% fuel and 7.48% electricity. These savings would exist in an optimum recirculation program combined with optimum ventilation.

2.4.4 Nomenclature

z	position in elementary layer
δz	thickness of elementary layer
T_a	air temperature
w_a	air absolute moisture
M	cereal moisture
T_m	cereal temperature
C_a	specific heat in air drying
C_g	specific heat in grain matter drying
C_v	vapor-specific heat
C_w	water-specific heat
w_m	air water content
i_m	air enthalpy
G	airflow rate
M_o	initial moisture content
M_e	equilibrium moisture content
t	time
k	drying constant
ρ	density
ε	porosity
h_c	heat transfer coefficient by convection
A	surface transfer
D_{eff}	effective diffusivity
E_a	activation energy

RH	air relative moisture
L	water latent vaporization heat
s	contraction bed coefficient
p	air pressure
p_s	pressure for saturated water vapor according to air temperature
i	enthalpy

2.5 MATHEMATICAL MODELING OF REFRIGERATION AND THERMAL STORAGE SYSTEMS

The design engineer requires adequate tools for the design and control of industrial food processing systems. The industry in general, and particularly the frigorific industry, must build expensive pilot plants to simulate and test the behavior of new processes, in order to scale up and apply acquired knowledge to establishment of a real plant. In recent years, the progressive accessibility to personal computers, numerical methods, and increasingly advanced computer tools have enlarged the use of processing and auxiliary system modeling and simulation (Creus, 1989; Cleland and Cleland, 1989).

Simulation studies of a physical system begin with development of a mathematical model capable of reproducing real behavior in different work conditions, and when process parameters change. Since a large number of parameters usually take part in the system's behavior, selection is made between those with the most influence. These parameters will be included in the simulation model. In this manner, the level of model adequacy to a said reality is given mainly by simplifications incorporated into the model (Touber, 1984).

Classic mathematical models of refrigeration systems describe the physical phenomena taking place by applying algebraic equations derived from mass and energy balances to each component of the system and by considering the existence of steady state. In practice, steady-state conditions are seldom reached. This is why models predicting the unsteady behavior of refrigeration systems are currently in demand. In recent years, this requirement has resulted in a huge research effort (James et al., 1986; Wong et al., 1985). According to several authors, the main reasons for dynamic modeling and simulation of refrigeration systems are (Lopez, 2000):

- *Design*. The correct representation of the refrigeration system's heat capacity, and the heat load at which the system is submitted, leads to adequate system design; this avoids oversizing of the equipment, which reduces its efficiency and the control of the system in difficult, low-capacity situations. Classic criteria for design generally do not consider the refrigeration system as operating in conditions far from the "usual working conditions," which are also the "design conditions." Models used for refrigeration system design can simulate system operation within a large variation of limits to possible working conditions. In this manner, optimization of the system's efficiency is possible.
- *Control*. Identification of "key parameters" in the system can be obtained by means of a sensibility analysis based on the mathematical model of the system. Adequate modes of control and set values for the controllers can be found in the range of overall operating conditions of the system.
- *Research* on improving the refrigeration system. Research costs can be reduced by means of preliminary research using mathematical models. Thus, design improvements of the refrigeration system can be researched at low cost. In addition, the limitations of research can be amplified by means of these models.
- *Diagnostic*. Methods that diagnose failures and breakdowns in the refrigeration system can be researched by means of mathematical modeling and simulation.

In fact, all of these aspects can influence the economic behavior of the system, because adequate models and simulation will significantly reduce the cost of design, research, and maintenance of a refrigeration system.

Usually, the mathematical models developed for the different components of a refrigeration system are based on the general theory of modeling and simulating an engineering system. In each element of the refrigeration system, a single-one system (or independent zone), mass, and energy macroscopic balances are applied, obtaining the differential and algebraic equations for the overall mathematical model (Costa et al., 1994).

The mass balance is simplified in the refrigeration system, since in each element of the system there is only one inlet of mass flow corresponding to the refrigerant. If the inlet mass flow is equal to the outlet mass flow, there will be no accumulation of refrigerant in the element, which will be in steady state without mass generation.

Generally, knowledge of the mass macroscopic balance is insufficient. Thus, it is important to know the temperature of each stream and the amount of thermal energy exchanged in certain equipment, etc. — that is, it may be necessary to apply an energy macroscopic balance around the system.

2.5.1 Modeling the Components of a Refrigeration System

A refrigeration system, from a modeling point of view, can be defined by means of an interactive set of components (Stoecker, 1989). This means that change in the component's behavior has a direct or indirect effect on the rest of the components.

In a refrigeration system simulation, each component must be defined by a mathematical equation set, along with operation parameters and other equations that include the thermodynamic properties of fluids working in these components. The simulation will perform all necessary calculations for the operation parameters, such as temperature, pressure, heat rate, and mass rate of the working fluids.

In this manner, the equations used to describe the behavior of each component in the refrigeration system are obtained from mass and energy macroscopic balances, applied according to the above methodology.

Generally, refrigeration equipment is designed for maximum refrigeration needs. However, the real heat load is frequently lower than the design load, and sometimes greater.

Simulation is a powerful tool for evaluating the behavior of equipment when the system is submitted to a different heat load (lower or greater than the design load). This allows the design engineer or the production engineer to determine the possible operation and control problems that might exist, because simulation can predict system behavior (Kasprowicz, 1990). For example, if the equipment has a refrigeration capacity greater than needed, the evaporation temperature will increase; in contrast, insufficient refrigeration capacity will lead to lower evaporation temperatures. These situations will affect the electric consumption of the compressor, the efficiency of the condenser, and so on.

Most food factories that use refrigeration systems as auxiliary systems to their food processing systems have mechanical refrigeration systems. The location points of the refrigeration used in the food factory are the main sources of variation in system behavior. However, the dynamic behavior of the overall system cannot be introduced into the model without considering the response of the refrigeration system to the cold requirements of the food factory.

The refrigeration system is composed of compressors, evaporators, condensers, etc. It is not enough to model only the refrigeration demand, representing the refrigeration equipment by means of velocity of heat given out, variable with time. Yet, it is not enough to model the refrigeration equipment with the cold demand system as a variable heat load, as a function of (or during) time. The building of an accurate behavior model should include both the refrigeration equipment and the cold demand systems, as food processing systems. On the other hand, if the refrigeration system is submitted to a constant heat load (same as above), at a constant evaporation temperature, the system will exhibit variable behavior. This is due to external factors, as the atmospheric conditions will affect the condenser behavior, which at the same time will affect the remaining components in the refrigeration system (Cleland, 1990).

Generally, as mentioned earlier, refrigeration installation designs are carried out assuming a steady-state condition, mainly because techniques have not been available to solve the dynamic behavior of refrigeration systems. This means that most refrigeration systems are not optimized with respect to many working conditions, leading to greater energy consumption and more difficulty in obtaining stable control of the refrigeration system (Cleland and Cleland, 1989; Cleland, 1990).

Today, many authors (e.g., Wang, 1991) agree that the development of mathematical models is essential to the design, and to the analysis of the economics and optimization of refrigeration systems.

The detail level of the mathematical modeling depends on the objectives desired. Several authors (e.g., Darrow et al., 1991) argue that the objective should not be to simulate the system's beginning, because it is difficult to justify the use of complicated mathematical models when simpler versions can obtain accurate simulation.

Next, actual mathematical models are shown for each component of the refrigeration system.

2.5.1.1 Compressor

Modeling of the compressor operation has been the objective of many research endeavors, conducted mainly on the reciprocating compressor. This research has been performed at a lower intensity on rotary compressors, including screw compressors.

In most research conducted, the reciprocating compressor is considered a system with a simple zone and negligible thermal capacity, in which the work done is determined by means of one of three methods (James et al., 1986):

a) Using the indicator diagram and the equation for polytropic processes

For example, Marshall and James (1973, 1975) obtained a good value for the enthalpy changes of the fluid through the compressor, considering the indicated power of the compressor, as follows:

$$h_e - h_s = k_1 \cdot (T_e + 273) \cdot \left[\left(\frac{p_s}{p_e} \right)^{k_2} - 1 \right] \qquad (2.174)$$

Constants k_1 and k_2 were determined using adequate values for γ and $\hat{c}_v$.

Considering the volumetric flow rate of the compressors constant, due to the variation of the compressor, velocity is minimum, and it is possible to obtain the mass flow rate through the compressor with the following equation:

$$m_r = \dot{V}_r \cdot \rho \cdot N_c \qquad (2.175)$$

where

$\dot{V}_r$ = volumetric flow rate of each cylinder (m^3/s)

ρ = density in kg/m^3 (calculated by the equation: $p = \rho \cdot R \cdot T/M$)

N_c = number of working cylinders

Other authors have obtained similar equations for the compressor (Cleland et al., 1982; Cleland, 1983). The enthalpy of the superheated vapor leaving the compressor is given as

$$h_{v-s} = h_v + \frac{\dot{Q}_{comp}}{m_r} \qquad (2.176)$$

where

h_v = enthalpy of the saturated vapor (J/kg)

m_r = mass flow rate of refrigerant (kg/s)

$\dot{Q}_{comp}$ = heat flow per unit of time given by the compressor (W)

This term for power transferred from the compressor to the vapor is calculated using the equation for adiabatic compression, modified with the volumetric efficiency of the compressor (Cleland et al., 1982):

$$\dot{Q}_{comp} = \frac{\gamma}{\gamma - 1} \cdot p_s \cdot Q_r \cdot \left[\left(\frac{p_d}{p_s} \right)^{(\gamma-1)/\gamma} - 1 \right] \qquad (2.177)$$

b) Using the equation for perfect gases and the equation for polytropic compression processes

James and Marshall (1974) and Hargreaves and James (1980) have used this method to obtain the refrigerant temperature at the outlet of the compressor, as follows:

$$T_s = \left(T_e + 273\right)\cdot\left(\frac{p_s}{p_e}\right)^{(n-1)/n} - 273 \qquad (2.178)$$

From this temperature value, the enthalpy of the superheated vapor is obtained from the enthalpy of the saturated vapor, and an average specific volume obtained for the superheated vapor, as follows:

$$h_{v-s} = h_s + 0.68\cdot\left(T_{v-s} - T_s\right) \qquad (2.179)$$

In the same way, other authors such as Colding et al. (1991) have obtained the refrigerant temperature at the outlet of the compressor as a function of evaporation and condensing temperatures (the inlet temperature at the compressor and the compression ratio).

c) Using a detailed model where the processes taking place in the cylinders of the compressor are related to the movement of the crankshaft

This kind of model has been used to simulate the start of the compressor and to improve the mechanical design of the compressor. However, these aspects have little importance in the dynamic behavior of the overall refrigeration system, as the operating mode of the compressor can be considered as constant (steady) for a determined velocity (Cleland, 1990; Wang, 1991). Some of the models developed are listed here:

- Model by Chi and Didion (1982) — A hermetic compressor
- Model by Yasuda et al. (1983) — An open reciprocating compressor with only one cylinder
- Model by MacArthur (1984) — A hermetic compressor in which the operation mode is described as a function of five variables: (1) compressor clearance, (2) piston displacement, (3) compression ratio, (4)

heat transfer coefficient between refrigerant and wall of cylinder in compressor, and (5) thermal capacity of compressor.

- Model by Gunther et al. (1984), simulating the start-up of hermetic compressors in refrigeration installations, considering the thermal capacity of the main elements of the compressor and the influence of temperature on mechanical and thermal loss in the compressor.
- Model by Beckey (1986), in which the flow rate of the refrigerant is obtained from the number of revolutions per minute of the crankshaft in the compressor.
- Model by James and James (1986) and James et al. (1987) — A dynamic model of a hermetic compressor in which the compressor is divided into six zones: (1) electric motor, (2) vapor around motor, (3) oil, (4) refrigeration coil, (5) part of metallic shell below oil level, and (6) part of metallic shell at oil level. The mathematical equations describing the behavior of each zone are obtained by means of mass and energy balances around each zone, and by using state equations and heat transfer velocity equations, taking into account the following simplifications:
  - Temperature gradients and heat transfer in the motor are negligible.
  - Heat transfer by radiation in the compressor shell is negligible.
  - Heat transfer between the shell (insulated) and the exterior is negligible.
  - The blend of fluids (water, oil, and gas refrigerant) is considered perfect.
  - The volume of gas and oil is considered constant.

Mathematical models are available that simulate the dynamic behavior of compressors by means of differential and algebraic equations. These models are seldom used to simulate the compressor of a refrigeration system, due to their complexity and the existence of a steady state in the system once the start time step is completed.

A good example of a dynamic mathematical model of a compressor is the one developed by Xi Shen et al. (1995) to simulate a compressor's capacity control system.

Equations describing the compressor's behavior follow:

- Mass balance

$$dm_r = dm_{r,s} + dm_{r,d} \tag{2.180}$$

where m_r is the mass flow rate of the refrigerant, and s and d are suction and discharge, respectively.

- Energy balance

$$d\left(M_r h_r\right)/dt = dQ/dt - pdV/dt + dE/dt \tag{2.181}$$

where
dV/dt = variation of volume in system
dQ/dt = heat transfer velocity from surroundings
dE/dt = heat transfer velocity associated with mass flow

dV/dt is obtained from the kinetic equation for the piston:

$$\frac{dV}{dt} = \frac{1}{4}\pi D^2 \omega L \left[\lambda sen\theta_{comp} + \frac{\lambda^2 sen\theta_{comp}\cos\theta_{comp}}{\left(1-\lambda^2 sen^2\lambda\right)^{1/2}}\right] \tag{2.182}$$

where
D = diameter of piston (m)
ω = angular velocity of compressor crankshaft (rad/s)
L = length of crankshaft (m)
θ_{comp} = angle of rotation of compressor crankshaft

The heat transfer velocity from the surroundings dQ/dt is determined using the heat transfer equation:

$$\frac{dQ}{dt} = \alpha_{c\ln} A_{c\ln}\left(T_w - T_r\right) \tag{2.183}$$

where
α = heat transfer coefficient (W/m^{2}K)
A = heat transfer surface (m^2)

T = temperature (where w = wall; r = refrigerant)

The term dM_r/dt is obtained from the equation for mass flow rate through the valves of the compressor:

$$\frac{dM_r}{dt} = \frac{C_{vl}A_{vl}}{V^2}\left[2\left(h_1 - h_2\right)\right]^{1/2} \tag{2.184}$$

where
C_{vl} = flow capacity of valve (m^3/s)
A_{vl} = valve area (m^2)

From a heat transfer point of view, a hermetic compressor is composed of two zones: the cylinder zone and the rest, including the electric motor and the shell.

Cylinder: from the Law of Conservation of energy:

$$\left(\hat{C}_p \rho V\right)_{comp} \frac{dT_{comp}}{dt} = \dot{W}_f - \dot{Q}_2 - \dot{Q}_3 - \dot{Q}_7 \tag{2.185}$$

Motor:

$$\left(\hat{C}_p \rho V\right) \frac{dT}{dt} = \dot{Q}_3 + \dot{Q}_5 + \dot{Q}_6 + \dot{Q}_1 - \dot{Q}_4 \tag{2.186}$$

where W_f is the work of friction; Q_1 is the heat transferred to the surroundings; Q_2 is the heat exchanged between the refrigerant and the cylinder while the refrigerant touches the cylinder head; Q_3 is the heat exchanged between the cylinder and the refrigerant outside the cylinder; Q_4 is the heat absorbed by the refrigerant coming through the suction tube; Q_5 is the heat transferred from the discharge tube to the refrigerant; Q_6 is the heat produced by the electric motor; and Q_7 is the heat exchanged between the refrigerant in the cylinder and the wall of the same.

Other dynamic models take into account the internal geometry of the compressor, is:

- Model by Yasuda et al. (1995), for dynamic simulation of a refrigeration system involving a scroll compressor.

2.5.1.2 Condenser

Mathematical equations explaining the dynamic behavior of condensers are obtained from the Law of Conservation of Mass and Energy in a defined system. Differences between the various models developed are mainly found in the number of zones dividing the system, which represents the condenser. The greater the number of zones, the greater the complexity, but the accuracy of the simulation is also greater.

A simpler mathematical model is one that considers the condenser as only one zone, around which only one energy balance is applied. This approach has been used by different authors (Cleland et al., 1982; Cleland; 1983, 1990), accordingly:

$$\left(Mc\right)_c \frac{dT_c}{dt} = m_r \Delta h_c - \left(UA\right)_c \Delta T_m \qquad (2.187)$$

where

$(Mc)_c$ = thermal capacity of the condenser (J/K)
T_c = condensation temperature (K)
m_r = mass flow rate of refrigerant (kg/s)
Δh_c = refrigerant enthalpy change in the condenser (J/kg)
$(UA)_c$ = product of overall heat transfer coefficient and exchange surface (W/K)
ΔT_m = mean temperature difference (K)

The model considers all processes in the condenser (cooling of superheated vapor, condensing and subcooling of saturated liquid) as having only one change in enthalpy at condensation temperature. In fact, the larger amount of heat exchanged in the condenser is due to the condensation process. In addition, the pressure drop in the condenser is considered negligible, with the condensation process taking place at constant temperature.

Another similar model (Grimmelius, 1995) considers the condenser as only one element but with three heat exchange zones: (1) cooling of the superheated vapor zone, (2) condensation zone, and (3) subcooling of the liquid zone.

There are other more complex kinds of condenser models where the condenser is divided into a greater number of zones, around which the same laws of mass and energy conservation are applied. Generally, the zones dividing the condenser are (1) the refrigerant (vapor and liquid), (2) the metallic wall of the condenser, and (3) the condensation medium (air or water).

Among the models used are the following:

- Model by Marshall and James (1975), for dynamic behavior of evaporative condenser, divided into four zones: (1) vapor zone, (2) limit layer between vapor and liquid, (3) liquid zone, and (4) tube wall. The vapor zone, including the tube between the compressor and condenser, the tubes of the condenser, and the vapor space within the liquid receiver, are all represented as one homogeneous zone. The limit layer includes the condensation vapor (zone 2), and all of the liquid is considered within zone 3.

The mass and energy balances in zone 1 of the vapor are given by the equations

$$m_4 - m_5 = \frac{d}{dt}\left(\rho_5 \hat{V}_{vc}\right) \tag{2.188}$$

$$m_4 h_4 - \dot{Q}_{45} - m_5 h_5 = \frac{d}{dt}\left(\rho_5 h_5 \hat{V}_{vc}\right) \tag{2.189}$$

Using the same procedure for zones 2 and 3, the differential equations explaining the dynamic behavior of the condenser are determined. In other works using a similar procedure (James and Marshall, 1973; Hargreaves and James, 1980), a model of the shell and tube condenser was obtained.

Solving the differential equation system by numerical methods is similar to solving simpler models (ones with fewer differential equations). For example:

- Model by Yasuda et al. (1983), for a shell and tube condenser

In this model, the following simplifications were made:

1. The heat transfer process is described by the heat transfer coefficient only, because the superheated vapor and liquid zones are considered one zone during the phase change.
2. The subcooling is constant.
3. The pressure drop is not considered.

The equations are obtained by applying the laws of mass and energy conservation to the following zones: refrigerant, tubes, condensing water, and metallic wall of condenser.

a) Refrigerant

$$\frac{d}{dt}\left(M_{v,c}+M_{l,c}\right)=m_{v,c}-m_{l,c} \tag{2.190}$$

$$\begin{aligned}\frac{d}{dt}\left(M_{v,c}h_{v,c}+M_{l,c}h_{l,c}\right)=m_{v,c}h_{l,c}-m_{l,c}h_{o,c}\\ -\alpha_{r,t}A_{r,t}\left(T_c-T_{t,c}\right)\\ -\alpha_{r,pc}A_{r,pc}\left(T_c-T_{t,pc}\right)\end{aligned} \tag{2.191}$$

$$\begin{aligned}M_{v,c}&=\hat{V}_c\cdot x_v\cdot\rho_{v,c}\\ M_{lc}&=\hat{V}_c\cdot(1-x_v)\cdot\rho_{l,c}\end{aligned} \tag{2.192}$$

b) Tubes

$$\hat{c}_{t,c}\frac{dT_{t,c}}{dt}=\alpha_{r,t}A_{r,t}\left(T_c-T_{t,c}\right)-\alpha_{ag,t}A_{ag,t}\left(T_{t,c}-T_{ag,c}\right) \tag{2.193}$$

c) Condensing water

$$\hat{c}_{ag}\frac{dT_{ag,c}}{dt}=m_{ag,c}\hat{c}_{ag}\left(T_{ag,e,c}-T_{ag,s,c}\right)+\alpha_{ag,t}A_{ag,t}\left(T_{t,c}-T_{ag,c}\right) \tag{2.194}$$

d) Condenser walls

$$c_{p,c}\frac{dT_{p,c}}{dt}=\alpha_{r,pc}A_{r,pc}\left(T_c-T_{p,c}\right)+\alpha_{pc,a}A_{pc,a}\left(T_{p,c}-T_{a,s}\right) \tag{2.195}$$

- Models by Dhar and Soedel (1979) and Martins-Costa (1993) represent the behavior of an air-cooled condenser.

2.5.1.3 Evaporator

Refrigeration requirements are satisfied by using the evaporator. This is probably the reason the evaporator has received more attention than the other components of the refrigeration system (James et al., 1985). There are two primary ways that refrigerant can be fed into an evaporator, and thus the evaporator has two main categories: dry expansion and flooded. The flow of refrigerant into a dry expansion evaporator is controlled by a thermostatic expansion valve, which allows superheating of the vapor refrigerant to avoid the liquid taken into the compressor. On the other hand, the flooded evaporator often uses a float valve to control the level of liquid refrigerant in the evaporator, which is completely filled with liquid.

a) Flooded evaporators

- *Flooded evaporator with liquid pumping*. A simpler model has been developed by Cleland (1983), where the evaporator is represented by only one zone, including the refrigerant side of the evaporator, the tubes connecting the evaporator to the vapor separator, and the liquid in the separator.

The model makes the following simplifications:

- The length of time the refrigerant is in the evaporator is short.
- The pressure drop in the evaporator is negligible and the vaporization process is at constant temperature.
- The liquid level in the separator is constant.

Considering the heat loss and gain as negligible, the energy balance around the evaporator is given accordingly:

$$\left(Mc\right)_{ev}\frac{dT_{ev}}{dt}=\sum m_r\left(h_{r,e}-h_{r,s}\right)+\left(UA_{ev}\right)\Delta T_m TS \quad (2.196)$$

where $(Mc)_{ev}$ represents the thermal capacity of the separator, evaporator, and connecting tubes (J/K); ΔT_m is the mean temperature difference in the evaporator; and TS is the ratio between the sensible heat and total heat.

- Marshall and James (1975) used a similar model for the flooded evaporator, but divided it into a greater number of zones. The liquid separator was divided into two zones: liquid zone and vapor zone, like the evaporator's metallic wall of tubing and refrigerant.

Equations for the evaporator are determined as follows: Energy balance in pump:

$$h_{20} - h_{19} = \frac{\left(p_{20} - p_{19}\right)}{\rho} \tag{2.197}$$

Relationship between pressure drop and mass flow rate in evaporator:

$$p_{21} - p_{24} = 159500 \frac{m_{r,21}^2}{\rho_{21}} \tag{2.198}$$

Mass and energy balance in refrigerant zone of evaporator:

$$m_{r,21} h_{21} + \dot{Q}_{R1} - m_{r,24} h_{24} = \frac{d}{dt}\left(\rho_{24} h_{24} \hat{V}_{e1}\right) \tag{2.199}$$

$$m_{r,21} - m_{r,24} = \frac{d}{dt}\left(\rho_{24} \hat{V}_{e1}\right) \tag{2.200}$$

Energy balance in metallic zone (walls of tubing) of evaporator:

$$\dot{Q}_{e1} + \dot{Q}_{e2} - \dot{Q}_{R1} = m_r \hat{c}_p \frac{dT}{dt} \tag{2.201}$$

The overall heat transfer coefficient was obtained from the suppliers to calculate the heat transfer coefficient between the tube and the refrigerant, and between the air and the exterior wall of the evaporator. In this manner, the heat transfer equations are determined:

$$\dot{Q}_{r,1} = 19\left(T_{M,1} - T_{r,1}\right) \tag{2.202}$$

$$\dot{Q}_{e,1} + \dot{Q}_{e,2} = 15.7 \cdot \left(T_{a,1} - T_{M,1}\right) \tag{2.203}$$

In the separator, the liquid and vapor can vary but total volume remains constant. The refrigerant stream is divided between the liquid and the vapor, in the outlet of the separator and in the return.

Mass and energy balances in the liquid space are given as follows:

$$m_{8l} + m_{30l} - m_{18l} = \frac{d}{dt}\left(\hat{V}_l \rho_{18}\right) \tag{2.204}$$

$$m_{8l}h_{8l} + m_{30l}h_{30l} - m_{18l}h_{18l} = \frac{d}{dt}\left(\hat{V}_l \rho_{18} h_{18}\right) \tag{2.205}$$

Similar equations have been developed for the vapor space in the separator.

- *Flooded evaporators without liquid pumping*. In these evaporators, the control of refrigerant is conducted using a float valve. In this case, the model is similar to flooded evaporators with liquid pumping but only when considering different heat transfer coefficients.

b) Dry expansion evaporators

These are the most used evaporators in refrigeration systems, where liquid is fed via a thermostatic expansion valve.

There are different types of mathematical models, each defining the number of zones dividing the evaporator. Many authors have developed models with only one zone, as in models by Chi and Didion (1982), Marshall and James (1975), Hargreaves and James (1980), and Cleland et al. (1982), where all of refrigerant in the evaporator is considered one zone, with a constant mass flow rate entering and leaving.

A simpler mathematical model representing the dynamic behavior of the evaporator has been developed by Cleland et al. (1982), where the evaporator is considered one zone, and the expansion valve is represented algebraically. The model supposes that the expansion valve will supply the necessary liquid needed to maintain the superheating as constant at the outlet of the evaporator. In this manner, the dynamic behavior of the valve immediately after is not considered. The energy balance in the evaporator is given by the expression

$$\left(Mc\right)_e \frac{dT_e}{dt} = -m_r \Delta h_e + \left(UA\right)_e \Delta T_m TS \qquad (2.206)$$

As for the remaining components in the refrigeration system, there are other models where the evaporator has been divided into a greater number of zones in order to obtain a more accurate simulation. In addition, models found in research literature can be differentiated as functions of the type of circulation regime used for the vapor-liquid mixture in the evaporator, and as whether or not the superheating zone is considered. The main models developed are as follows:

- Models by James and Marshall (1974), and Hargreaves and James (1980), for a shell and tube evaporator or chiller, divided into three homogeneous zones.

In the models, the different types of refrigerant flows taking place in the evaporator are not considered.

Mass and energy balances in a single zone are given as follows:

Refrigerant side:

$$m_{11} - m_{12} = \frac{d}{dt}\left(\rho_{12} \hat{V}_e\right) \qquad (2.207)$$

$$m_{11}h_{11} + \dot{Q}_{e1} - m_{12}h_{12} = \frac{d}{dt}\left(\rho_{12} h_{12} \hat{V}_e\right) \qquad (2.208)$$

Water side during cooling process:

$$m_{19} = m_{20} \tag{2.209}$$

$$m_{19}h_{19} - \dot{Q}_{e1} - m_{20}h_{20} = \frac{d}{dt}\left(\rho_{20}h_{20}\hat{V}\right) \tag{2.210}$$

- Model by Broersen and Van der Jagt (1980), where the evaporator is divided into two zones: one containing liquid and vapor flow and a second containing superheated vapor.

Equations obtained from mass and energy balances on the refrigerant side follow:

$$m_{d-f,l} - m_{d-f,v} = \frac{d}{dt}\left(m_{r,l} - m_{l,v}\right) \tag{2.211}$$

$$m_{d-f,l} + \alpha_{r,p-e}\pi D_{i,e}y\left(T_{p-e} - T_e\right) = \frac{d}{dt}\left(m_{r,l}h_l - m_{r,v}h_v\right) \tag{2.212}$$

where y is the point of complete drying of the refrigerant.

Masses M_l and M_v were obtained as follows:

$$M_v = fA\rho_v y \tag{2.213}$$

$$M_l = \left(1-f\right)A\rho_l\left(y + k\frac{dy}{dt}\right) \tag{2.214}$$

where k is the time constant for the liquid distribution (s), and f is the dry fraction of the refrigerant.

Equations obtained from the energy balance on the wall of the evaporator:

$$\rho_p\hat{c}_pA_p\frac{dT_p}{dt} = \alpha_{p,ag}\pi D_{ext,e}\left(T_{ag,ext} - T_p\right) - \alpha_i\pi D_{int,e}\left(T_p - T_e\right) \tag{2.215}$$

Energy balance in the superheating zone:

$$M_v\hat{c}_v\frac{\partial T_{v-s}}{\partial x} + \rho_vA\frac{\partial T_{v-s}}{\partial t} = \alpha_{r,p}\pi D_{\text{int},e}\left(T_{p,v-s} - T_{v-s}\right) \tag{2.216}$$

This equation is in partial derivatives because the limit between the double flow zone and the superheating zone, given by the distance *y,* is variable.

- Model by Yasuda et al. (1983), for a dry expansion evaporator with a thermostatic expansion valve, which considers two zones: the evaporating zone and the superheating zone. In this model, the temperature of the refrigerant at the evaporator outlet is fundamental to the operation's instability flux. The main simplifications used in the model are described next:
  - A limit exists between the evaporating and superheating zones.
  - In the evaporating zone, the characteristics of the refrigerant remain constant.
  - The double flow of liquid-vapor in the evaporating zone is homogeneous and in equilibrium.
  - A pressure drop exists at the end of the evaporating zone and within the superheating zone.

Equations from mass and energy balances that are applied to the refrigerant, the wall of tubing in the evaporator, and the water in the cooling process are similar to the above. Numerical solutions are found by dividing the total length of the evaporator into a large number of sections, on which finite differences techniques are applied.

- Model by MacArthur (1984) takes into account the difference between the liquid and vapor flows, as well as the temperature and enthalpy profiles in the evaporator, working in both steady state and unsteady state.
- Model by Yasuda et al. (1995) considers the evaporating and superheating zones. These zones are defined by means of differential equations obtained from mass and energy balances in each zone.

Other similar models are those by Beckey (1986), and Grimmelius (1995).

Different authors have studied tank and coil coolers, where an evaporator coil is placed in a tank full of liquid that is then chilled. But in the models usually developed, the evaporator is a single zone where mass and energy balances are applied. This is the case in the following models:

- Model by Darrow et al. (1991), a simple version based on thermal analysis, only considers heat transfer and ignores the hydrodynamic aspects of the behavior of refrigeration equipment. The model supposes that the distribution of refrigerant in the evaporator is constant at all times. The evaporating temperature is obtained from the energy balance in the entire evaporator:

$$\left(Mc\right)_e \frac{dT_e}{dt} = m_r\left(h_{e,e} - h_{s,e}\right) + \left(UA\right)_e\left(T_{ag} - T_e\right) \qquad (2.217)$$

- Model by Finer et al. (1993), which is based on the above work, represents a tank and coil evaporator that includes the ice formation on the evaporator coil once the temperature of the water is below 0°C. It is considered a thermal storage system model.
- Model by Jekel et al. (1993) represents the behavior of an ice bank fed by brine. In this model, analyses of the freezing and ice fusion processes in the evaporator coil are studied. Equations are obtained from an energy balance in the ice tank and from heat transfer velocity laws.

2.5.1.4 Expansion Valve

The function of the expansion valve is to reach a certain pressure and to maintain the pressure difference between the low and high zones caused by the compressor, and to control the flow of refrigerant according to the refrigeration requirements of the system.

The thermostatic expansion valve (TEV) has been the most studied since it is the one most used in refrigeration systems. This valve is a proportional controller, which responds to the pressure difference between the evaporator inlet and the evaporator outlet.

The valve maintains adequate superheating at the evaporator outlet. The superheating changes as the heat load changes in the evaporator, which occurs at the same time as the opening of the valve, activated to reach the previously fixed superheating level. The superheating level (generally between 4°C and 8°C) must be the lowest possible, to obtain maximum efficiency in the evaporator.

Modeling of the mass flow of refrigerant through the thermostatic expansion valve has been demonstrated as a function of temperature and pressure. Valve models developed as a function of temperature are listed next:

- Model by James and Marshall (1974), which represents the valve behavior by means of a differential equation, considers the refrigerant mass flow rate entering the evaporator as a function of superheated vapor at the outlet of the evaporator and its saturation temperature:

$$\frac{dm_{r,11}}{dt} = -m_{r,11} + k\left[\left(T_{v-s,14} - T_{v,14}\right) - 4.5\right] \qquad (2.218)$$

- Model by Hargreaves and James (1980) is a more complex version based on the capacity of the valve, the defined superheating, and the time of opening as a function of temperature change.

By knowing the valve's capacity, and by using the equation of flow through a hole, the refrigerant mass flow is given by

$$m_r = 0.0683 x_{VET}\left(p_{s,v\exp} - p_{e,v\exp}\right)^{0.5} \qquad (2.219)$$

where x_{VET} is the displacement of the shaft closing the valve.

If the dynamics of the valve are more rapid than the dynamics of the remote bulb, the pressures actuating in the valve can be represented as a function of temperature. The error in temperature can be calculated as follows:

$$T_E = T_p - T_8 + C \tag{2.220}$$

where T_p is the temperature of the remote bulb, T_8 is the temperature after the expansion valve, and C is the superheating where the valve opens.

The relation between the opening of the valve and the error in temperature is obtained from Equation 2.219 and Equation 2.220. Finally, the dynamics of the remote bulb are given by the following equation, with the time constant obtained from the supplier:

$$\frac{T_p}{T_1} = \frac{1}{1+5S} \tag{2.221}$$

where S is the operator of Laplace.

- Model by Yasuda et al. (1983), for an expansion valve in steady state, takes into account the intervals of time considered in valve displacements as very small compared to those actuating the refrigeration system behavior. The behavior of an expansion valve at steady state is considered similar to that of a proportional controller obtained from the next equation:

$$m_r = m_{nom} \frac{\Delta T_{ops} - \Delta T_{ss}}{\Delta T_{os}} \tag{2.222}$$

where
m_{nom} = nominal mass flow rate (determined using data from the supplier).
ΔT_{ops} = operation superheating
ΔT_{ss} = static superheating
ΔT_{os} = opening superheating

Listed next are models developed as a function of pressure:

- Model by de Broersen and van der Jagt (1980). In this model, the operation of an expansion valve is given by the sum of pressures actuating in the diaphragm of the valve:

$$m_r = k\left(p_b - p_e - p_{st}\right) \tag{2.223}$$

- Models by MacArthur (1984) and Yasuda et al. (1995). These models consider the mass flow rate of refrigerant through the expansion valve in steady state, which is related to the pressure drop via the equation of flow through a hole:

$$m_r = k_{VET} A_{VET} \sqrt{2\rho_{VET1}\left(p_{VET1} - p_{VET2}\right)} \qquad (2.224)$$

where k_{VET} and A_{VET} are the flow coefficient and the opening level of the valve, respectively.

- Model by Xi et al. (1995). The authors consider the time constant of the expansion valve as very small compared with the rest of the system, and that it is not necessary to consider refrigerant behavior. Modeling of the valve can be done with overall parameters:

$$m_r = k_{VET}\left(A_{VET}\right)\sqrt{p_{VET1} - p_{VET2}} \qquad (2.225)$$

where the valve coefficient k_{VET} is a function of the opening level of the valve, and is obtained experimentally.

- Model by van der Meer (1987). The dynamic properties of the thermostatic expansion valve are studied by means of experiments that consider the following factors: contact between the bulb and the suction tube; the wall and the bulb content; the capillary tube; the diaphragm, etc.

The float valve is generally used in flooded evaporators. It maintains the liquid level at constant in the separator feeding the evaporator. Models that consider the evaporator as having this type of control system do not exist in literature. However, there are authors researching the mass flow rate constant using this type of valve (Cleland, 1990).

In respect to the flooded evaporator fed by liquid pumping, the mass flow rate of circulation through the evaporator can be considered constant, since the real rate of liquid supply is four times the evaporating rate. In this manner, for example, an increase of 25% in the evaporation rate supposedly only changes from 75% to 69% in the liquid fraction at the return stream (Cleland, 1990). The mass flow rate of refrigerant is also considered constant by other authors such as Marshall and James (1975).

2.5.2 Trends in Refrigeration Systems Modeling

From the literature, analysis of the last 20 years indicates the increasing interest of researchers and refrigeration engineers in developing and using mathematical modeling. In the last few years, the number of research papers on refrigeration system modeling has increased from (65 in 1995 to 147 papers in 1999). The use of mathematical models and simulation is becoming increasingly appreciated in the optimization of refrigeration system design and control.

Analyzing the ratio of study in 1999 on refrigeration systems modeling, the most studied topics are as follows:

- Alternative refrigerants (17%)
- Absorption and adsorption systems (16%)
- Evaporators and condensers (14%)
- Whole refrigeration systems and control systems, including thermal storage systems (11%)
- Household refrigerators and supermarket display cabinets (8%)
- Compressors (7%)
- Air-conditioning systems (6%)
- Capillary tube and throttling valves, piping, and thermal insulation (5%)
- Emergent refrigerating systems (5%)

However, some work on the interaction between food processing systems (including freezing equipment and cold rooms) and refrigeration systems has been conducted (only 2% of total research). Accordingly, papers on refrigeration control systems modeling and optimization comprise only 3% in number, whereas knowledge of the system's dynamic behavior is necessary.

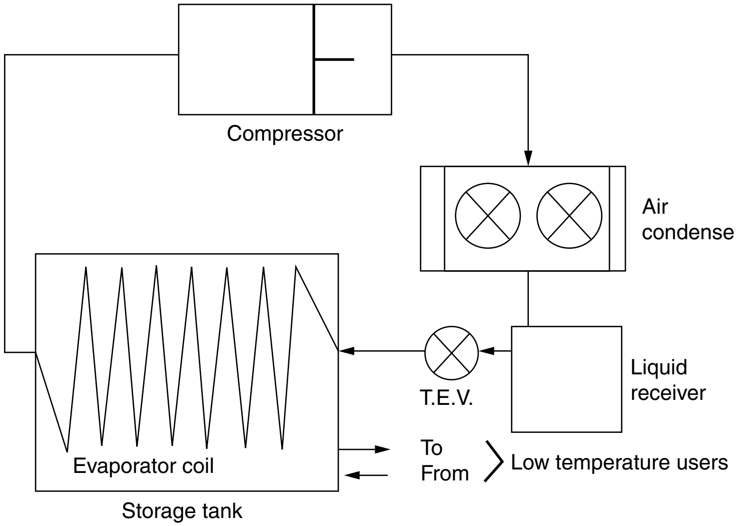


Figure 2.18 Layout of ice-bank system (adapted from Lacarra, 1998).

2.5.3 A Case Study

The mathematical modeling of a thermal storage system has been studied, in order to optimize the use of refrigeration in food industries.

2.5.3.1 Model Formulation

The ice-bank (Figure 2.18) and holding tank systems were the two thermal storage systems studied. In developing a mathematical model, equations of maximum simplicity that could define the behavior of the refrigeration system components were sought. The aim was to obtain a simulator with enough precision that could be easily run by entering simple characteristics found in technical information available from suppliers.

The models were developed by means of mass and energy balances around each component of the studied refrigeration systems. Each component was treated like an open system or zone around which the mass and energy balances were performed.

As other authors have already established, the compressor behavior is expressed by means of a single algebraic equation, considering the compressor as a zone with negligible thermal capacity. Constant compressor speed and constant volumetric flow rate are assumed. The volumetric efficiency is calculated in a simple manner with data from manufacturers.

The main refrigerant thermodynamic properties have been calculated with equations developed by Cleland, due to their great computation speed (compared to others existing in literature).

The condenser model is obtained via mass and energy balances around the condenser, which is considered a single homogeneous zone. The global heat transfer coefficient and exchange area may be obtained from the technical characteristics supplied by manufacturers, but it is always advisable to confirm this data by means of steady-state runs in the equipment.

In the evaporator model, the system around which the mass and energy balances are applied includes the evaporator and flow control device, assuming a stable performance for the shell and tube evaporator and submerged evaporator coil.

Concerning the holding tank and ice-bank models, the equations follow the works of other authors quite closely.

The holding tank (Figure 2.19) is divided into two parts, separating the cold and warm zones; equations for each follow:

$$\frac{dT_{11}}{dt} = \frac{1}{\left(M_1 \cdot c_{pw}\right)_l}\left[\begin{array}{l} m_{b1} \cdot c_{pw} \cdot \left(T_{weo} - T_{11}\right) \\ \quad + m_{b2} \cdot c_{pw} \cdot \left(T_{12} - T_{wto}\right) \end{array}\right] \tag{2.226}$$

$$\frac{dT_{12}}{dt} = \frac{1}{\left(M_2 \cdot c_{pw}\right)_l}\left[\begin{array}{l} m_{b1} \cdot c_{pw} \cdot \left(T_{11} - T_{wei}\right) \\ \quad + m_{b2} \cdot c_{pw} \cdot \left(T_{wti} - T_{12}\right) \end{array}\right] \tag{2.227}$$

if

$$\frac{dT}{dt} = \frac{1}{\left(M \cdot c_{pw}\right)}\left[\begin{array}{l} m_{b1} \cdot c_{pw} \cdot \left(T_{weo} - T_{wei}\right) \\ \quad + m_{b2} \cdot c_{pw} \cdot \left(T_{wti} - T_{wto}\right) \end{array}\right] \tag{2.228}$$

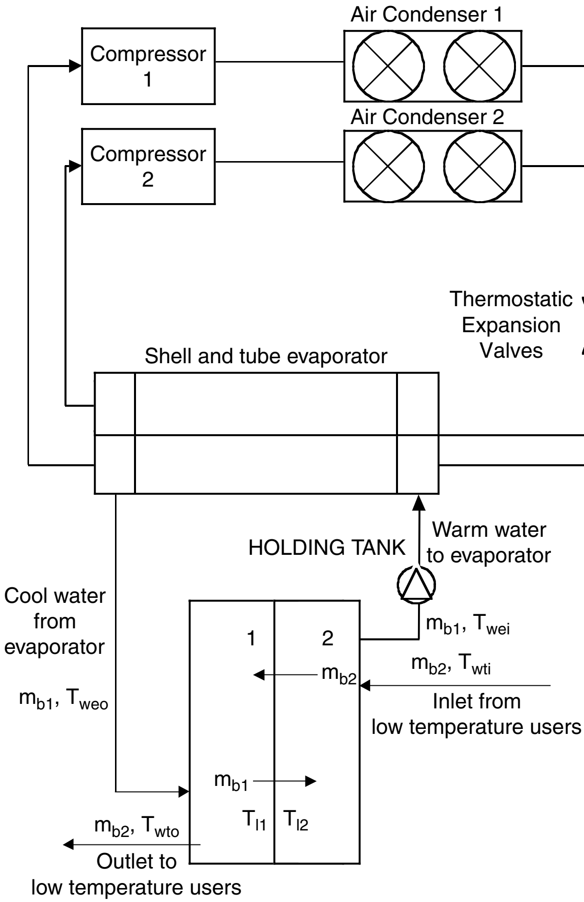


Figure 2.19 Layout of holding tank system (adapted from López and Lacarra, 1999).

and if

$$M = M_1 + M_2, \text{ and } T = (T_{11} + T_{12})/2 \qquad (2.228)$$

Equation 2.226 and Equation 2.227 are simplifications of different mass flows existing in the holding tank, from one zone to the other. Only the mass flows m_{b2} and m_{b1} are considered (m_{b2} from T_{12} zone to T_{11} zone, and m_{b1} from T_{11} zone to T_{12} zone). These equations attempt to explain the temperature differences existing between the two tank zones. Figure 2.19 defines all parameters appearing in Equations 2.226, 2.227, and 2.228.

2.5.3.2 Heat Transfer Coefficients Analysis

Since the evaporator is a component of the refrigeration system where heat exchange with the thermal storage medium takes place, the heat exchange phenomenon has been studied in depth. Different equations from literature have been used to determine individual heat transfer coefficients. Finally, values obtained have been introduced into a single expression called UA, which is a product of the overall heat transfer coefficient and heat transfer area using the thermal resistance method showed in Equation 2.229:

$$UA_e = \left[\frac{1}{A_{\text{int}}\alpha_{rt}} + \frac{\ln\left(D_{ext}/D_{\text{int}}\right)}{2\cdot\pi\cdot k_t\cdot L} + \frac{1}{A_{ext}\alpha_{ta}} \right]^{-1} \tag{2.229}$$

Individual heat transfer coefficients have been used in cases more common in thermal storage systems such as: (1) the shell and tube evaporator for cooling liquid (water or brine), which is stored in tank for later use; (2) the evaporator coil submerged in tank; and (3) the coil submerged in tank fed by a brine previously cooled.

When a thermal storage tank contains a submerged evaporator coil, the water temperature descends below 0°C and ice formation around the evaporator tubes begins. As a result, a new resistance factor (thermal conductivity k_{ice} of the ice layer) to heat flow must be included in the UA expression:

$$UA_{ice} = \left[\frac{1}{A_{\text{int}}\alpha_{rt}} + \frac{\ln\left(D_{ext}/D_{\text{int}}\right)}{2\cdot\pi\cdot k_t\cdot L} + \frac{\ln\left(D_{ice}/D_{ext}\right)}{2\cdot\pi\cdot k_{ice}\cdot L} + \frac{1}{A_{ice}\alpha_{ta}} \right]^{-1} \tag{2.230}$$

It is important to highlight that in the case of an energy balance around only the ice layer, the correct expression for UA_{ice} to describe the total conductance between the evaporating refrigerant and the surface of the ice is

$$UA_{ice} = \left[\frac{1}{A_{\text{int}} \alpha_{rt}} + \frac{\ln\left(D_{ext}/D_{\text{int}}\right)}{2 \cdot \pi \cdot k_t \cdot L} + \frac{\ln\left(D_{ice}/D_{ext}\right)}{2 \cdot \pi \cdot k_{ice} \cdot L} \right]^{-1} \quad (2.231)$$

2.5.3.3 Experiment Validation

Experiment validation of the ice-bank system and centralized refrigeration system for chilled-water production was carried out.

Validation of the ice-bank storage system was conducted in an external melt ice-on-coil storage system at pilot plant scale (see Figure 2.20). The parameters measured in the ice bank were water tank temperature; evaporation pressure; condensation pressure; temperature at evaporator outlet (superheating); temperature at condenser outlet (subcooling); temperature at compressor outlet; and ice mass formation around the evaporator tubes. The ice mass formation was measured from the water volume increase, using a water level measuring device in the tank. The parameters were measured every 15 seconds using automatic data acquisition equipment.

Evaporation pressure, condensation pressure, temperatures at the evaporator and condenser outlets, and the ice mass evolution in the ice-bank system were simulated using the above equations (see Figure 2.21, where thin and thick lines correspond to actual and simulated parameters, respectively). Agreement between the experiment and the simulated results was considered good in all cases.

Validation of the second refrigeration systems model was conducted by the food industry, in which water was cooled in shell and tube evaporators and stored in a holding tank for later use. In this case, a conventional refrigeration system exists, in which the water cooled inside the evaporator is sent to a holding tank (Figure 2.22). From there, the points of consumption are replenished. Generally, the precooling process causes vast energy consumption, resulting in cooling demand profiles with relatively significant peaks of consumption. This could signify the importance of introducing some thermal storage system. A simple scheme for the refrigeration system used in validation is shown in Figure 2.19.

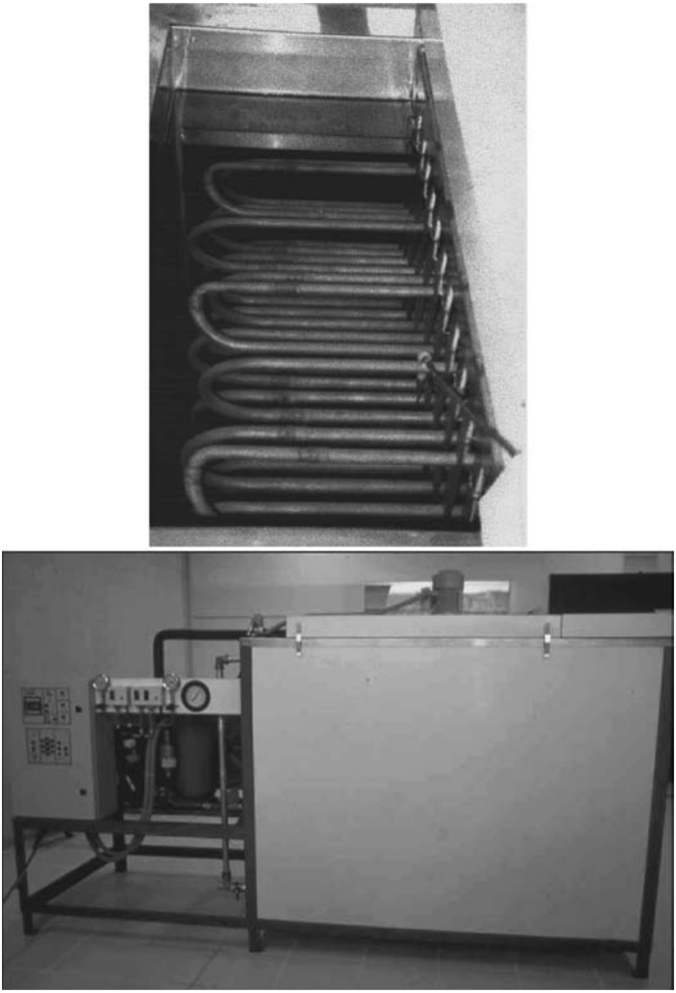


Figure 2.20 Ice-on-coil storage system at pilot plant scale.

The temperature and mass flow rate of the cooled water were measured by means of automatic data acquisition equipment. Figure 2.23 shows the data collected. Figure 2.24 shows the hourly average loads estimated from Figure 2.23.

Figure 2.25 shows the results of one corresponding with the date, October 12. By comparing Figure 2.23 and Figure 2.25, it can be seen that the simulation results are very

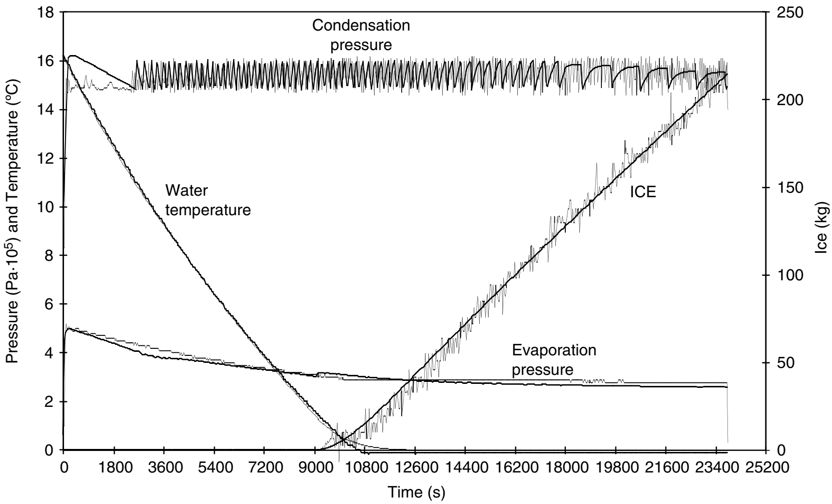


Figure 2.21 Evaporation pressure, temperatures at evaporator and condenser outlets, and ice mass evolution formed in the ice-bank system (adapted from López, 2000).

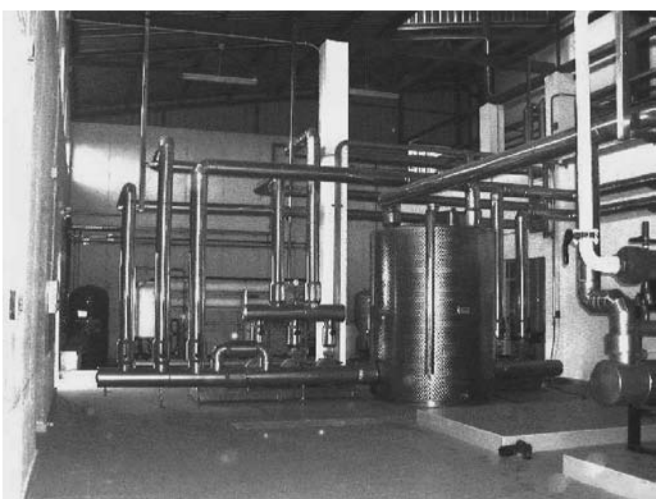


Figure 2.22 Holding tank in a refrigeration system.

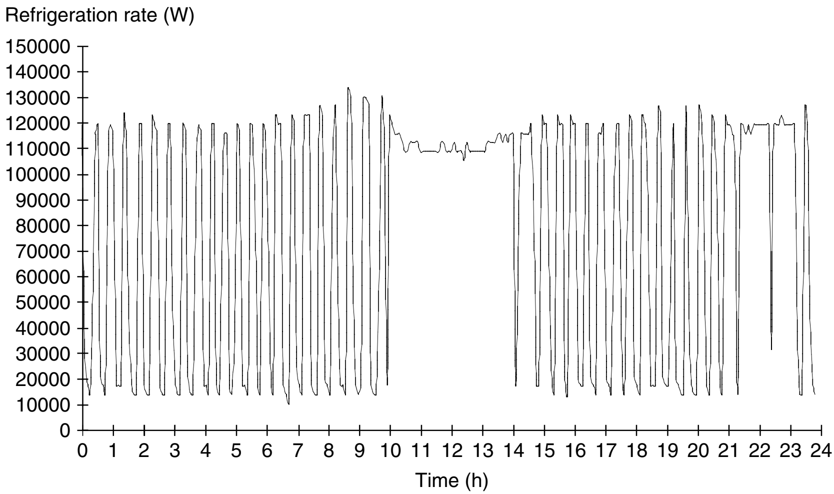


Figure 2.23 Refrigeration rate measured in study of a winery (adapted from López and Lacarra, 1999).

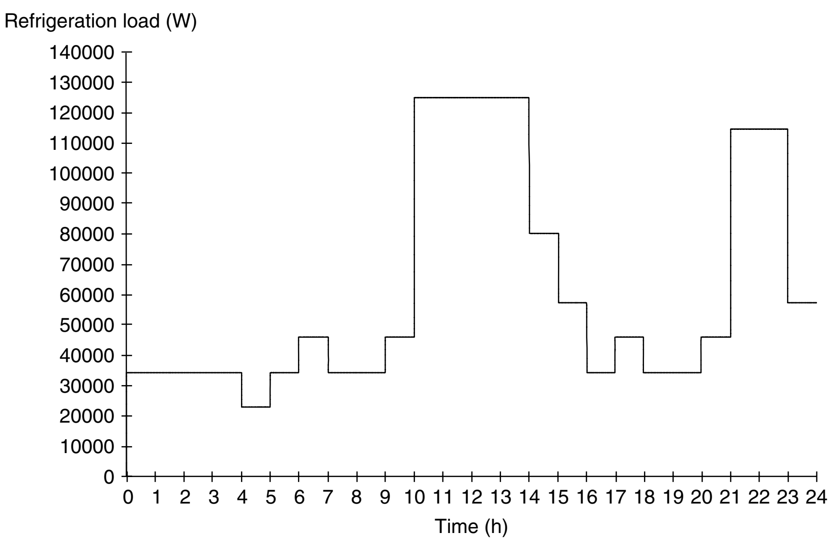


Figure 2.24 Refrigeration load deduced from data in Figure 2.23 (adapted from López and Lacarra, 1999).

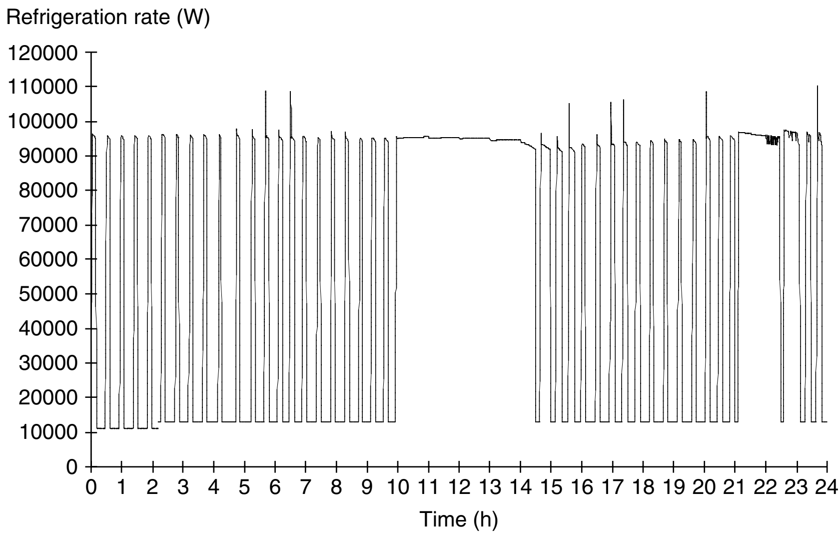


Figure 2.25 Results from simulation of data in Figure 2.24 (adapted from López and Lacarra, 1999).

similar; there are 41 on and off cycles in Figure 2.23 (from data collected) and 42 in Figure 2.25 (from simulation), and the observed and simulated total compressor on-time are similar (for the 20 days studied). It can be observed that certain discrepancies exist between the total refrigeration rate and the interval times when the equipment is working or stopped. Error in the refrigeration rate may be due to lack of correlation between the real characteristics of the refrigerating equipment and those introduced into the simulation program. Some of these characteristics (e.g., total effective heat exchange area) are difficult to know, and as a result, the *UA* calculated is somewhat minor compared to the real one. Errors in the demand profile acquisition from the refrigeration rate profile are mainly due to the time interval of data collection. Although the time interval is 300 s, some work time in the compressor can be lost between two consecutive measures. Despite all this, the simulation results show a large correspondence with the refrigeration system's real performance; therefore it can predict the expected behavior of a

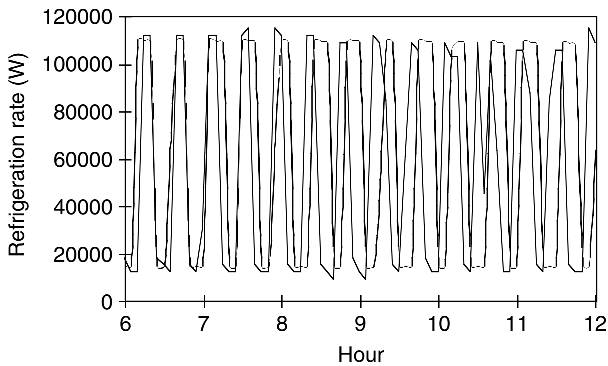


Figure 2.26 Comparison between simulation and experimental data during a 6–hour period chosen at random (adapted from López and Lacarra, 1999).

refrigeration system with a time-variable load. In this case (Figure 2.23 and Figure 2.25), the number of picks (compressor's on/off) before and after 12:00 a.m. is the same, which gives an idea of the simulation precision achieved.

Figure 2.26 shows the comparison between simulation and experiment data during a 6-hour period chosen at random (October 14, 1995; thin and thick lines correspond to simulated and observed refrigeration rates, respectively), and confirms the above-mentioned on simulation precision achieved. In this figure, it is possible to see that the tendency is the same for each type of data, but little variation exists in the peak positions, making it impossible to compare data statistically as the error measurement would be very high.

Concerning the holding tank model, the results obtained by simulation are similar; temperature differences between the two tank zones ranging from 3°C to 7°C (common in this type of holding tank) have been observed. With this model, the cooled water temperature at the holding tank outlet has been accurately simulated. It has been noted in simulated and real observations that cooled water temperature can reach undesirable levels (at holding tank outlet) if the refrigeration demand (e.g., in winery) is very high, due to the holding tank's insufficient capacity. This case can be studied by simulation: if the holding tank volume is increased from 6 m^3 to 50 m^3, the total compressor on-time is reduced by approximately 7% and the cooled water temperature is well controlled.

2.6 FOOD PLANT SIMULATION

2.6.1 Malting Plant

The malting process consists of several operations. The most important are (1) barley soaking or steeping at controlled temperatures, until a predetermined moisture content is obtained; (2) barley germination at controlled temperatures (around 16°C), cooling with saturated air; significant power consumption, especially during summer in interior zones; (3) hot air drying of green malt with increasing temperature from 60°C to 80°C. This type of food industry has a high level of energy consumption (López and Cabezas, 1993), despite the existence of energy-recovery systems (e.g., air-air heat exchangers, hot air recirculation in final drying steps, and cold air recirculation in the germination process) in the majority of malt plants. Management of these operations still requires a high level of experience and observation, as in final soaking point determination, soaking and germination process control, and green malt drying process control. The most significant energy consumption operations are in (1) refrigeration systems (electric energy), germination processes and refrigeration of soaking water; and (2) the boiler-house (thermal energy) with hot air drying of green malt.

A research project conducted as a result included (1) computer modeling of operations consuming the greatest amount of energy, thus those with the most empirical control and those determining malt quality (i.e., barley germination and green malt hot air drying); and (2) development of a knowledge-based system allowing simulation of an entire malting plant dynamic behavior, regarding cold requirements and production, and thermic energy requirements.

2.6.1.1 Knowledge-Based System Development

The knowledge-based system (KBS) for intelligent simulation of a malting plant was developed with object-oriented programming using the Nexpert Object 3.0 tool. The KBS was considered a multiagent system with distributed reasonement (López et al., 1993), where each process and auxiliary equipment, as subsystems, were represented within a knowledge island by means of design and operation characteristics, and operation rules including quantitative mathematical models (D'Ambrosio, 1990).

For simulation of the green malt hot air-drying operation, a deep-bed malt drying mathematical model was used, based on the Bala and Woods (1984) model, and then modified by López et al. (1997).

In germination process modeling, the barley deep bed is also divided into elementary layers with differential thickness (dz), as in the following equations:

- Cooling with heat generation

$$\frac{dT_m}{dt}\left(C_m \cdot \rho_m \cdot dz\right) = \frac{dS}{dt} \cdot \rho_m \cdot dz \cdot \frac{2.835 \cdot 10^3}{0.180} - G_a \cdot dT_a \cdot C_a \quad (2.232)$$

- Germination rate, solved as a system with consecutive reactions (Lewin and Lavie, 1990; Villota and Hawkes, 1992):

$$\frac{dS}{dt} = \frac{180}{6 \cdot 44} \cdot \frac{k_1 k_2 S_0}{k_1 - k_2} \cdot (e^{-k_2 t} - e^{-k_1 t}) \quad (2.233)$$

where dS/dt is the rate of germination (dry matter consumption), and k_1 and k_2 are the reaction rate constants. The temperature effect follows the Arrhenius equation $\left(k = k_0 e^{-E_a/RT}\right)$. The barley germination temperature in this operation can be considered constant.

- For soaking operations, assuming the rehydration is similar to the falling rate period during drying, the equation describing water intake is

$$\frac{M - M_e}{M_0 - M_e} = C \cdot e^{-k_r.t} \tag{2.234}$$

where k_r is the coefficient of hydration (Okos et al., 1992).

For the centralized refrigeration system, the Cleland (1990) model has been used:

- Condenser

$$\left(Mc\right)_c \frac{dT_d}{dt} = m_r \Delta h_c - \left(UA\right)_c \Delta T_m \tag{2.235}$$

Compressor

$$m_r = Q_s \eta_V / v \tag{2.236}$$

- Evaporator

$$\left(Mc\right)_e \frac{dT_e}{dt} = -m_r \Delta h_e + \left(UA\right)_e \Delta T_m \tag{2.237}$$

- Cold water tank

$$\left(Mc\right)_w \frac{dT_w}{dt} = \left(UA\right)_e \Delta T_m + \Phi_i \tag{2.238}$$

where Mc is the thermal capacity, T is the temperature, UA is the product of the overall heat transfer coefficient and heat exchange area, ΔT_m is the mean temperature difference, Δh is the change in refrigerant enthalpy, m_r is the mass flow rate of refrigerant, v is the specific volume of vapor, Q_s is the compressor swept volume and η_V the volumetric efficiency of the compressor, Φ_i is the total instantaneous refrigeration requirements of the malting plant, and subscripts *e, c*, and *w* are the evaporator, condenser, and water, respectively.

These models have been developed and solved at pilot plant and industrial levels, and implemented first with Microsoft Visual Basic version 3.0 and then incorporated into the overall malting plant model implemented with Nexpert Object 3.0. To represent the different plant elements (subsystems), malting plant decomposition in processing and auxiliary systems

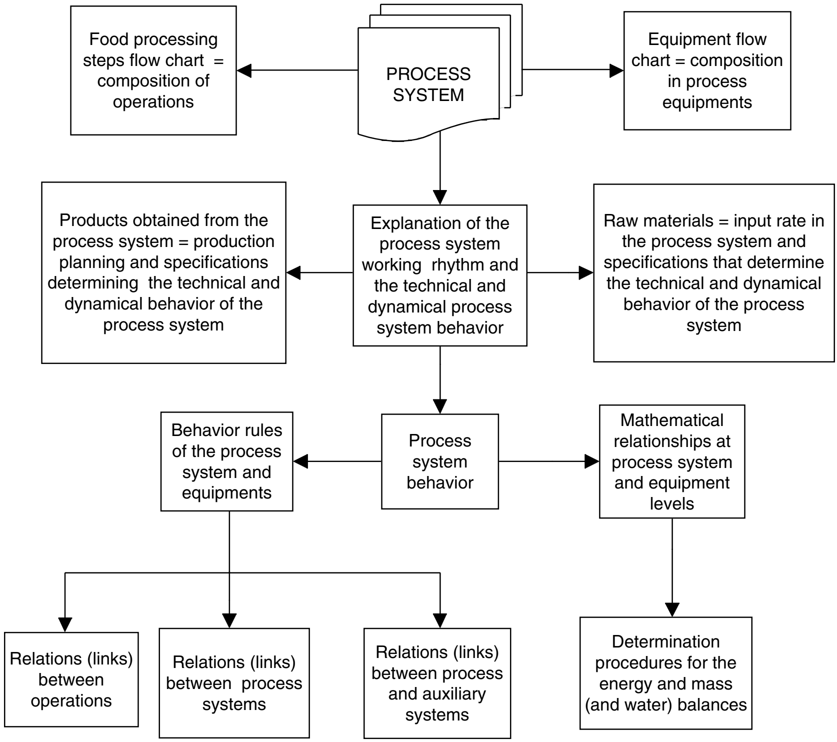


Figure 2.27 Information handled in a process system.

(López, 1990) has been carried out, generating an objects hierarchy of relationships ("a kind of" or "a part of"). Flow of information by processing system and equipment is shown in Figure 2.27.

Rule categories were established for all equipment (subsystems) used (D'Ambrosio, 1990):

1. Processing of material streams
2. Electric energy consumption
3. Thermal energy consumption
4. Refrigeration consumption
5. Labor consumption
6. Water consumption
7. Relationship between different equipment used in the same operation

8. Relationship between previous, current, and subsequent operations
9. Relationship between individual processing equipment and auxiliary systems (materials handling and energy handling)

2.6.1.2 Simulation Results

The results from simulations of refrigeration power requirements have been validated at industrial levels. It has been found, for example, that different drying conditions promote a decrease in thermal energy consumption and an increase in productivity (processing time reduction). Also, it is now possible to improve the design and control of refrigeration systems, minimizing cold losses, which is very important since the daily consumption of energy can be greater than $40{\cdot}10^3$ kWh in a malting house.

An intelligent system has been developed that simulates the dynamic behavior of the entire malting plant and aids in the production planning tasks, permitting optimization of the design and operation of processing and auxiliary systems (including control, energy, and material handling systems).

2.6.2 Winery

Good design and control of the refrigeration system is critical in achieving adequate product quality and process reliability in wineries. Refrigeration is often used, especially in white wine-making and mainly in (1) cooling of must for clarification and fermentation, and cooling of crushed grapes for cold maceration; and (2) fermentation with temperature control (Grenier et al., 1992; López et al., 1992). Moreover, the electric energy consumption by the winery's refrigeration system is quite significant (up to 50–70% of the overall electrical energy consumed in an entire winery) (López, 1995).

There is abundant literature on the calculation methods used for the refrigeration demand profiles of air conditioning (ASHRAE, 1993). However, the refrigeration needs of many food factories have not been studied in much depth, as in the case of wineries. This is explained in part by the complexity of the winery operation itself, which must be taken into account when determining the refrigeration system's design and operation. Because of the wide variety of raw materials ranging in quality and quantity and the seasonality of production, grape harvesting is concentrated over one or two months a year, during which the winemaker must rapidly prepare the winery, adapting the wine-making technology and engineering to control of the wine's quantity and quality on a daily basis. This has led to designs based on experience from previous installations. However, it can lead to oversizing of the equipment with poor consequences in efficiency and behavior.

On the other hand, fermentation control in the winemaking process is critical for the production of wines possessing the correct aromatic and sensory quality. But control is also fundamental to minimizing the energy consumption of cooling systems in wineries. Fermentation control automation requires sensors to monitor fermentation evolution. Temperature has traditionally been used for control because it is easy to measure. However, temperature data cannot provide information on the evolution of the fermentation. Such data only establish whether the fermentation is progressing in a safe state. The fermentation state can be identified by properties such as density, CO_2 evolution sensors, etc. Also, the analysis of heat generation, called "exotherm," has been proposed by the brewing industry (Cumberland et al., 1984; Daould et al., 1989; Ruocco, 1980; Stassi et al., 1989).

For these reasons, a series of research projects have been conducted in order to optimize refrigeration in wineries:

1. Refrigeration requirements profile for wineries through knowledge-based systems
2. Thermal behavior of the fermentation process
3. Use of thermal storage systems through modeling and simulation
4. Fermentation control for rational use of refrigeration in wineries

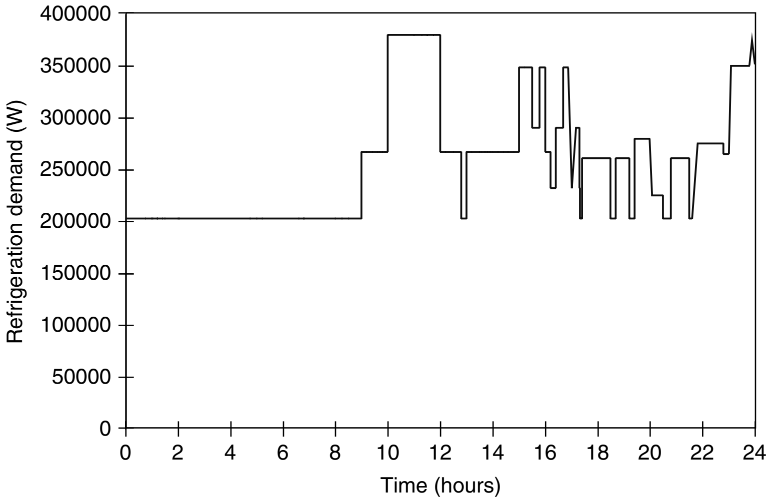


Figure 2.28 Refrigeration demand in a winery (adapted from López and Grenier, 1993).

2.6.2.1 Refrigeration Requirements Profile for Wineries

It is important to understand, as thoroughly as possible, the real heat load profile that is capable of supporting a determined application, in order to achieve proper design and operation of the refrigeration system. The cooling needs are often time varying because many of the processes occur intermittently for indefinite periods throughout the day. Figure 2.28, for example, shows the typical daily cooling needs of a winery during grape harvest. The load peak lasts for approximately 4 hours, during which the load value is double that of other times (López and Grenier, 1993). Hodson (1991) presented similar results.

A computer model for intelligent dynamic simulation of mass and energy balances in wineries has been developed in the CEMAGREF at Montpellier (France). Object-oriented programming techniques (with the C++ language) have been used for its implementation. This model is used to predict the refrigeration requirement dynamics in the winery during the wine-making process, for defining grape harvest distribution and quality, and in wine-making technology and engineering (López et al., 1992; Nivière et al., 1994).

Computer simulation can provide a framework for designing experiments that evaluate process technology alternatives (Gosling, 1992). Computer simulator optimization techniques can then be applied to determine the wine-making technology and scheduling conditions, minimizing the instantaneous refrigeration requirements in the winery (López et al., 1993).

2.6.2.2 Thermal Behavior of the Fermentation Process

The production rate of CO_2, as a control parameter in fermentation, has received a lot of attention in the last few years (Daould et al., 1989) since its production is proportional to the quantity of fermented sugar. But it has also been shown that generated heat during alcoholic fermentation is related to microbial activity, and has a good relationship with other physiologic parameters, including production of CO_2 (Monk, 1978; Moud and Cooney, 1976).

In efforts to advance this area, work contributing to the mathematical model of thermal behavior in alcoholic fermentation tanks (solving the heat generation rate term, exotherm, in the heat balance) has been carried out at the Public University of Navarra (Spain).

Viura grapevine musts (from Navarra, Spain) with sugar contents corrected have been used in fermentation experiments. This fermentation process was carried out in an air-circulation cell with a MICRO DSC Setaram microcalorimeter at several temperatures (between 16°C and 24°C). Figure 2.29 shows the fermentation exotherms obtained with the microcalorimeter.

The "exotherms" were fit to a mathematical model bearing in mind that fermentation follows consecutive reaction kinetics (López and Secanell, 1992; López et al., 1997; Villota and Hawkes, 1992):

$$\frac{dQ}{dt} = \frac{k_1\left[A_o\right]}{k_2 - k_1}\left[\exp\left(-k_1 t\right) - \exp\left(-k_2 t\right)\right] \qquad (2.239)$$

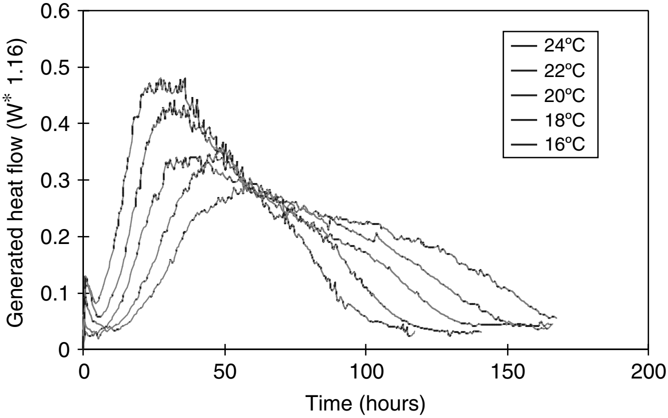


Figure 2.29 Generated heat flow with Viura grape must with 190 g/l of sugar content (adapted from López et al., 1999).

where dQ/dt (kcal/h) is the generated heat rate, A_0 is the must sugar content (mole/l), t is the fermentation time (s), and k_1 and k_2 are time constants (s^{-1}), depending on temperature (T, absolute) as

$$k_1 = 9.4137 \cdot 10^{20} \exp - \left(\frac{14307.4}{T} + 0.016125 S_o \right) \quad (2.2.40)$$

$$k_2 = 1060.6720 \exp - \left(\frac{3020.99}{T} \right) \quad (2.241)$$

Depending on the must sugar content (So, in g/l), the amount of heat generated per mole of sugar fermented (ΔH) ranges between 20 and 27 kcal/mole (Williams, 1982).

2.6.2.3 The Use of Thermal Storage Systems

Two simple dynamic mathematical models of two separate thermal storage systems used in the food industry to produce chilled water have been studied: the ice-bank system and holding-tank system. In developing the models, equations of maximum simplicity that defined the behavior of the refrigeration system components were sought. The aim of this work was to develop a simulation system capable of sufficient precision for industrial design that would be easy to run by entering simple data available from manufacturers (see the introduction of this chapter).

The models were developed from mass and energy balances around each component of the studied refrigeration systems (Lacarra, 1998). Each component was treated like an open system or zone (Cleland, 1990), around which the mass and energy balances were performed (Jekel, 1991). Since the evaporator is a component of the refrigeration system in which the heat exchange with the thermal storage medium takes place, heat exchange phenomena were studied in more depth (Lacarra, 1998). Experimental validation of the ice-bank storage system was carried out in an external melt, ice-on-coil, pilot scale storage system; validation of the refrigeration systems with holding tanks was carried out in an industrial winery (López and Lacarra, 1999).

It was shown in both simulation and real observations that cool water temperature can reach undesirable levels (at the holding tank outlet) when winery refrigeration demands are very high and the holding tank capacity is insufficient (volume of 6 m^3). A solution was developed through simulation showing that, if the holding tank volume was increased from 6 m^3 to 50 m^3, the total compressor on-time would be reduced by around 7% and cool water temperature would be well controlled (Figure 2.30).

In evaluating the winery's refrigeration system and holding tank, the system ice bank needed to satisfy that the refrigeration requirement profile was clearly smaller at 48 kW (prior was at 130 kW without the ice bank and holding tank; see Figure 2.31), and that the necessary ice-bank volume was only 5.8 m^3 (with 2696 kg of maximum ice mass stored).

2.6.2.4 The Use of Advanced Control Systems in Fermentation

It is considered in modeling or measuring the sugar content that density, CO_2 production, and heat generation during

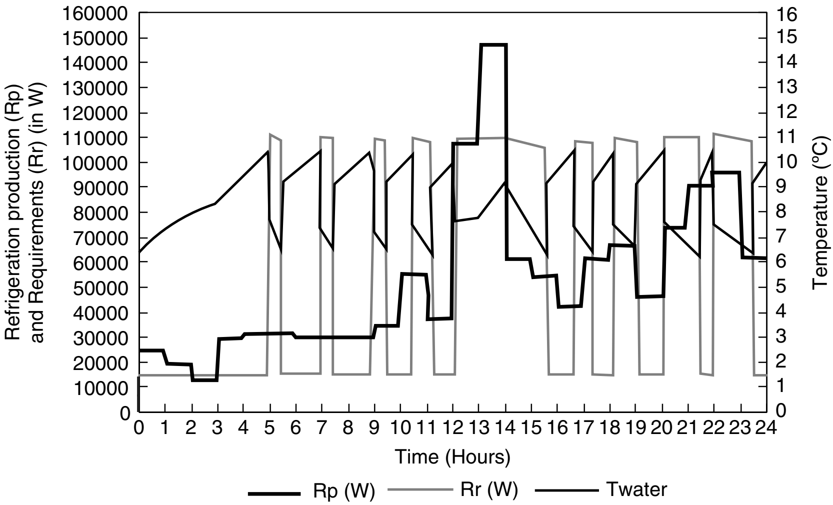


Figure 2.30 Simulation of holding tank refrigeration system with a 50 m^3 holding tank (adapted from López et al., 1999).

must fermentation are equivalent, and that a model predicting any of these three can predict the others. A more detailed description of the model, including how to calculate such variables, was described by Martínez et al. (1999). This model has been used to develop the nonisothermal kinetics model of must fermentation, using a finite differences technique. The model predicts the relationship existing between temperature evolution and the amount of heat removed from the fermentation vessel; thus, it can be used to test new control techniques based, for instance, on temperature control, fermentation rate control, or any other advanced control technique. It can also be applied to optimize the use of refrigeration, by providing a means to simulate a set of fermentation tanks.

The chosen controller was a double-input single-output fuzzy controller, which uses the fermentation rate and temperature measurements as input and the refrigeration action as output (Martínez et al., 1999). The control objective was to maintain a fermentation rate that was always lower than a certain level, since the higher the fermentation rate, the higher the flavor loss in the must.

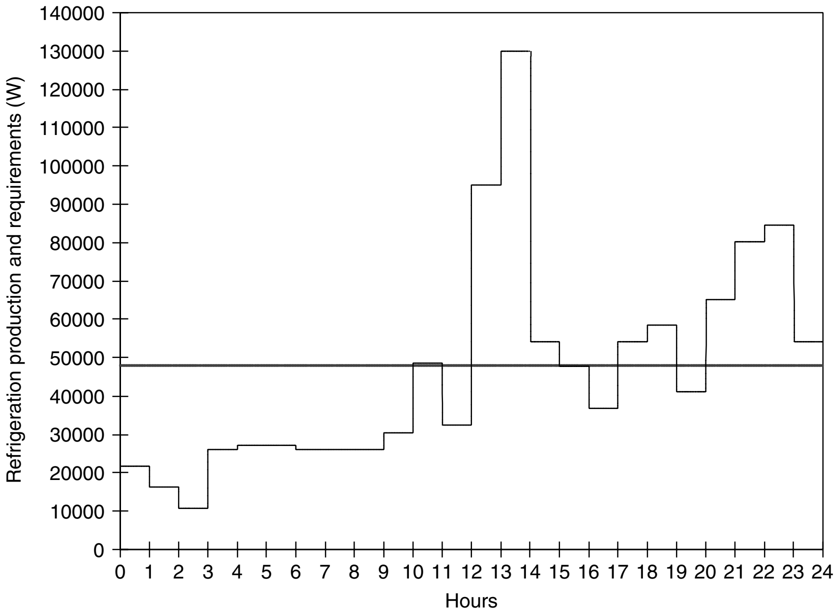


Figure 2.31 Refrigeration production and requirements for a refrigeration system with an ice bank in a winery (adapted from López et al., 1999).

In this way, controlled fermentation can lead to refrigeration and energy savings (about 30% in some cases) and high savings in fermentation time (about 20%), thus leading to higher productivity. By increasing the use of refrigeration at the end of the process, the fermentation time can be reduced even more without affecting wine quality.

This control system demonstrates the possibility of change in conventional fermentation procedure in white winemaking. Both the fermentation model and the control system have already been tested successfully in a pilot plant several times. This control system is being integrated into a commercial control system for use in industrial wineries, which will provide a new control alternative and a means of good prediction for density and fermentation rate.

From these studies, interesting conclusions have been made, suggesting a more efficient and reliable use of refrigeration in wineries through means of (1) adequate wine-making operation scheduling, (2) good design and control of refrigeration system, (3) use of thermal storage systems, and (4) use of advanced control systems in fermentation.

2.6.3 Frozen Vegetables Plant

In manufacturing frozen vegetable products, several operations are carried out. From an energy cost and a product quality point of view the following are most important: (1) blanching in hot water, with significant steam and water consumption; (2) freezing, using cold air freezers or plate freezers, with significant refrigeration power consumption; and (3) cold storage at –25°C. This type of food plant consumes a high level of electrical and thermal energy as well as water (López, 1995), despite the fact that most frozen vegetable plants are at a high technological level equipped with modern integrated water-blancher-coolers and energy recovery systems, efficient fluidized bed and spiral belt freezers, and PLC-controlled refrigeration systems for cold stores and freezers.

To obtain an adequate simulation tool for use in optimization studies on frozen vegetable plant designs and operations (i.e., energy, water, wastewater, steam, waste solids, and operation parameters of refrigeration systems; processing equipment), the CIMFROZEN project was carried out (López et al., 1998). The project involved (1) computer modeling of refrigeration systems and operations with the highest energy and water consumption, including determination of product quality; and (2) development of a knowledge-based system to allow simulation of the entire plant, including refrigeration systems for freezers and cold stores, and food-processing systems (e.g., freezing, blanching and cooling, cold storage and other operations such as washing, peeling, size grading, slicing, etc.).

Models and frozen vegetable plant simulators have been developed and tested at pilot plant and industrial levels, implemented first in the C++ language and then incorporated into an overall frozen vegetable factory model (implemented with C++) (López et al., 1995, 1996; López and Lacarra, 1999). Figures 2.32, 2.33, and 2.34 are three windows, respectively,

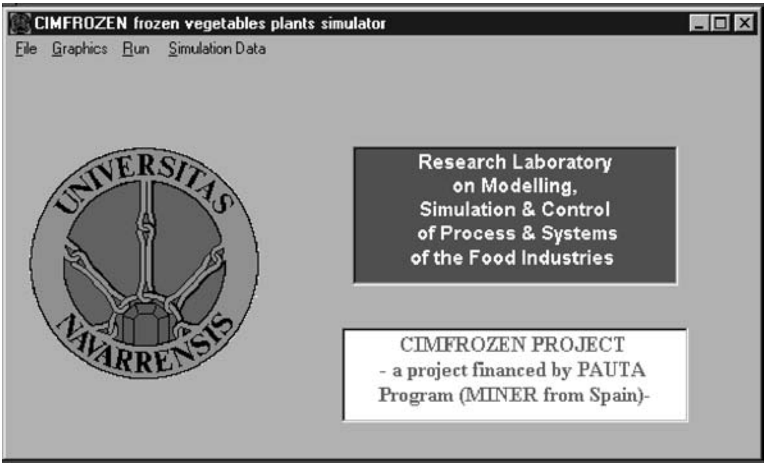


Figure 2.32 Window showing the CIMFROZEN Project (adapted from López et al., 1998).

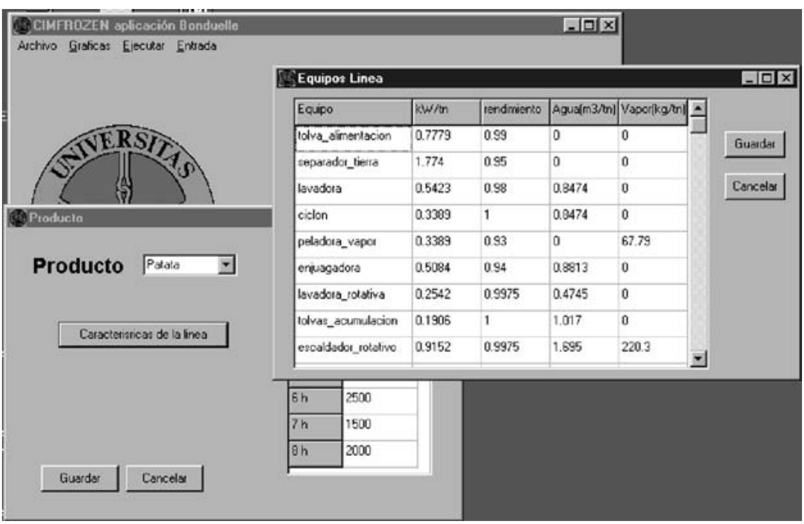


Figure 2.33 Window introducing data for simulation (adapted from López et al., 1998).

Figure 2.34 Window showing graphics obtained from freezers and refrigeration system simulation (adapted from López et al., 1998).

one presenting the CIMFROZEN project, one introducing data for simulation, and another displaying graphics obtained from freezers and refrigeration system simulations.

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3

Documentation of Food Plant Design

3.1 INTRODUCTION

As outlined in Section 1.2 of Chapter 1, a series of preliminary studies is needed on all aspects and conditions determining the final food plant design. These studies would describe the context of the food plant design and should be included in the appendix of the preliminary or final project document of the food processing system and food plant, and developed as follows:

1. Preliminary study of products
2. Preliminary study of raw materials
3. Preliminary study of different alternatives in food processing technology and engineering

Analysis and evaluation of alternatives requires much gathering of information from different bibliographic sources and, in some cases, data from process development laboratory studies and/or pilot plant experimentation.

A representation of some of this information in diagrammatical form can be very useful. Elaboration is especially practical when using the *basic modules general diagram*, *process flow diagrams* (or *flowcharts*), and *mass and energy balances in diagrammatical form*.

3.2 PRELIMINARY STUDIES OF FOOD PRODUCTS AND RAW MATERIALS

Studies of food products examined must include the following:

- Characterization of products (as broad as possible), including legal and commercial aspects, as well as consumption trends. The aim is to define the technical, legal, and commercial quality of each food product manufactured.
- Market analysis of products studied based on quality and product specifications. For example, in the case of sterilized milk, it would be important to analyze the qualities of all varieties: whole milk, semi-skim, and skim. This market evaluation must include an analysis of competing firms for every product, determining their technology, and if possible, their probable reaction to the project.
- Study of response to product price, as well as difficulty in distribution and supply of product according to different specifications.

On the other hand, studies of raw materials should consider the following:

- Availability and location of raw materials, which will have a great influence on the food factory's location and corresponding food processing systems.
- Cost of raw materials and transportation costs. This cost could be influenced by the production and marketing of said raw materials in the zone or region where the food plant is located, for example, processing fruits where a habitual market for fresh consumption exists. However, this can be a problem when a competitor market raises prices. In other situations, it might be necessary to produce the raw material, due to lack of an appropriate raw material in the zone where the food plant is located.
- Definition, specification, or characterization of the most suitable raw materials for processing into desired food products. In these studies, aptitude tests for processing of raw materials must be included.

The document containing all of the above-mentioned preliminary studies must include as much information and details as needed to determine the product demand level, as well as production volume according to specifications of the food product evaluated.

3.3 LITERATURE REVIEW AND LABORATORY STUDIES ON FOOD PROCESSING TECHNOLOGY AND ENGINEERING

Studies of products and raw materials usually encourage interest in obtaining further information on process technology and engineering. If the results show that the project is worth continuing, a literature review and/or laboratory studies must be carried out (Giral et al., 1979; Peters and Timmerhaus, 1991). The maximum data and information related to food processing systems, technology, and engineering alternatives are acquired at this stage:

- Description of process technology and engineering alternatives, analyzing their influence on product quality and mass and energy balances, while at the same time studying the by-products and waste formation.
- Approximate evaluation of raw materials and products costs for different technical and engineering alternatives, as well as labor and energy costs.
- Approximate description of auxiliary installations or systems (energy, materials handling, and control systems needed, configuring the so-called auxiliary systems or utilities) (see Section 1.2.2 of Chapter 1).

Information and bibliographic sources normally used include

- Specialized journals on food science, technology, and engineering
- Food technology and food engineering books (Bartholomai, 1987).
- Food processing equipment bulletins and brochures from corresponding firms

- Existing food plants erected by current firms or other firms
- Government departments and administration (FDA, USDA, European Commission, etc.), companies, scientific and technical institutes and associations (IFT, ASAE, etc.), research and development centers (university departments, European scientific institutes, etc.), monographs, standards, and technical reports

Today, this information and data are available on paper (journals, reports, etc.) and on Internet and CD-ROM databases (Web sites of firms, institutes, universities, government administration, and so forth).

Interesting sources of information and data (including Web sites), journals, and specialized research centers on food technology and engineering covering the different aspects of food processing systems and food plant design are presented in the bibliography at the end of this chapter.

3.4 PILOT PLANT STUDIES

Once a research team has developed a new product or interest in industrializing an "until now" handmade product, it is necessary to evaluate the corresponding and necessary documentation that allows the food processor and food plant engineer to develop the appropriate technology and engineering as well as the design of the food processing system. During the pilot plant experimentation stage, information and data that were previously obtained from laboratory and literature surveys are applied to achieve an accurate design; many hypotheses are proven and better information on a series of process factors and parameters is obtained (including some equipment design parameters and the most suitable processing conditions needed for the food product studied).

Pilot plant studies are physical simulation studies, as compared with mathematical simulations in a computer (still not used much in studies of processes in the food industry, though interest is shown in Chapter 2). Interest in modeling and simulation of an entire food plant or food processing system (or part of a unit operation) lies in the fact it is easier and cheaper to experiment at the computer or pilot-plant level than at the industrial level. For example, to determine the most suitable drying conditions for a new product, it is necessary to experiment in a drying pilot plant since the operating costs are lower than in an industrial plant and the margin of operation is bigger. In this case, the most adequate air velocity conditions, operating temperature, drying bed load, and so forth can be determined.

In some cases, if the pilot plant physical model is too simple, only tendencies in the process behavior are deduced. In other words, the results may not be exactly reproduced at an industrial level. In other cases, there may be a mathematical model representing the process, but this is only occasionally seen in the food industry, mainly with new products where no data are available from the different information sources. If a mathematical model exists, physical simulation in a pilot plant is not necessary since it can be done in a computer, without any doubt a cheaper approach.

3.5 FOOD PROCESSING SYSTEMS AND FOOD PLANT PRELIMINARY AND FINAL PROJECTS

3.5.1 The Food Processing Plant Preliminary Project

The following can be defined from information and data presented in documents corresponding to the above-mentioned studies, and from analysis of different alternatives:

1. Mass and energy balances of food processing systems and corresponding flowcharts
2. Specifications of food processing equipment and necessary auxiliary systems
3. Total investment needed (error lower than ±30%) and global economic evaluation

In other words, using the information and data from the previous mentioned studies we can define the Food Processing

Systems and Food Plant Preliminary Project. This document might include layout drawings of necessary food processing equipment and layout drawings of corresponding auxiliary systems, indicating the layout inside different rooms and necessary buildings (see Figures 3.1, 3.2, and 3.3).

The preliminary project would lack the following documents:

- Technical specifications document (where specifications for components of adopted solution are described in detail)
- Detailed budget document
- Detailed drawings document; requirements for erecting food processing systems and corresponding food plant

However, almost all of the research from previous studies would be complete. The report document of a food processing plant preliminary project could contain the following parts:

1. Justification for adopted food plant design solution
   - Food plant design basis
   - Antecedents, including:
     - Descriptions of food processing plant design problems from the technical, legal, and commercial points of view. Possible food plant project cases: (1) design of new food plant; (2) design optimization from the technical (including energy and water savings, and automation reasons), product quality, or cost points of view in an existing food plant; (3) enlargement of existing food plant.
     - Socioeconomic, legal, and technical context of food plant design (summary of previous studies)
     - Products to manufacture (summary of previous studies)
     - Raw materials (summary of previous studies)

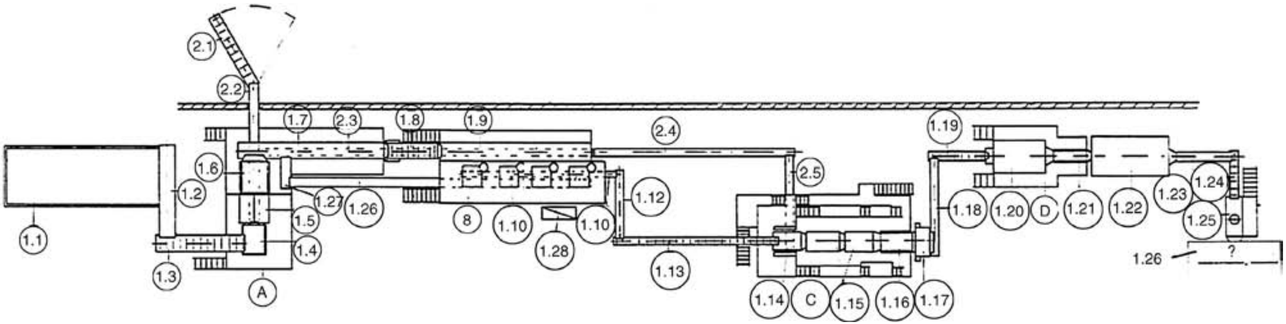


Figure 3.1 Layout drawing of a sweet corn freezing line. This line is composed of raw matter feed installation (1.1), belt conveyors (1.2, 1.7, 1.12, 1.18, 1.23, 1.26, 1.27, 2.2, 2.3, 2.4, 2.5), elevators (1.3, 1.8, 1.13, 1.19, 1.24, 2.1), vibrating conveyors (1.4, 1.6, 1.9, 1.11, 1.14, 1.16, 1.21), leaf removing equipment (1.5), grain separator (1.10), washing equipment via flotation (1.15), and freezing equipment (1.26).

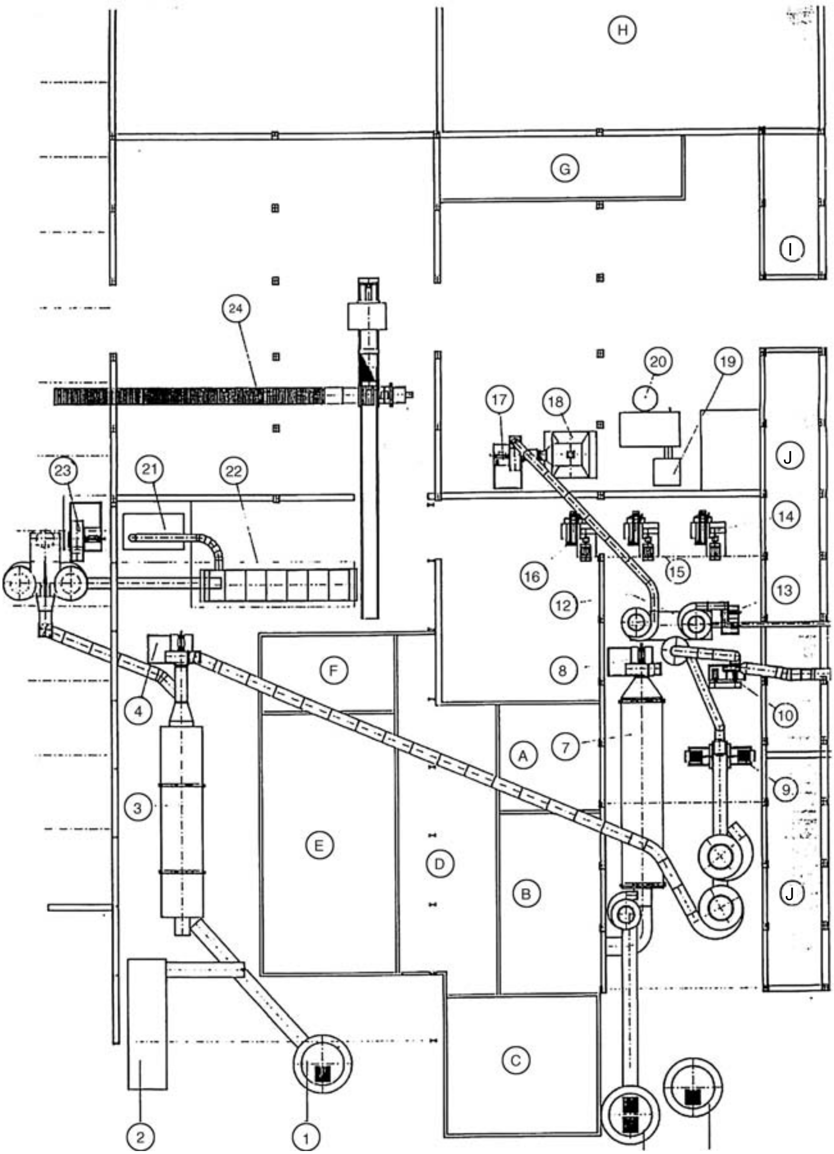


Figure 3.2 Layout drawing of an alfalfa drying plant. A, F = Electric transformer rooms; B, C, E = Engine rooms; D = Filter room; G = Office; H = Atelier; I = Steam generator room; J = Electric panel room. The remaining space is used for two drying lines with rotary dryers (art by López-Gómez).

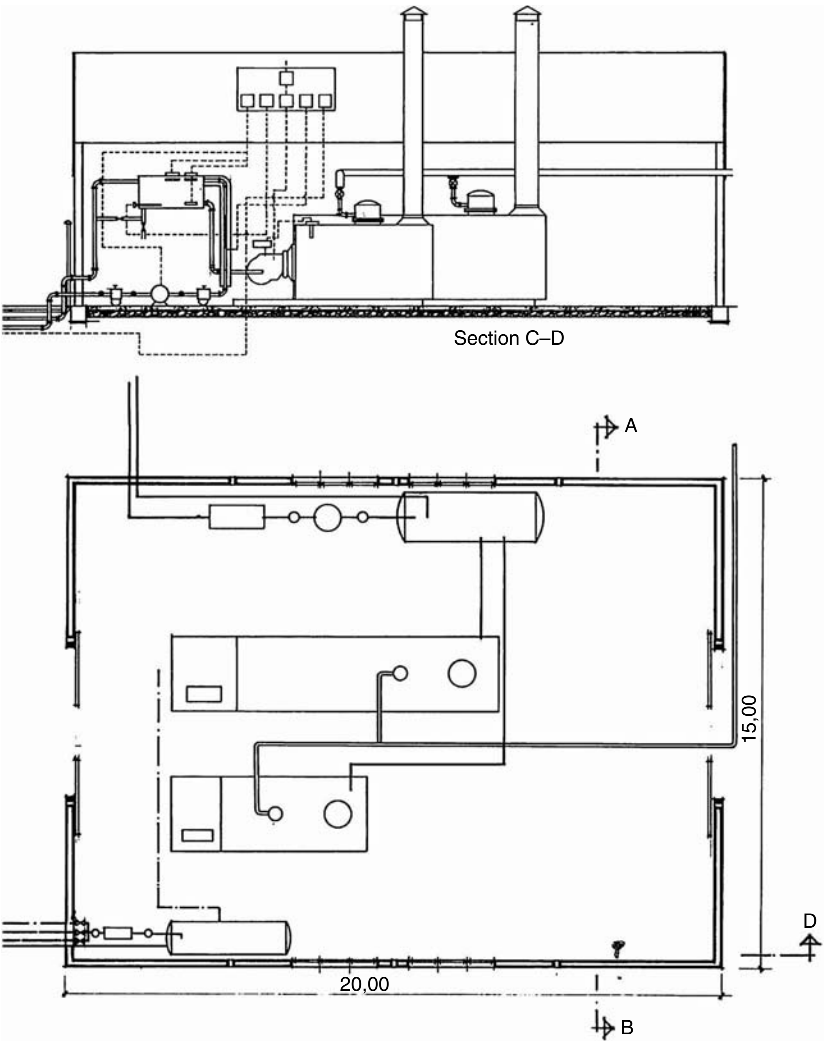


Figure 3.3 Layout drawings of steam generator's room in a food factory.

2. Adopted solution description
   - Process technology and production capacity
   - Process engineering
   - Mass and energy balances. Requirements for auxiliary systems:
     - Materials handling systems and wastewater treatment
     - CIP cleaning system
     - Energy handling systems (steam and refrigeration, and electrical installations)
     - Control systems
   - Requirements for buildings, access road, parking, and gardening
   - Requirements for quality control laboratory
   - Requirements for man power, qualified or not
   - Approximate budget. Necessary investment estimation (±20–30%)
   - Working costs estimation
   - Economic and financial analysis of investment

Preliminary studies and the analysis of food processing systems and auxiliary systems alternatives can be included in the appendixes of the report document. The schematic diagrams or flowcharts (process steps flowchart and mass and energy balances in flowchart form) must appear in the report document or drawings document. Detailed flowcharts that explain better the adopted design solution (for process equipment and auxiliary systems) must also be in the drawings document.

3.5.2 The Food Processing Plant Final Project

Analysis of the Preliminary Food Plant Project determines whether the adopted solution may be used in the plant's erection. If so, it is then necessary to describe the food processing plant at a detailed engineering level in order to meet the requirements of the final project, and thus estimate the required investment with certain accuracy. The food plant is composed of several parts: food processing systems (processing lines), auxiliary systems (utilities), and buildings (lodging for food processing and auxiliary systems, administration offices, and other necessary services). In this manner, the food plant final project is the sum of all final projects carried out in each area of the plant:

Food processing systems
Auxiliary systems
Buildings
Other services (gardens, access roads, fire safety, etc.)

3.5.2.1 Food Processing System Final Project

Every Food Processing System Project should include the following documents.

3.5.2.1.1 Report Document

1. Justifying the adopted food processing system design solution (similar to the Food Plant Preliminary Project Report Document)
2. Adopted solution
   - Process technology. Capacity and production planning.
   - Process engineering (including description of special design equipment)
   - Mass and energy balances. Requirements of auxiliary systems.
     - Materials handling systems. Wastewater treatment systems. CIP (cleaning-in-place) systems.
     - Energy handling systems (steam and refrigeration systems, and electrical installations).
     - Control systems
   - Requirements for buildings and other civil works
3. Budget general summary (not including auxiliary systems and civil works, except necessary civil works to install process system)
4. Operation or running costs
5. Economic analysis (at previous study level but more exact since detailed budget is now available)

In the appendix of the report document, preliminary studies on the products, raw materials, and process technology and engineering can be included, as well as calculations for special design equipment.

3.5.2.1.2 Budget Document

1. Process engineering (ascertaining differences between the "standard design" equipment, which the design engineer must select among models existing in the market (patented equipment), and "special design" equipment, which the design engineer must design and define in detail)
2. Structures, construction and, in general, civil works requirements to erect the process system

3.5.2.1.3 Technical Specifications Document

1. Food processing equipment construction material and component specifications
2. Hygienic design specifications, concerning food processing equipment and auxiliary equipment in contact with foods (materials handling)
3. Supply and reception specifications for food processing system, including all related components
4. Food processing equipment construction, installation, and startup specifications
5. Structures and civil work specifications for erecting food processing equipment

3.5.2.1.4 Drawings Document

1. Schematic diagrams or flowcharts
   - Block flowcharts
     - Basic flowchart
     - Process steps flowchart
     - Process equipment flowchart
     - Mass and energy balances in flowchart form on process equipment flowchart

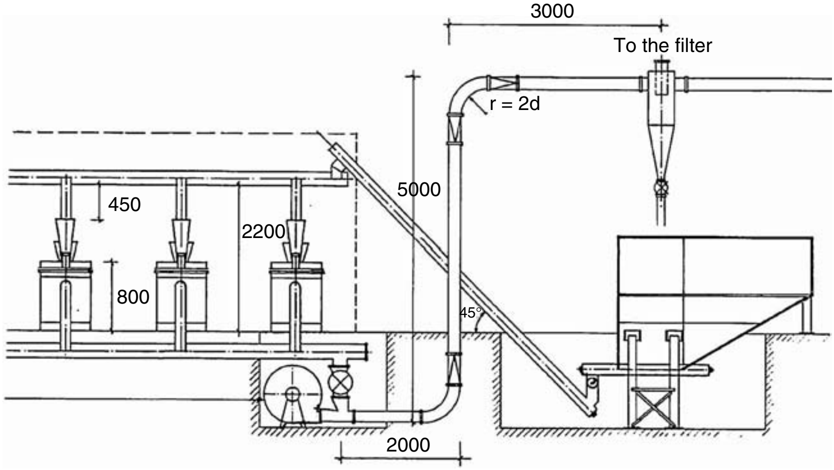


Figure 3.4 Front elevation drawing of a paprika milling installation connected to the pepper-feeding system and paprika powder pneumatic conveyor.

- Detailed flowcharts
  - Flowcharts for process equipment connected with auxiliary systems
  - Process control flowcharts
  - Detailed flowchart of all process equipment, indicating control systems and connections to materials and energy handling systems (cleaning systems, steam, refrigeration, and materials handling systems)

2. Overall layout and detailed drawings
   - Overall layout drawings, in plant and front elevation, of food processing systems inside the containment buildings, indicating connections to the utilities distribution systems (auxiliary systems) (Figure 3.4)
   - Detailed drawings
     - Section and isometric drawings of process equipment connected to auxiliary systems
     - Metallic structures and civil works drawings needed for process equipment erection (Figure 3.5)
     - Construction details of special design equipment (Figure 3.6)

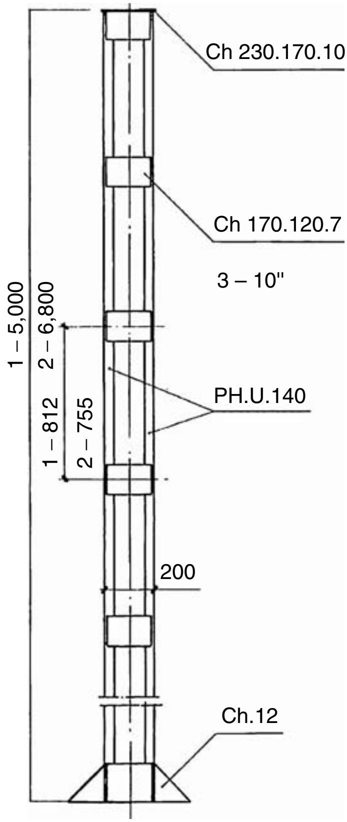


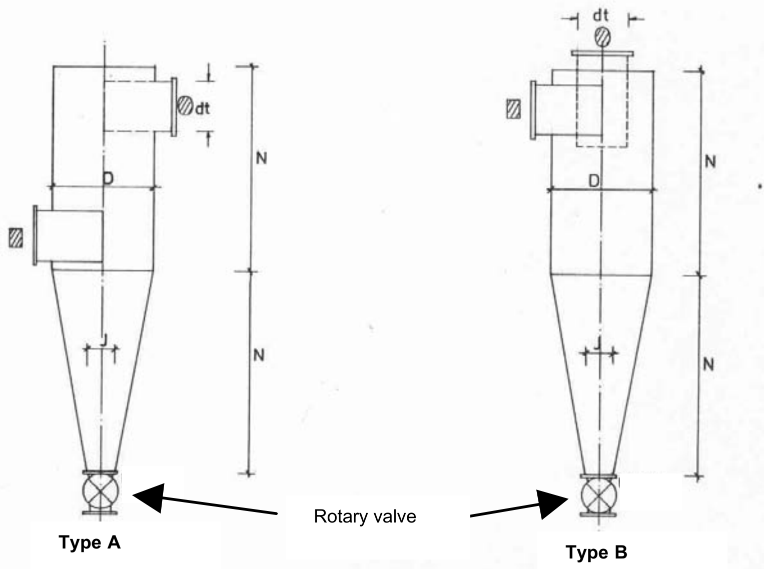
Figure 3.5 Metallic pillar necessary in the erection of processing equipment.

3.5.2.2 Auxiliary System Final Project

The Auxiliary System Final Project includes the following documents.

3.5.2.2.1 Report Document

1. Justification of the adopted design solution, indicating the existing relationship between the corresponding auxiliary system design and the food processing systems design and operation



Type	D	N	dt	J
A	500	1000	250	125
B	400	800	200	100
B	600	1200	300	150

Figure 3.6 Construction details for special design equipment: powder-separating cyclones.

2. Adopted solution description, dividing between the main elements of the auxiliary system and the secondary components (e.g., in a refrigeration system, dividing between the compressors, evaporator, and condensers — as main components — and the valves, accessories, piping and controls devices — as secondary components)
3. Budget general summary, dividing between the main components and secondary components of the auxiliary system

3.5.2.2.2 Report Document Appendix

1. Calculation basis for each auxiliary system component
2. Calculations for all components

3.5.2.2.3 Technical Specifications Document

1. Construction materials and/or components specifications
2. Supply and reception specifications
3. Setup or erection specifications
4. Civil works specifications, requirements for auxiliary system erection

3.5.2.2.4 Budget Document

1. Batches corresponding to different main components and secondary components as fittings, piping, insulation, control devices, etc.
2. Batches of civil works requirements for system erection

3.5.2.2.5 Drawings Document

1. Schematic diagrams or flowcharts, including main and secondary components and connections to food processing equipment
2. General layout drawings (Figure 1.11 and Figure 3.3)
3. Detailed drawings
   - Sections and isometrics drawings
   - Detailed drawings for construction and erection of system
   - Civil works drawings needed for system erection

3.5.2.3 Buildings and Services Final Project

3.5.2.3.1 Buildings

The Buildings Final Project includes the following.

Architectural Design
  a) Descriptive report
  b) Budget

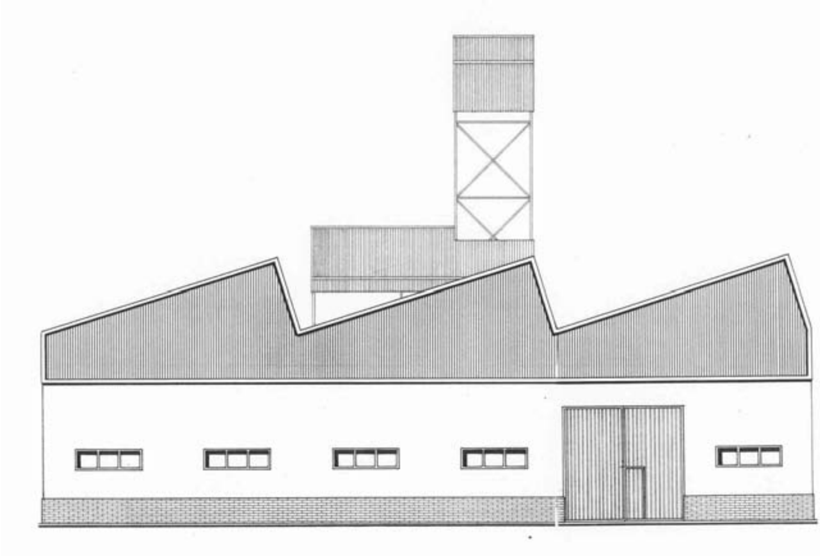


Figure 3.7 Drawing of building front elevation for food plant project.

c) Drawings (urbanization drawings, buildings construction detailed drawings, and building front elevation drawings) (Figure 3.7)

Structural Design

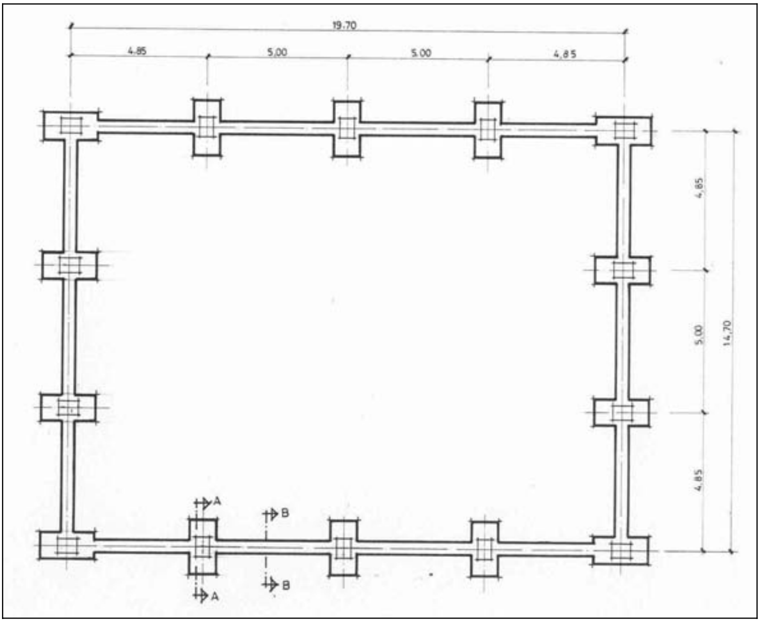
a) Description report
b) Static calculations
c) Drawings (detailed drawings for erection of buildings: site preparation, excavations, foundations–Figure 3.8, concrete slab, etc.)

3.5.2.3.2 Other Services

Final projects for various food factory services include the following:

Electrical Design (Low and High Voltage)
- Lighting
- Electric power supply
- Power transformers (Figure 3.9)

Ventilation, Heating, and Air-Conditioning Designs



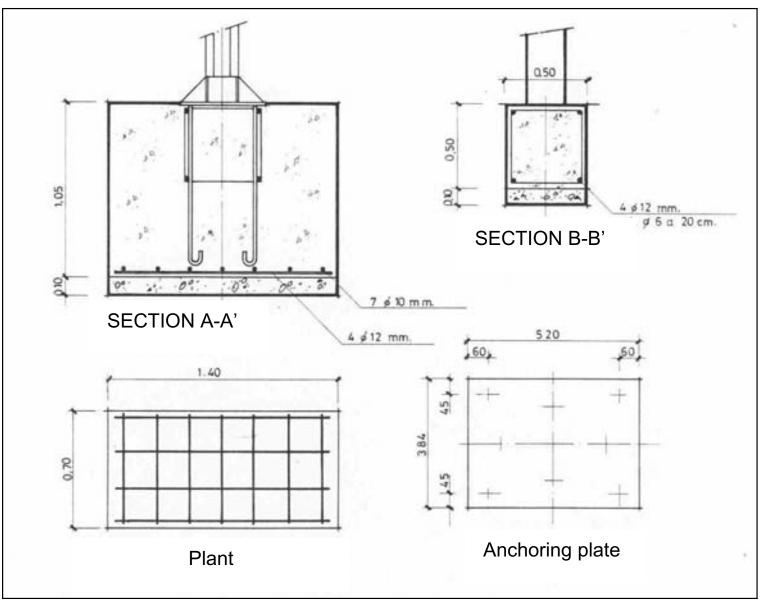


Figure 3.8 Foundation drawings of steam generator room in plant building (see Figure 3.3).

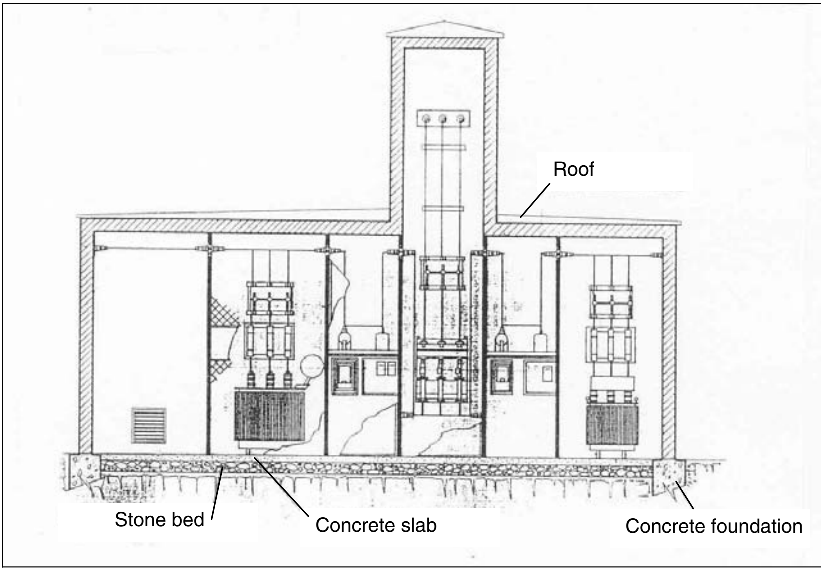


Figure 3.9 Layout of power transformers and building drawing of food factory.

Quality Control Laboratory
Fire Protection System Design
Roads and Access
Gardening Design

The Final Project for each service mentioned, which as a document describes the corresponding design solution, will have a corresponding report document, budget document, drawings document, and technical specifications document, including the concepts analyzed above.

This is a convenient time to consider the possibility of obtaining official grants or fiscal help, and the location of the food factory, etc.

3.6 INFORMATION HANDLING IN FLOWCHART FORM

3.6.1 Basic Modules General Flowchart

The basic modules general flowchart graphically displays the more significant aspects of selecting a given food processing technology and the engineering, in each preliminary study step.

As a block flowchart, each block represents one of four preliminary studies: (1) raw materials, (2) food processing system–technology and engineering, (3) auxiliary systems, and (4) food products under evaluation. Each block contains the most important aspects to consider in evaluating the food processing technology and the engineering alternative studied.

In this flowchart, information is usually divided into four blocks drawn horizontally without any connection arrows between them. The first block, on the left, is dedicated to the raw materials, the second to the food processing system (describing food processing technology and engineering), the third to the auxiliary system, and the fourth to the food products. The last block (products) shows the possible increase in demand with time, and its sensibility as to price and product specifications according to potential competitors. The raw materials block describes the price fluctuation according to its capacity for processing (or raw materials specifications) or to the availability of a raw material, etc. The process system and auxiliary system blocks contain the main information needed to define the food processing technology and engineering, and in certain cases, to determine the food processing plant, as to process technology data, production planning, and operation costs data, efficiencies, investment, and so forth.

In principle, a basic modules general flowchart is necessary that shows the potential solutions to a given food processing system design problem. At any rate, flowchart preparation must be preceded by a report that contains all of the available information for each module (Figure 3.10).

3.6.2 Flowcharts

A number of different flowcharts are commonly used in various forms. However, all have the same objective of representing certain aspects of a process (either technology or engineering, or both) pictorially or semi-pictorially. This means of representing the process is useful in the following ways:

ALTERNATIVE 1. LARGE-SCALE SUGAR PLANT

Raw Matter

Raw material specifications
Industrial crops highly specialized in farm production needed for sugar cane and sugar beets.
Commonly farmed varieties appropriate.

Need for raw materials
Consumption of sugar cane (1000-2000 tones/day) requires large supply in process system.
Need extensive nearby plantations with high levels of land infrastructure and transport systems. Important investments in irrigation systems possible.
Lack of extensive and appropriate land for sugar cane cultivation.
Cultivation of small and scattered areas increases transportation costs.
Transport of products to factory by rail or truck if average distance is 12 km, so corresponding infrastructure needed.
Harvest mainly mechanical.
Manual harvest reduces impurities and increases process efficiency. Suitable for many rural areas with high unemployment levels.

Evolution of farm production
In some countries, sugar cane and sugar beet production reduces import of sugar. Due to high price of cane sugar, cultivation of sugar beets increasing. At present, around 40% overall sugar production from sugar beets, 60% from cane.

Product

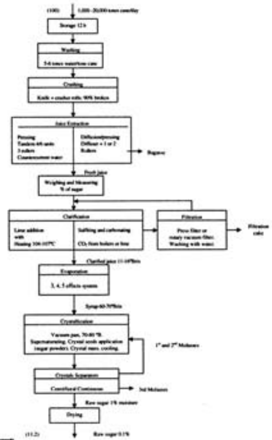
Product specifications
Raw sugar: Sucrose 97, 5-98, 5%; Red sugars 1%;
Ash 0, 8%; Moisture 0, 3%
White color (refined sugar); Yellow color (unrefined sugar)

Market forecast
Sugar consumption worldwide: 20 kg/year (50 kg in developed countries). (In some countries, higher consumption of other types of sweeteners, such as gur)
Regular increase of annual sugar production 2,000,000 tons (60% cane sugar; 40% sugar beet). Around 8-9 new factories/year needed with 6,000 tons capacity.
Production and consumption evolution is similar. 70% of production is internal consumption within producing countries. 30% of production goes to world market. 15% traded via international agreements. Rest distributed to free market. However, international control of prices exists.
Rich countries are importers. Expansion of production within. Larger production of glucose-fructose syrup. Imports only required for fluctuations.
Poor countries are exporters. Increasing internal consumption. Fall in exports.
Poor countries are importers. Increasing consumption and difficulty with importation. National production of sugar more profitable.

By-products
The larger the production scale, the larger the recovery. High level infrastructure is necessary.
Opportunity from important sales when balanced demand exists and amount considerable.
By-products: bagasse (used mainly as fuel for boilers); filter cake (for livestock, some agricultural uses); molasses (as raw material in different industries; same as bagasse). Other by-products: cane leaves, ash, and proteins from extraction juice.

Process System

Process Steps Flowchart



Economic aspects
Technology with intensive use of capital. Financial facilities in countries where industrialization is encouraged. Big initial investment. Lower unitary annual costs. Lower labor employment. Big production. Possible government control of production and prices. Lower cost/tone sugar ratio for production periods less than 130days.
Sophisticated technology. Possible equipment importation. Does not help local engineering development. Requirements for qualified staff in control and services. Training of local team.

Technical aspects
If crushing appropriate, both extraction technologies result in similar total sugar recovery (80-83%). Higher sugar extraction efficiency with diffuser, but lower recovery at crystallization stage. One diffuser and 3 conveyor belts can replace 3 roller mills. Requires more space. Investment equivalent to 2-2.5 mills. Combined with 3 mills, diffuser uses half the energy required for 6 mills. Diffuser produces cleaner juice (less sediment; less filtration surface needed). Diffuser needs less maintenance. Diffuser needs more specific control.

Yield
Sugar = 80-85% (sugar cane); Bagasse = 220-230 kg/tone cane; Molasses = 7.9 % cane; Filter cake = 0.2-1% cane.

Auxiliary Systems

Energy aspects
Energy consumption depends on processing equipment. A self-supply of energy using bagasse is possible. Mills require more energy than a diffuser. A multiple-effect 3-stage evaporator requires more steam than 5-stage installation. A triple-effect system needs 500-600 kg of steam to process 1 tone of cane. Distribution of energy consumption: 10-20% pumps, mills, electricity; 70-80% condensed losses. Interest exists in heat recovery systems and TVR or MVR systems.
Using bagasse as fuel for boilers: 2.5 kg steam/kg bagasse, and necessary 200-240 kg bagasse/tone cane. Suitable moisture < 48%. 1 tone bagasse = 0, 34 tone fuel (heat power terms). Excess of bagasse decreases efficiency of furnace used to remove it.
Electricity production possible from excess bagasse.

Figure 3.10 Basic modules general flowcharts for a cane sugar processing plant (from data of Bruinsma et al., 1985).

ALTERNATIVE 2. SMALL-SCALE SUGAR PRODUCTION PLANT

Raw Matter

Need for raw materials
Supplying 300-800 tones cane/day.
Better adaptation for farming in scattered areas.
Good system for mixed agriculture with smaller farmers.
More labor used because of manual harvest.

NOTE: Similar considerations as Alternative 1 for raw material specifications and farming production evolution.

Product

By-products and applications

- Bagasse: used as fuel (steam production), fibrous products (paper, cardboard).
- Molasses: fertilizer, livestock feeding, industrial fermentation substratum.
- Filter cake : fertilizer, livestock feeding, wax.
- Ash
- Proteins

The smaller the scale, the smaller the possibility of exploitation. Small production increases transport costs. By-products processing may increase employment opportunities.

NOTES: Similar considerations as Alternative 1 for product specifications and market forecast.

Process System

Technical and economic aspects
Simplification of large-scale process (see flowchart Alternative 1).
Smaller initial investment. Smaller risk implanting in new zones than in large-scale alternative. Must consider possible design expansions.
Only 3 roller-mills used with water wetting on second and third mills.
About 10% sugar lost in bagasse with moisture content 50-52%.
Mud filtered in press filter; more labor intensive than vacuum rotary filters.
Evaporation in 2 stages to 60° Brix. Each kg steam can evaporate nearly 2 kg water.
Crystallization in only 2 stages.
Cooling and centrifugation are batch operations.
More labor used per mass unit of product.

Yield

- Overall recovery: 72% (80-85% in large-scale process).
- Larger production of bagasse, molasses, and other by-products compared with large-scale processes.

Auxiliary Systems

Energy aspects

- Energy self-supply is impossible using only bagasse. Other energy sources necessary.
- Energy efficiency of this process system is smaller compared to Alternative 1.

ALTERNATIVE 3. KHANDSARI PRODUCTION. OPS PLANT.

Raw Matter

Need for raw materials
50-200 tones cane/day are needed

NOTES: Similar considerations as Alternative 2 for farming production and raw material specifications.

Product

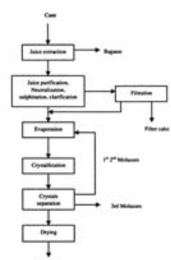
Product specifications
Khandsari: composition

- Sucrose: 99, 5-99, 9%
- Reduced sugar: 0, 1-0, 4%
- Ash: 1%
- Moisture content: 0, 15-0, 50%
- Color: yellow/white

Although pure enough to be accepted as domestic sugar, refined white sugar is preferred unless price makes advantageous.

By-products
Bagasse can be dried in sun before use as fuel. Possible sugar recovery from molasses by means of ionic exchange.

Process System



Technical, economic, and social aspects
Capacity: 50-200 tones cane/day.
Juice extraction by roller mills with water before 2nd mill: 70-80% extracted.
Raw juice purification by lime addition and sulfitation followed by settling. Mud and scum separated in single bag filter or press filter.
Evaporation in 4-5 steps with open pans.

Temperature increase from first step to last. Crystallization during slow cooling (24h) with manual intermittent shaking of crystals and molasses mixture. Separation of crystals in batch centrifugal separators. Drying of crystals in rotating drum dryers or in sun. High energy specific consumption.
Process has huge labor requirements (makes higher outputs impossible). Bagasse transported manually, restricting capacity and making organization of work difficult. For 100 tones/day, 163 workers are needed. The cheaper the labor and shorter the productive period, the more profitable the OPS plant is. More labor interesting in areas with high unemployment. Higher annual costs besides less investment. Easy adaptation to technical development of different countries. Local engineering development.

Yield
Sugar recovery: 57-64%

Auxiliary Systems

Energy aspects
Amount of bagasse is inadequate. 10% additional fuel needed (fuel, firewood).
Use of firewood can be very limited.

Figure 3.10 (continued)

ALTERNATIVE 4. GUR PRODUCTION PLANT

Raw Matters

Need for raw materials
15 tones sugar cane /day

NOTES: Similar considerations as Alternative 2 for farming production and raw material specifications.

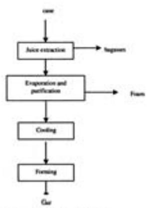
Product

Product specifications
Gur is concentrated cane juice.
Small impurities removed, so contains practically all material originally present in cane juice.
Contents:
4-8% moisture
90-95% carbohydrates
(sucrose 73-80%, glucose, fructose)
0, 15-1, 50% mineral salts
(mainly P and Ca)
Traces of proteins, fats, vitamins
Very hygroscopic product. Difficult to preserve.
Difficult to introduce in markets where unknown.
Main sweetener in some countries (e.g., India).

By-products
Little opportunity for use due to small production (see Alternative 2)

NOTES: Similar considerations as Alternative 3 for market forecast.

Process System



Technical, economic, and social aspects
Small or medium-scale production.
Crushing by mechanical or animal power. Mechanization allows bigger production and better efficiency: max by machine 2 tones/day; max by animal 1, 2 tones/day.
Final yield gur production: 110 kg/tone cane using motorized crushers; 100 kg/tone cane using animal-drivers.
Juice concentrated in only 1 step, in open pan.
Juice clarified during evaporation by skimming off impurities.
Usually traces of plants or other agents such as milk or lime added to improve clarification.
After required concentration reached, mass is cooled by shaking.
Afterwards spheres are shaped, becoming available as lumps of brown sugar.
Valid for small productions.
Intensive process and labor.
Small initial investment.
Yield
60-65% sugar recovery in extraction process.
44-52% overall sugar recovery.

Auxiliary Systems

Energy aspects
Bagasse can be used as fuel for evaporating boilers; previously dried in sun.
Possible use as firewood or fuel.

Figure 3.10 (continued)

1. Helps design and layout the food processing systems and auxiliary systems equipment, clearly showing the connection with different equipment.
2. Provides a clear schema of processing systems and food plant that allows a posterior detailed design of each part separately.
3. Helps prepare a list of necessary food processing equipment and auxiliary systems for a preliminary estimation of food plant investment cost.
4. Gives the basis for estimating the size of equipment necessary.
5. Trains the staff on use of food processing and auxiliary systems during startup stage.

Flowcharts are useful not only for studying problems on running food plants but also for designing new ones. They are also useful in making a flowchart prior to the study of mass and energy balances in a food processing system.

The most commonly used flowcharts are:

1. Basic flowchart
2. Food processing steps flowchart
3. Process equipment flowchart

The *basic flowchart* represents the steps and essential conditions for the food processing system. Its objective is to express the basic organization of the process without detailing every step involved or its particular conditions. An example of this type of diagram is illustrated in Figure 3.11.

The *process steps flowchart* displays the concrete technology of a food processing system alternative, specifying each step and the conditions by which it must be carried out, such as process temperature, holding time, concentrations, raw materials quality, etc. (Figure 3.12).

The *process equipment flowchart* displays a block for each type of food processing equipment as a component of the food processing system. It represents the process engineering of a given alternative for a food processing system (Figure 3.13). The flowchart may have scaled sketches of the equipment (e.g., a synoptic scheme) placed either in vertical or horizontal form. This flowchart is the *process equipment detailed flowchart* (Figure 3.14). In this way, the relationships between the types of equipment in the food processing system become more explicit, an interesting aspect in preparing the construction drawings as well as the electrical and piping or solids transport systems (Figure 3.14, Figure 3.15). The process equipment flowcharts can include standard symbols to represent the food processing equipment and the auxiliary system components from chemical engineering or food process engineering, in which different types of symbols are valid. Similar detailed flowcharts are made for the auxiliary systems (steam generation and distribution systems, refrigeration systems, and control systems) (Figures 3.16, 3.17, and 3.18).

3.6.3 Mass Balance in the Process

The mass balance tries to express, quantitatively, all of the materials taken in or going out through the process. It is beneficial to prepare the mass balance in flowchart form in order to avoid any omission.

Figure 3.11 Basic flowchart steps in white wine-making process.

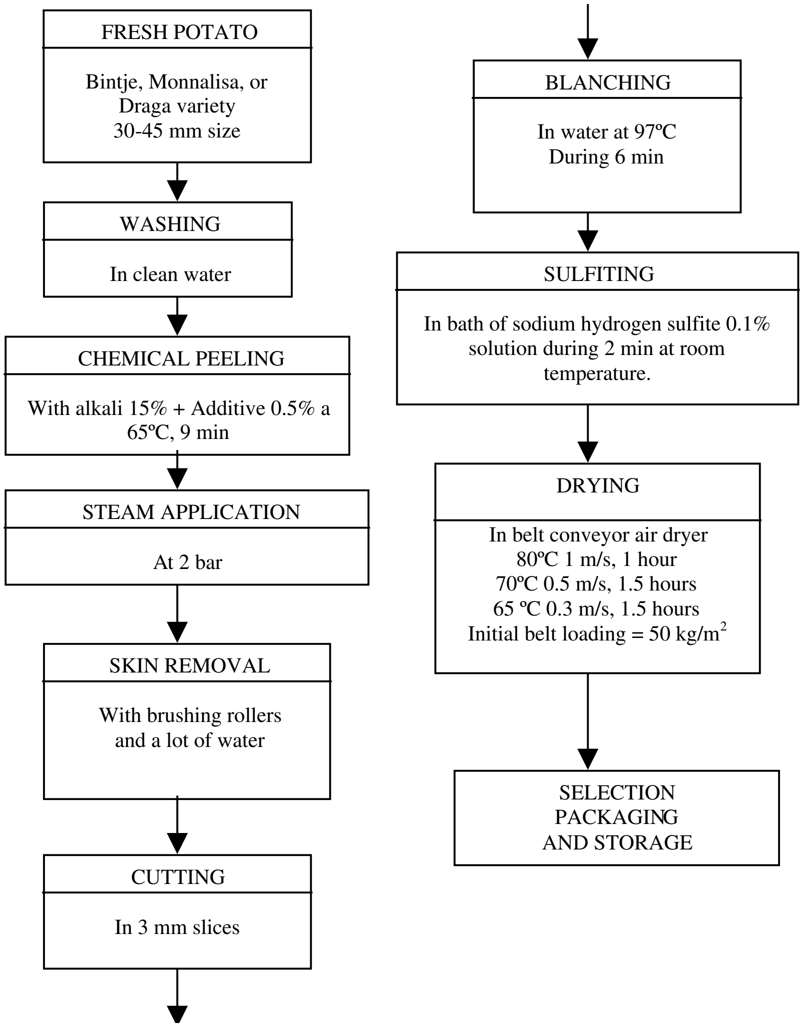


Figure 3.12 Process steps flowchart for potato slice drying.

Mass balance is necessary at a detailed engineering level in designing even the simplest operations, in sizing of equipment, and in considering the relationships between the different types. Mass balances are also very useful for improving the efficiency of a running food plant because they allow

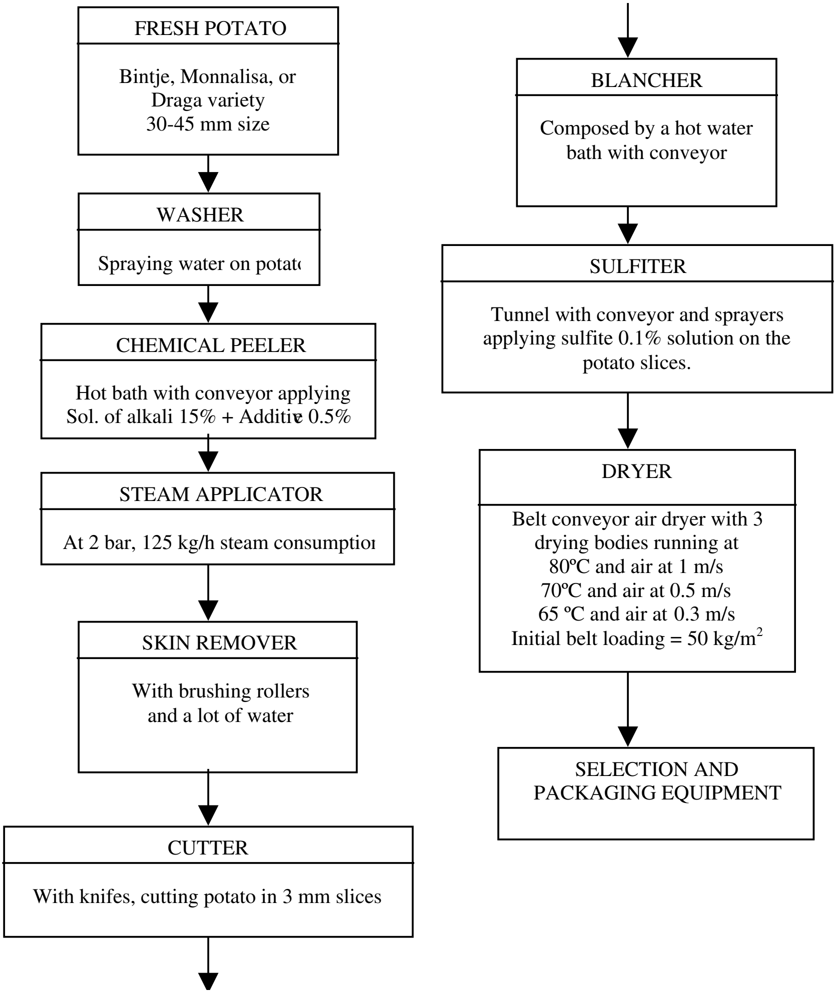


Figure 3.13 Process equipment flowchart steps in potato slice drying.

identification of the nature, magnitude, and location of each efficiency loss point.

There are various representations of the mass balance flowchart, although there is certain interest in standardization. Examples of mass balance flowcharts are shown in Figure 3.19

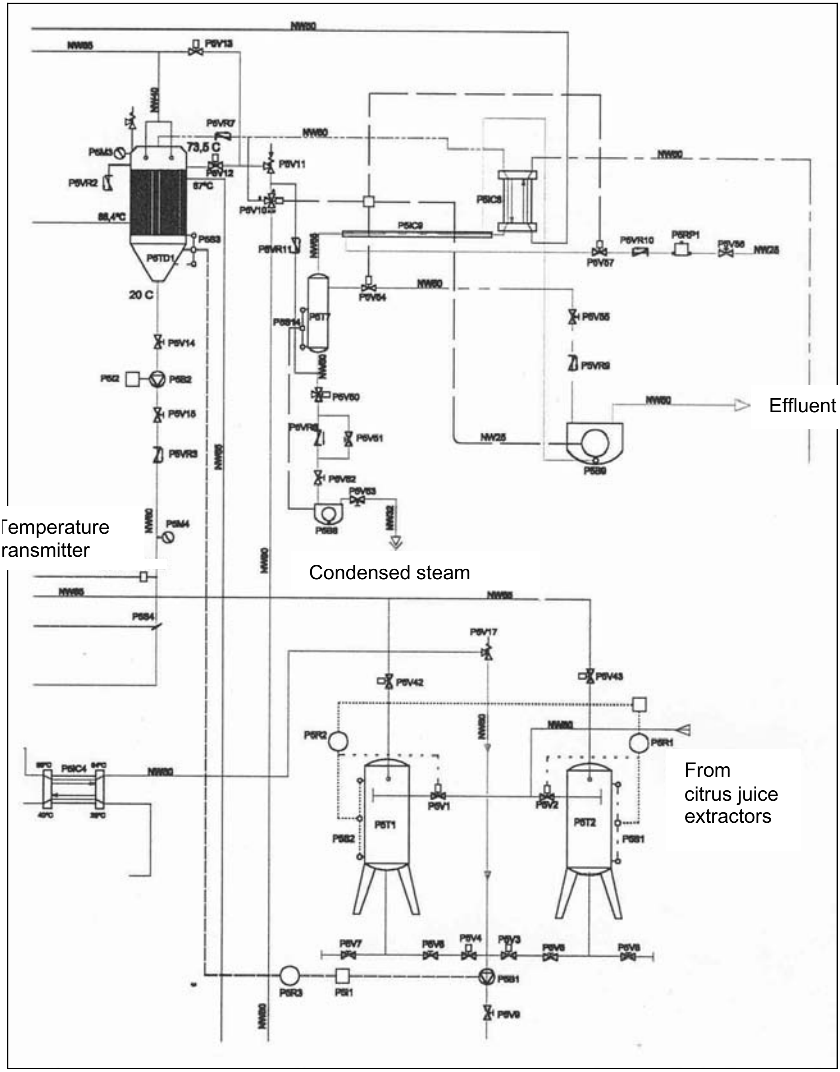


Figure 3.14 Process equipment flowchart, showing connections with auxiliary systems (CIP system, piping and pumping, control system).

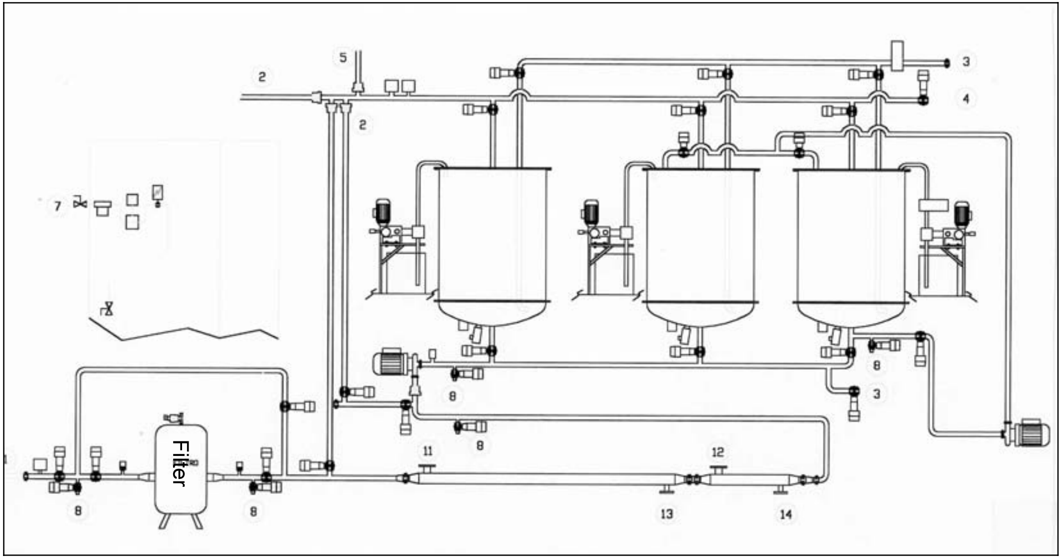


Figure 3.15 Auxiliary equipment flowchart of a CIP system.

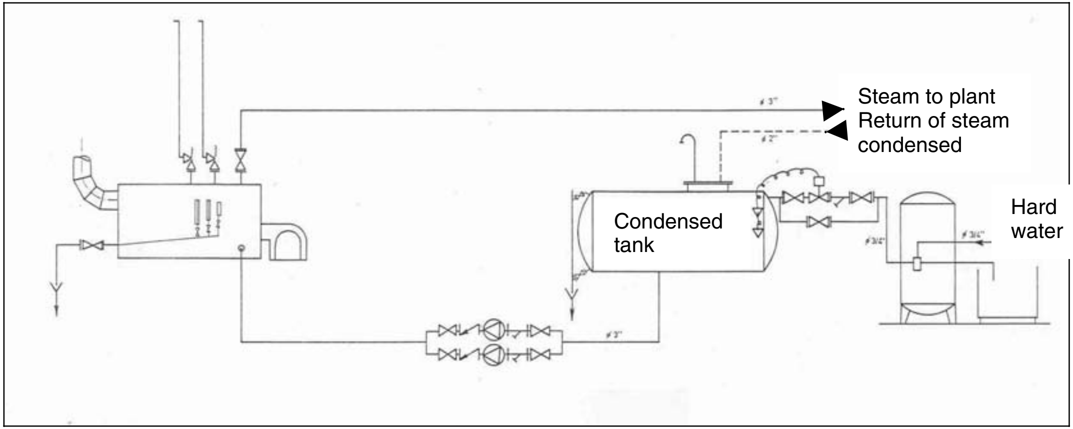


Figure 3.16 Steam generation and distribution flowchart in a food processing plant.

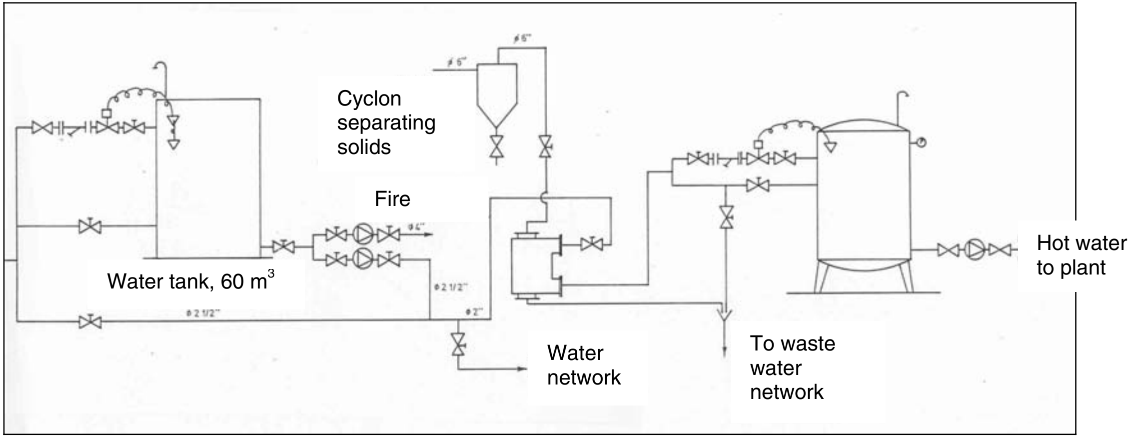


Figure 3.17 Water supply system flowchart of a food plant.

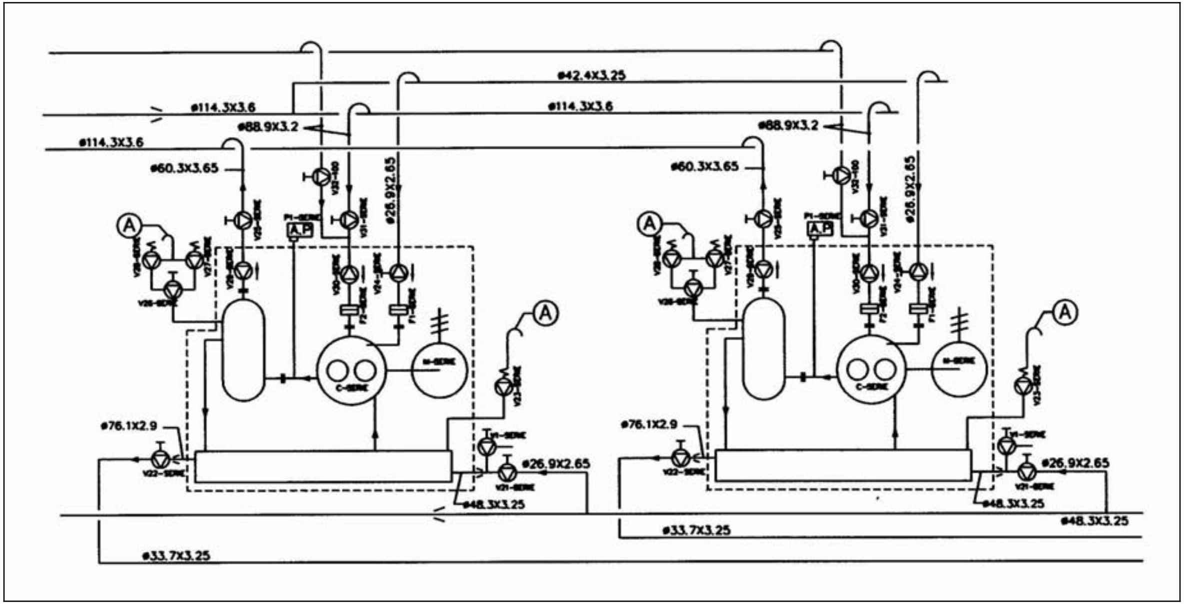


Figure 3.18 Refrigeration system flowchart of a food plant.

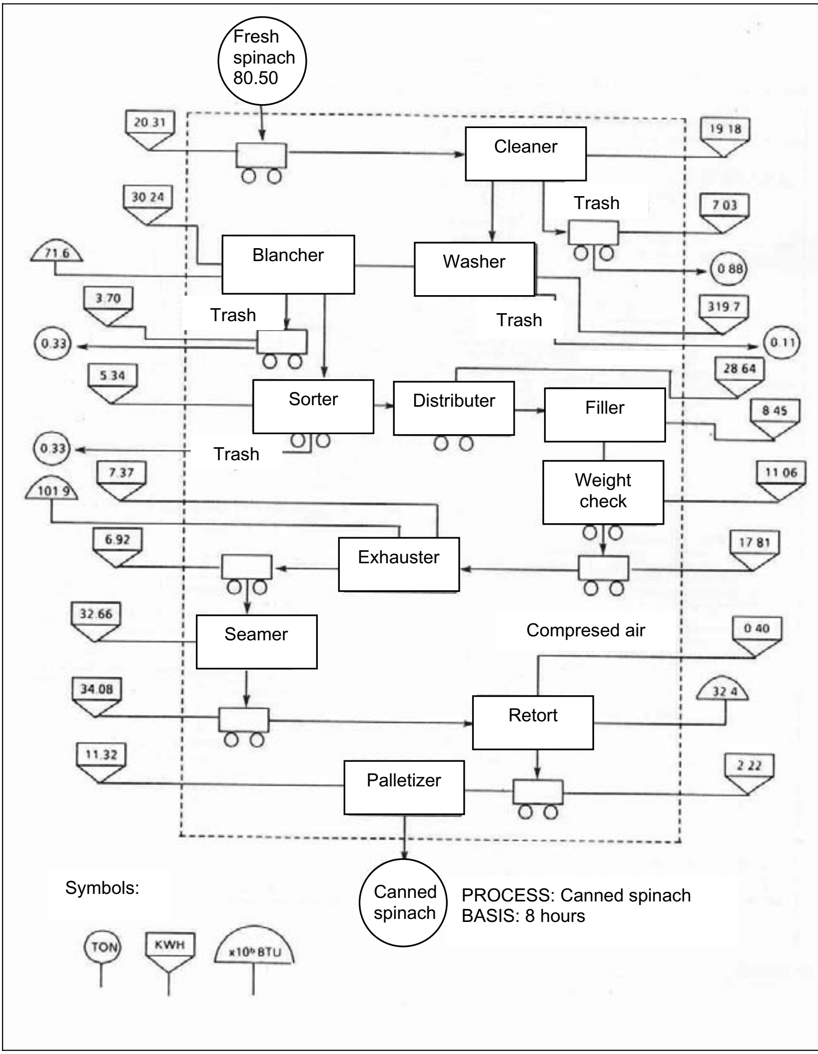


Figure 3.19 Energy and mass balances of a canned spinach processing line in flowchart form (adapted from Singh, 1986).

and Figure 3.20. The mass flow rates going in or out through the food processing system are expressed in mass/time units (e.g., kg/s), not in volume/time units (L/s).

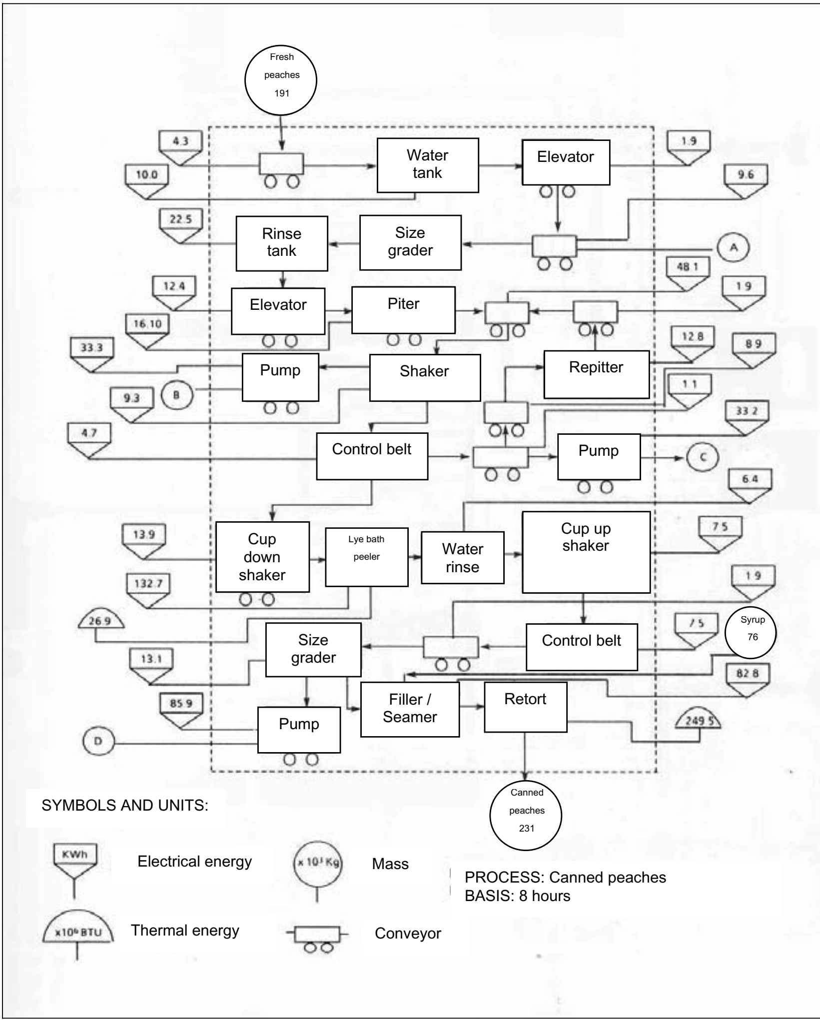


Figure 3.20 Energy and mass balances in a canned peach processing line in flowchart form (López, 1985).

When these balances are based on a running food processing system, the resulting numbers express the mean values of the flow rates quantified during the time needed to take into account all possible mass flow rate fluctuations. It is a very common practice to take measurements for several days, and during one, two, or three labor shifts each day. Energy balances in a food processing system are determined in a similar way.

3.6.4 Energy Balance in a Food Processing System

Once the mass balance is evaluated, the energy balance can be determined using the corresponding mass flow rates. It is helpful to represent the energy balance in flowchart form (same for mass balance) using heat units (J, kJ, or GJ) per time units (s or h). There are different types of balances in flowchart form, although there is a certain trend toward their standardization (Figure 3.19 and Figure 3.20).

3.6.4.1 Energy Accounting in Food Processing Plants

A method that accounts for energy use in a food processing plant was presented by Singh in 1978. A brief description of the energy accounting steps in this method (Singh, 1986) follows:

1. *Determination of the objective*. The energy accounting study that is conducted depends on the objective one desires to obtain. An example may be to seek information needed to develop energy use profiles for a given food processing plant. Another accounting objective may be to investigate the possibilities of technology and engineering modifications on a specific food processing equipment to obtain energy savings.
2. *Selection of a system boundary*. A system boundary allows a choice in choosing the items that will be considered or neglected in the accounting study. It is important for correctly interpreting the results, and for determining the total cost of the study.
3. *Process flow diagram or process steps flowchart making*. This flowchart assists in the identification of different types of equipment included in the energy accounting study. Symbols useful in drawing the energy accounting flowchart or energy balance in a flowchart form could be the ones that Singh (1978) proposes. These symbols are shown in Figure 3.21.

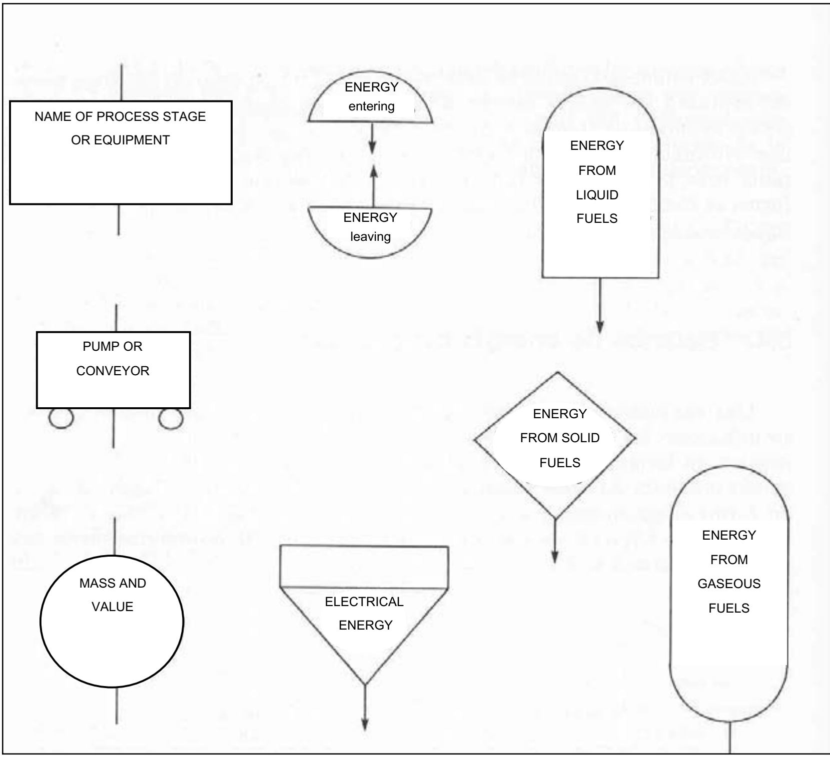


Figure 3.21 Symbols for energy and flowcharts of mass balances (Singh, 1986).

4. *Identifying mass and energy inputs.* Any mass and energy input crossing the system boundary must be correctly identified. Mass flow rates of primary matter — fruit, milk, meat, etc., and other matter like sugar, salt, water, etc. — must be identified. Energy flow rates from different sources such as steam, hot and cold water, hot and cold air, electricity, heat transfer by conduction through system walls or insulation, and so forth must also be identified.
5. *Quantifying mass and energy inputs.* Using a reasonable amount of time as a basis, flow rates of mass and energy inputs must be measured. The total

period for measurement of mass and energy flow rates should be sufficient to allow observation of any variations. This step can involve the installation of mass and energy measuring instruments for a short time (if the flow rate is measured in steady state conditions), or for long periods, if the measured flow rate changes. Today, this last step can be done automatically by means of flow meters connected to the equipment point being analyzed. These devices record the flow rate value for fixed amounts of time; recorded data can then be downloaded to a computer for data processing and discussion.

6. *Identifying mass and energy outputs.* To study the mass and energy balances around the selected system, it is necessary to identify the mass and energy outputs.
7. *Quantifying mass and energy outputs.* Once the mass and energy outputs are identified, the corresponding flow rates must be measured.

From such data, the mass and energy balances can be studied and the value of energy specific consumption (e.g., given in GJ/kg of food processed, using steam or hot water as an energy source) can be obtained. In this manner, by comparing the observed consumption (mass and energy) in the selected system with the data corresponding to an optimum design and operation of the same system, it is possible to know the mass and energy savings potential. To achieve this energy savings, it is helpful to modify the process technology (operation conditions of system), sometimes without cost, or to the contrary, to change the process engineering (by modifying the processing equipment or its control system) with associated investment.

3.6.4.2 Measuring Energy Flow Rates

3.6.4.2.1 Electric Motors

Two measurements are used to check the energy consumption of electric motors, voltage, and current that will make sure the motors are operating under the conditions they were designed for (Singh, 1986).

Electric companies provide a specific voltage according to variation possibilities, for example, 220±9 V (in Europe) or 115±5 V (in the U.S.). In addition, indicated on the motor's nameplate is the voltage for which it was designed.

If a motor does not work under the right voltage design conditions, it will operate inefficiently. It can also be damaged. Most motors can tolerate only a small deviation from their designed operating voltage (usually ±10%).

If the supplied voltage is higher than the tolerated voltage, then a motor designed for the supplied voltage must replace an inadequate motor. If voltage is lower than the tolerated one due to an excessive voltage drop, the current increases. This elevates the energy consumption accordingly, and results in excessive heating of the electrical system. It is simple to verify an excessive fall in tension by measuring the voltage at the beginning and end of the electric supply line. A qualified electrician can measure the voltage with a voltmeter or a volt-ohm meter.

If the measured current moving through a motor is the one indicated on the nameplate, the motor is fully loaded and works at 100% efficiency. On the contrary, if the current is lower, the motor is underloaded. The current can be measured with a clamp-on ammeter.

Another method to measure the energy consumption in electric motors is to use the watt-hour meter. With the kilowatts obtained from the watt-hour meter and accurate voltage and current measurements, the power factor (F) can be evaluated using one of the following formulas:

$$\begin{aligned} &\text{single phase:} \quad F = \frac{kilowatts\ (kW)}{VI} \\ &\text{three phase:} \quad F = \frac{kW}{\sqrt{3} \cdot VI} = \frac{kW}{1.73 \cdot VI} \end{aligned} \tag{3.1}$$

where V is the voltage (in V, from the voltmeter) and I is the current (in A, from the ammeter). Using this method, the energy consumed by an electric motor can be calculated by measuring the voltage and current, if the power factor is known.

Table 3.1 includes formulas concerning watts and electric motors.

3.6.4.2.2 Steam Flow in Pipes

The steam flow rate measurement is an important part of energy accounting studies (Singh, 1986). This measurement can be carried out by different methods, but two valid and simple methods are to use the orifice meter and the Pitot tube.

The orifice meter consists of a flow-restricting device. When an orifice plate is inserted into a pipe, it produces a pressure drop, which varies with the velocity and density of the fluid. Figure 3.22 presents an orifice meter in a steam pipe.

Under these conditions, it can be written (in SI units) (Singh, 1986) as

$$W = C_1 \left(D_2\right)^2 \cdot \alpha \cdot K \cdot Y_1 \cdot \sqrt{\rho_1 h_w} \tag{3.2}$$

where

W = mass flow rate of steam (kg/s)
D_2 = orifice diameter, in mm (at 16°C)
α = metal thermal expansion factor (dimensionless)
K = orifice discharge coefficient (dimensionless)
Y_1 = expansion factor based on absolute static pressure at upstream tap (dimensionless)
ρ_1 = steam density (kg/m^3)
h_w = differential pressure across the orifice (kPa)
C_1 = dimensionless conversion factor = $35.11 \cdot 10^{-6}$, or 1.11 when diameters and pressures are expressed in basic units, m and Pa, respectively.

The exact position of the orifice meter in the tube must be carefully determined in order to obtain a correct measurement (Singh, 1986). The meter should be located in a tube point that has uniform flow. Therefore, it should be placed far enough from any pipe fittings, elbows, or valves that could

Table 3.1 Formulas Concerning Watts and Electric Motors

	Single-phase	Three-phase
Volt-Amperes (VA)	VI	$\sqrt{3} \cdot VI = 1.73 \cdot VI$
Kilovolt-Amperes (kVA)	$VI/1000$	$\sqrt{3} \cdot VI/1000 = 1.73 \cdot VI/1000$
Watts (W)	VIF	$\sqrt{3} \cdot VIF = 1.73 \cdot VIF$
Kilowatts (kW)	$\dfrac{VIF}{1000}$	$\dfrac{\sqrt{3} \cdot VI}{1000} = \dfrac{1.73 \cdot VI}{1000}$
Reactive volt-amperes (VAR)	$VI\sqrt{1-(F)^2}$	$\sqrt{3} \cdot VI\sqrt{1-(F)^2} = 1.73 \cdot VI\sqrt{1-(F)^2}$
Reactive kilovolt-amperes (kVAR)	$\dfrac{VI\sqrt{1-(F)^2}}{1000}$	$\dfrac{\sqrt{3} \cdot VI\sqrt{1-(F)^2}}{1000} = \dfrac{1.73 \cdot VI\sqrt{1-(F)^2}}{1000}$

Adapted from Singh, 1986.

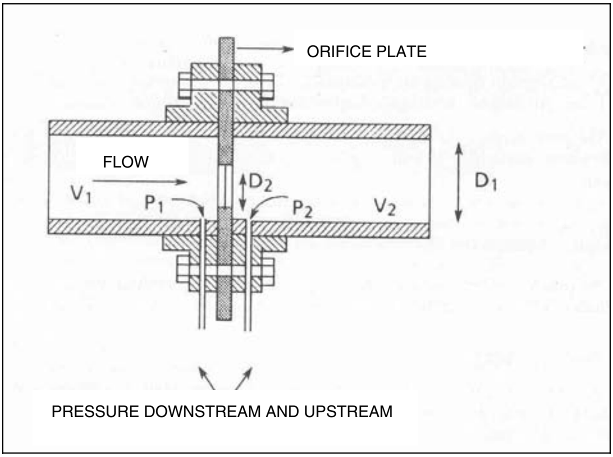


Figure 3.22 Orifice meter installation.

cause an increase in the turbulence. If the meter is fitted in a horizontal pipe, a condensed trap, or drain holes in the orifice plate near the bottom of the line, should be provided. It must not be fitted in pipes with a diameter smaller than 2 in. (50.8 mm). The pressure difference must be measured between two strategically located points, usually separated 1 in. from each face of the plate.

When orifice meters are used to measure steam flow, many measurements are required. These include static pressure, either upstream or downstream from the orifice plate, and temperature of the steam (with a ±1°C accuracy), which will be used to calculate the physical properties of the steam. Other necessary measurements are differential pressure, determined using a mercury manometer or a differential pressure cell, and steam properties such as viscosity, specific heat, and specific volume, which may be obtained from a handbook. The rest of the parameters needed for the steam flow determination, using an orifice meter device, are obtained from empirical relationships based on experiments conducted by the American Gas Association, the American Society of Mechanical Engineers, and the National Bureau of Standards, as well as graphics and tables from Singh (1986).

The Pitot tube is used extensively to measure the velocity of a flowing liquid at a specific point in a pipe. The measurement is based on two parameters: the impact pressure and the static pressure.

The Pitot tube causes virtually no pressure drop in the flowing stream. Several companies sell Pitot tubes that are specially designed for steam flow, such as Annubar® tubes and the Accutube® Pitot tube (Singh, 1986).

Annubar tubes have sensors consisting of two probes inserted into the pipe. One of the tubes faces the flow to sense velocity pressure. The second probe faces downstream and allows the determination of static pressure. The steam mass flow rate (W) is calculated (in British Imperial System units) as follows:

$$W = 8211.4 \cdot K_A \cdot A_1 \cdot Y_1 \sqrt{2g\rho_2 \Delta P} \tag{3.3}$$

where K_a is a (dimensionless) flow coefficient depending on the device's design, and provided in tables by manufacturers. The rest of the parameters are obtained in the same manner as for the orifice meter. The Accutube Pitot tube has only one sensing tube, and it is easy to install in a pipe. The equation used to calculate steam flow rate is (in British Imperial units)

$$W = 360.05 \cdot C_A \cdot D_1^2 \sqrt{\rho h_w} \tag{3.4}$$

where $C_A = C_g \cdot V_f$, and C_g can be obtained in tables by manufacturers and V_f is the velocity distribution factor (equal to 0.82 for turbulent and transitional flow).

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4

Processing System Alternatives: Process Synthesis

4.1 INTRODUCTION

The work of selecting, transferring, adapting, and developing the most suitable technology in any one food factory often lacks an appropriate methodology. The time factor or urgency to carry out production frequently justifies the use of already existing proven technology and engineering. The simplest solution is to copy the designs from similar food plants. This procedure, however, is not always the most suitable solution. For example, a change in the industrial scale of the process alone is enough to make ultrafiltration in juice clarification (in a concentration processing system) impracticable (Giral et al., 1979; Bruinsma et al., 1985).

Thus, the need for more suitable methodology to create a proper food processing system is clear. A process design engineer must be provided with the necessary tools to design a complete food processing system and corresponding food plant, understanding the data related to the raw materials and the auxiliary system, in order to produce desired products at a minimum cost. The process synthesis theory has aided the development of a whole series of design techniques, permitting the systematic and ordered generation of suitable alternatives for process configuration. However, these techniques cannot replace the expertise of a good process design engineer, although such techniques can help one acquire the necessary experience.

Process synthesis techniques have not received much attention, whereas analysis techniques of the process equipment design have. The reason for this is that analysis techniques of process equipment design require the use of deductive logic, as the engineer dissembles the entire process into its component parts for study. In contrast, process synthesis techniques necessitate inductive logic, thereby combining the elements of a process into a whole, and so are difficult to study and systematize.

Over the years process analysis techniques have received a great deal of attention, especially when Arthur D. Little first introduced the concept of *unit operation* in 1915. Recently, the importance of these techniques has been reinforced thanks to the *transfer phenomena theory* and to the appearance of tools for process simulation, the importance of which grows daily due to the extensive use of computers.

It was not until a few years ago that several researchers began working on developing different techniques of process synthesis (Douglas and Woodcock, 1985; Knopf et al., 1982; Laine and Kuoppamaki, 1979; Nishio et al., 1989, 1985). These techniques are now becoming important tools for use in managing industrial processes. One aim pursued in the development of new and more powerful process synthesis techniques has been to rationalize the inductive method used by research engineers in selecting a particular process, starting with product specifications and data.

Investigating the process synthesis techniques has been more important in the field of chemical engineering than in the field of food engineering. Nishida et al. (1980) revised the bibliography for system synthesis in chemical engineering, concluding that auxiliary systems (mainly heat exchanger networks) were the best studied systems.

According to Nishida et al. (1980), process synthesis is the design part in which the engineer selects all the components of the process to construct a flowchart or flow diagram. Through process synthesis, the aim is to decide the most interesting configurations that a food processing system can adopt.

In this manner, four groups of systematic synthesis methods have been established:

1. Evolutionary
2. Heuristic
3. Structural
4. Algorithmic or mathematical

The evolutionary and heuristic methods are the most commonly used techniques to solve the different system synthesis problems. However, these methods are specific to each individual problem, and there is no assurance that an engineer will achieve the optimum alternative. This also occurs with the structural methods, because there is no guarantee of obtaining the best option.

In fact, few synthesis methods have general validity. In addition, since the structure of solutions is generally not clearly defined, the iterations are frequently used to find the optimum alternative. The analysis of sensibility is therefore necessary in analyzing the possible variations of initial conditions, but we can only move near the chosen optimum solution.

On the other hand, heuristic methods inconveniently lack a theory to explain why an experimenting engineer chooses a certain solution over another.

4.2 SYNTHESIS METHODS

4.2.1 Evolutionary Methods

4.2.1.1 Basic Modules Method

The basic modules method is a synthesis method in which it is necessary to maintain a perspective of the entire problem as a set. It takes into consideration the selection of the most convenient raw materials (bearing in mind cost, availability, and economic activity generation), as well as the finished products (bearing in mind suitable minimum specifications, influence of price fluctuations in demand elasticity, and whether it meets social needs).

In this methodology of basic modules, there are four steps in the synthesis of a food processing system:

1. Specification of product
2. Study of available raw materials
3. Study of food processing technology and engineering alternatives
4. Study of auxiliary systems

The basic modules methodology has the following characteristics:

- Provides a procedure for designing a food processing system and food plant
- Based on the simple focus traditionally used in process design, to emphasize food processing system design while creating a concept of the whole food plant (process systems in addition to auxiliary systems)
- Tries to fully utilize every component in the global optimization of the food processing plant

The application of the basic modules method is iterative and evolutionary, as are other process design methods. There is a preliminary study of each of the four methodological steps to structure the overall model. Then a more in-depth study of the steps is completed, increasing the investment in resources as more information and more security in the final stage are acquired. In other words, an exhaustive study of the product (first stage) is not done before starting the study of available raw materials (second stage), etc. This is because separate investigations could give rise to the squandering of resources, and the global perspective that is only achieved once the whole problem is structured could be lost.

In short, this methodology establishes the following sequence in acting to solve a synthesis problem:

1. *Food product studies*. Researching the items listed in Chapter 3, and afterwards creating the corresponding document, *Study of the Product*.
2. *Raw materials studies*. Carried out according to Chapter 3. The results will be reflected in the corresponding document, *Study of the Raw Materials*.

3. *Food processing system alternatives study.* Will mainly determine (a) the quality of the product; (b) the biggest part of the investment in the food plant; and (c) the consumption and sizing of the auxiliary systems (materials handling, energy handling, and control systems).
4. *Auxiliary systems study.* Once the processing conditions are fixed, the auxiliary systems are designed to satisfy the utilities demand from the food processing system, and to optimize the materials, energy handling, and control systems. The wastewater and waste treatment systems must also be considered at this stage. While these systems must be considered a part of the overall design of the food plant, their study is not as clearly related to the rest of the modules.

The synthesis of the different food processing system alternatives will use all the necessary information sources, among them the following: bibliography (books and specialized journals on food technology and engineering), food processing equipment bulletins from the corresponding firms, existing food plants, and technical reports from administration. In some cases, experimentation in process development laboratories and/or pilot plants will be necessary.

The design of auxiliary systems can be a critical step for the success of the food plant. The combination of the other three modules will determine the production costs concerning raw materials consumption, the production capacity of the plant, the ratio of food product obtained to raw material used, and the product quality. The auxiliary systems, however, have a very important influence on production costs (up to 30–40% of the total costs, depending on the type of food factory), due to consumption of water, electricity, and fuel, as well as the costs of maintenance, control, and wastewater treatment. The auxiliary systems are one of the most complex and dynamic areas of process engineering. For this reason, the collaboration of a detailed engineering team is frequently required, with the assistance of specialists in refrigeration, steam, control, materials handling, and so forth.

4.2.1.2 Evolutionary Design Method

Traditionally, the development of most established food plants begins when the research and development staff proposes a particular design for the food processing system. After carefully analyzing and making certain that the design is economically feasible, engineers carry out the plan at an industrial level in one or more food production plants. Later, they might discover possible modifications in the design that will make the food processing more efficient and economical, and these modifications are included in future new food plants. In this way, the original design has gradually evolved into a more suitable one.

The aim of this method is to acquire experience in a systematic way. This experience allows proposed modifications to the basic design of a food processing system to improve reliability or profitability without leaving the food plant installation stage at the industrial level.

Evolutionary design consists of generating, empirically, or by means of other systematic design methods, a simple basic process configuration that meets all engineering and food product specifications or restrictions.

This initial or basic solution is evaluated both technically and economically in order to find the elements that contribute most to the required investment and maintenance costs of the process, or the factors causing problems during the start-up and running stages, control problems, and so forth. Once the elements are identified, modification to improve the basic design is selected. This modification must improve the selected objective function (total costs, investment costs, running costs, reliability, profits, etc.). In this case, the modification is included in the process, and the new process results are evaluated. If the modification fails and the objective function is not improved, the modification is rejected. Another one is selected and incorporated into the same basic process. On the other hand, if the modification enhances the basic process (improvement of results achieved), the modification is incorporated into the basic design and a new food processing system design results. The same procedure is repeated in an

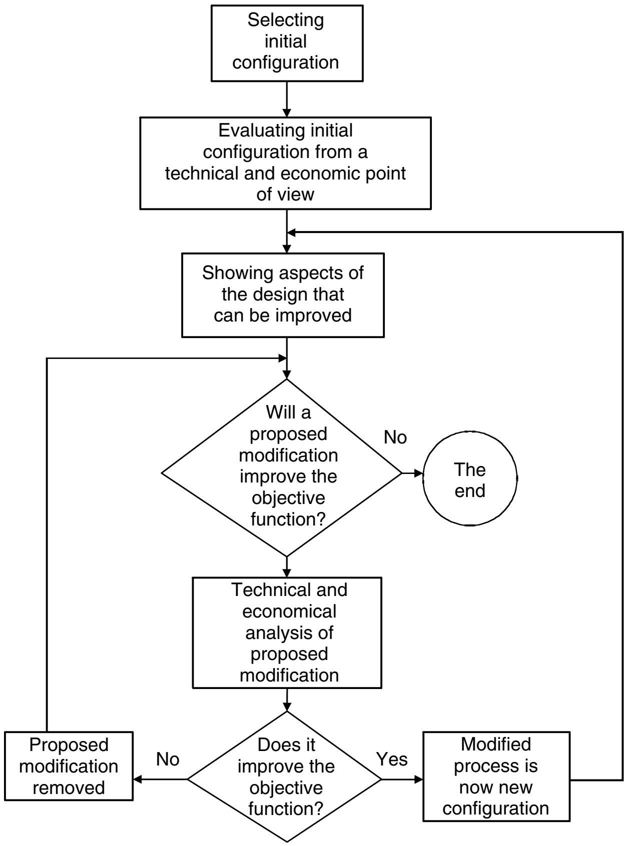

Figure 4.1 Evolutionary design method used to design a food processing system (adapted from Giral et al., 1979).

iterative way (proposing new modifications one at a time and evaluating the new process results) until further modifications do not improve the results of the objective function. The procedure of this evolutionary method is shown in Figure 4.1.

To evaluate each food processing system configuration, some evaluation criteria or a given procedure is needed, or a mathematical model or a pilot plant representative of the process that can measure efficiency. The food processing system is modified by making only one change in each step and measuring the effects of this change in the objective function quantitatively and qualitatively. Finally, selecting the change must be based on results obtained from evaluations of previous configurations. Here, the development of heuristic rules is very useful since they reduce the universe of feasible modifications to a manageable number.

The evolutionary method can be compared to the optimization method, as both explore only one variable at a time. It is not certain whether the optimum value is obtained, but it is guaranteed that every modification incorporated into the basic food processing system will improve the selected objective function. Another advantage of this method is that it allows a designer to discriminate among modifications with only marginal repercussions in the overall economy of the process, with the possibility of incorporating criteria other than economic measures into the selection procedure (as in the heuristic method).

4.2.2 Methods Based on Problem Solving

These methods are part of the structural methods, and mainly involve dividing a large, complex problem into a relatively small number of simple problems. These problems can be solved by means of available technology or subdivided into a recurrent form, and by using the same procedure, into even simpler problems, the solutions of which can be known.

The purpose of this method is to identify the functions being developed by the food processing system and to establish criteria that permit evaluation of the validity of any proposed alternative solution for the system. Therefore, sufficient information must be acquired in order to obtain adequate criteria for selecting alternatives.

This technique does not solve the problem of generating specific alternatives, or allow efficient evaluation of all possible combinations using the proposed alternatives. It does, however, provide a logical structure that permits finding a solution to complex problems by means of combining the solutions of simpler problems. Thus, it is certain that all the interesting alternatives are considered. In the same way, it allows the development of completely new processing systems by means of previously unconsidered alternatives.

For example, in a practical application of the problem decomposition method in the synthesis of a vegetable drying system (onions, in this case), the main functions to be developed by the drying system are the following:

- *Materials handling*. The materials must be loaded and unloaded from the dryer and, if the operation is continuous, must be conveyed through.
- *Supply of heating energy.* The system must provide the energy needed to remove the water in the product.
- *Moisture removal*.

The problem constituting the materials handling function is solved when the following are specified:

1. Operation regime
2. Transport mechanism
3. Load and unload mechanism

The most convenient system is a continuous operation due to the high production capacity required. Thus, it is necessary to define the conveying or transport mechanism through the dryer. The most common mechanisms are gravity (spray and rotary dryers), pneumatic (fluidized bed dryers), and mechanical transport (tunnel and belt dryers). The use of spray dryers is not recommended due to product characteristics (the onion is solid and cut into rings or strips before drying). Any other dryer is suggested, although the tunnel dryer incurs very high loading and unloading costs, as does the tray dryer. The most rational and inexpensive system is the continuous belt dryer, though it must be carefully analyzed. Finally, there are two product loading and unloading mechanisms in the dryer, referred to as hand and automatic. The second one is appropriate when high production is required.

To solve the function of transferring energy to the product in the dryer, it is necessary to specify the transfer mechanism, means of heating, number of stages, and flow sense. In this case, since the material can be damaged and contaminated by the heating process, the use of combustion gases

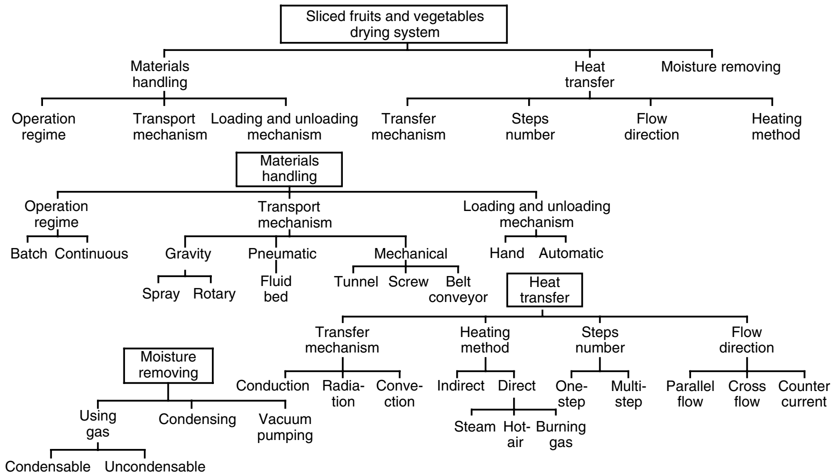

Figure 4.2 Problem solving in the design of a food processing system (fruits and vegetables drying system).

directly applied to the product is not recommended. The most suitable drying method for onions seems to be the use of hot air. In this product, since moisture content must be removed, it is advisable to use several stages in order to improve thermodynamic efficiency. The flow choice (parallel, crossed, or countercurrent flow) is determined by the required holding time and capacity of each individual stage.

For a high-capacity system, a multiple-stage dryer with crossed airflow is required. For moisture removal, there are several available alternatives, as shown in Figure 4.2. In this case, since the air is used as a means of direct heating, it can also be used to remove the moisture content.

In any other food processing system the corresponding process steps flowchart would indicate the main functions to be developed by the system (function = process step). These functions could be complex problems (e.g., a drying problem) and, as such, could be reduced to simpler problems using the concepts mentioned earlier (materials handling, energy supply; control and processing as in fermentation, moisture removal, etc.). Every function that the food processing system

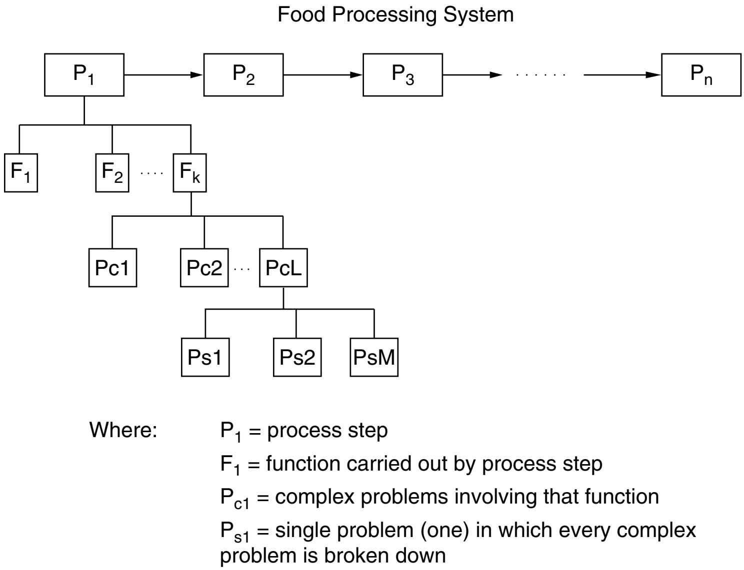

Figure 4.3 Problem solving in the design of a general food processing system.

simultaneously or sequentially carries out is solved according to different alternatives. The most interesting combinations become specific subproblems, which can be further broken down by additional detailed analysis (Figure 4.3).

4.2.3 Heuristic Design Methods

Heuristic design is a method based on results obtained from the analysis of alternatives of previous problems or experiences similar to the design under investigation. From these experiences, a series of empiric or heuristic rules can sometimes be formulated. These rules can lead to the selection of the best alternative in many cases. The rules are used during the decision-making stage when a new situation is approached, under the tacit assumption that the rules are still valid under the new design conditions.

Using this method, a large number of alternatives are rejected without previous evaluation. Nevertheless, it is impossible to know for sure if among such alternatives a more appropriate option exists under the new design conditions.

The use of heuristic rules is common in equipment design. Often-used heuristic rules include using a recommended velocity in the design of piping networks, or designing a heat exchanger in function on a given pressure drop and minimum approaching temperature.

Despite some exceptions, these rules serve as very useful design tools that save effort and money, especially in the beginning of the design when analysis of every possible alternative can be very tedious.

4.2.4 Algorithmic or Mathematical Programming Methods

These methods are based on mathematical algorithms, from which it is possible to generate and exhaustively analyze all possible alternatives, in an explicit or implicit manner, in order to find the optimum alternative according to a given objective function.

The main advantage of these methods is that the selected process configuration is guaranteed to be optimal. Despite this advantage, the application of these methods is restricted to few cases, of which the possible configuration alternatives can be expressed mathematically. Therefore, mathematical programming methods are not appropriate for studying other problems with a different model (Radovic et al., 1979; Singh and Saraf, 1981).

Sometimes it is possible, by means of heuristic rules, to reduce the possible alternatives of a process or problem, permitting the application of some of these methods.

The most frequently used mathematical tools are dynamic programming (DP), nonlinear programming (NLP), and linear programming (LP) (Takamatsu et al., 1982)..

An example is the application of linear programming and the simplex algorithm method to the calculation of the optimal energy supply from different energy sources in various process systems (Nishio et al., 1984, 1985).

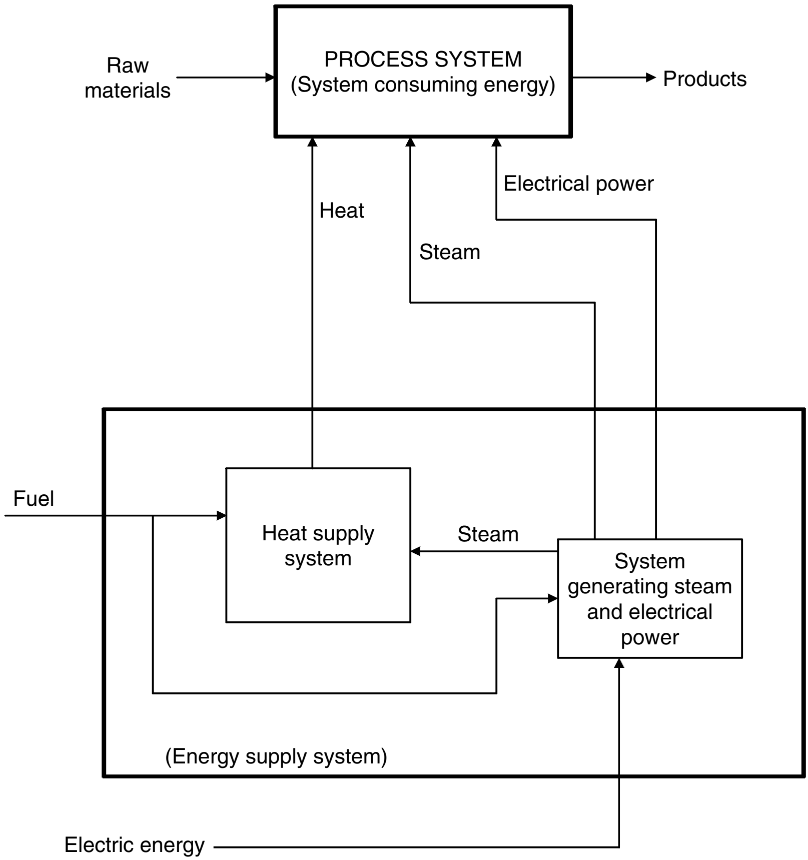

Figure 4.4 The processing system consumes energy under different forms, supplied by the energy handling auxiliary systems.

The synthesis of auxiliary systems, allowing the saving of energy, is increasingly important due to the rising cost of energy. Mathematical programming methods have been applied to the synthesis of energy supply systems using steam and electricity as energy sources.

Figure 4.4 shows a process plant (e.g., food plant) where the process system (the energy consumer) and the energy supply system as an auxiliary system (the energy supplier) are observed.

The energy supply system can also be divided into the heat supply system and the power supply system that uses steam. Due to energy conservation, fuel consumption in the energy supply systems must be minimized under given energy demand conditions from the process system.

Fuel is consumed in the heating processes (during direct application of the combustion gases) and in the gas burner of the steam generator. The steam is used as a heating vapor and in the steam turbines for electricity generation. This way, the problem involves synthesis of the auxiliary systems so that the fuel consumption is minimized, determining the most suitable percentage of energy, as applied in

1. Direct heating using combustion gases
2. Heating using the steam produced in the turbines
3. Electric power generated in the steam turbines

The problem can be solved using the linear programming optimization method, the simplex algorithm, setting an objective function that allows the minimization of fuel consumption.

It is assumed that the demand for heat and power is given as shown in Figure 4.5.

The problem can be formulated as follows:

$$\text{Minimize } Z = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \tag{4.1}$$

meeting with

$$\eta_{F1}x_1 + R_1\eta_{T1}x_3 = \left(1-f\right)\cdot Q \quad \text{Heat demand I} \tag{4.2}$$

$$\eta_{F2}x_2 + R_2\eta_{T2}x_4 = f\cdot Q \quad \text{Heat demand II}$$

$$R_2\eta_{T2}x_5 = H \quad \text{Process steam demand}$$

$$\eta_{T1}x_3 + \eta_{T2}x_4 + \eta_{T2}x_5 + \eta_{Tc}x_6 \geq W \quad \text{Electric power demand}$$

These relationships describe the heat supply and demand conditions with medium and low energy levels, of process steam and power, respectively.

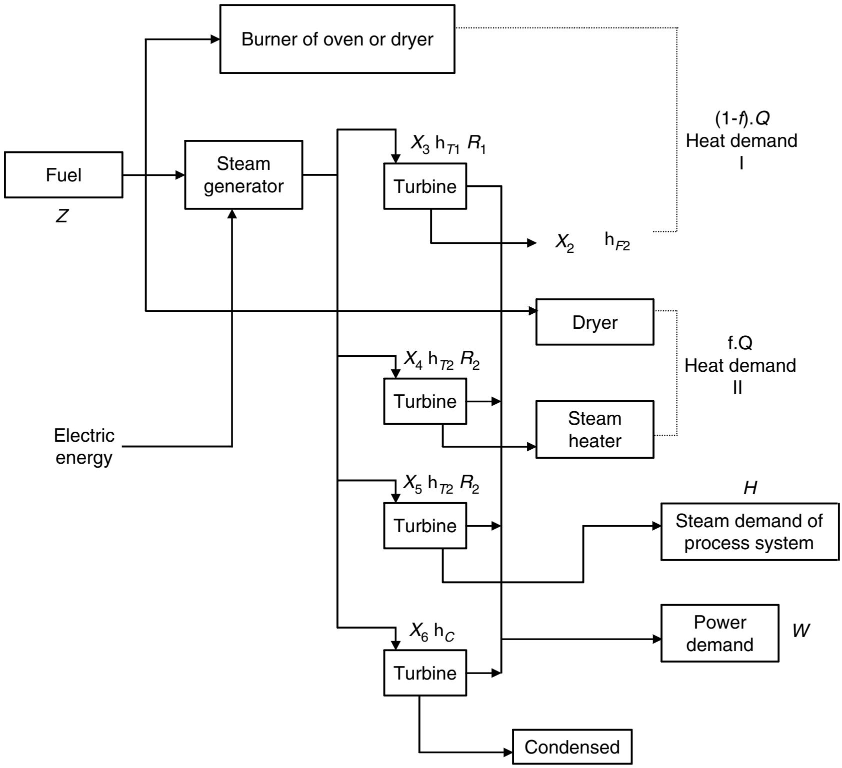

Figure 4.5 Flow diagram of energy supplied in a processing system.

NOMENCLATURE

x_1, x_2 = amount of fuel consumed by kilns in demand levels I and II, in kg/h

x_3, x_4 = amount of fuel consumed in co-generation of power and steam production, with demand I and II, in kg/h

x_5 = amount of fuel consumed by process steam demand, in kg/h

x_6 = amount of fuel consumed by power generation with condensing, in kg/h

η_{Fi} = thermal efficiency obtained in kilns in kcal/kg

η_{Ti} = thermal efficiency obtained in power generation using steam turbines, with the outgoing steam at lower pressure, used to heat the different parts of the process system in kW/kg.h
R_1, R_2 = recovery index from heat to power in order to determine heat demand I and II, in kcal/kWh
W = power demand, kW
Q = global heat demand, kcal/h
f = heat demand index level II in regard to global heat demand
H = process steam demand, kcal/h
η_{Tc} = global thermal efficiency in the turbine with final condensing, kW/kg.h
Z = global amount of consumed fuel, objective function, in kg/h

Thus, using the simplex algorithm in this linear model of system behavior, the value of each x_i that minimizes the energy and fuel consumption is obtained.

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5

Food Processing System Alternatives Analysis

5.1 OUTLINING THE PROBLEM

In food processing system synthesis, the aim is to generate possible configurations for a particular process system through knowledge of the product and raw material specifications as well as the results obtained. To achieve an optimum design, every alternative must be carefully analyzed by using certain analysis techniques. Process system analysis is the art and science of selecting the best alternative from among a large number of possibilities, with the extensive use of engineering methodology (Giral et al., 1979; Bruinsma et al, 1985). The selected alternative must meet the overall objectives of those making the decisions, always taking into consideration any legal, economic, and technical restrictions. The purpose of this chapter is to study the use of process system analysis in acquiring an optimum system design. System analysis techniques can also be used in making decisions during food plant construction and process plant running periods.

In practice, the evaluation of process alternatives mainly consists of measuring the technical (product quality and reliability) and economic results (profitability and investment payback).

By applying the unit operations and transfer phenomena theories, the technical or engineering behavior models of many unit operations (configuring different food processing systems) can be developed. With these models, the technical results of a process can be found for a given physical configuration alternative (including size and type of equipment in a unit operation) and a set of operating conditions (process technology) (Himmelblau and Bischoff, 1976).

The economic results for every alternative can be measured using appropriate economic criteria called design economic criteria.

To understand the results of every alternative exactly, industrial-level installations and operations of all possible alternatives would be necessary. However, this is a very expensive method and requires too much time to implement. Another method would be to build the process system on a smaller scale. In this manner, the operating conditions could be changed and the results observed at real levels. This would be a pilot plant study, which is a physical simulation tool of the process system and designed at an industrial level. However, this is also an expensive alternative (Backhurst and Harker, 1973). There is no guarantee an optimum solution would be obtained, because it is very costly to reproduce physically all process possibilities.

The methods of alternative analysis, using conceptual representations of the process, are usually convenient and economic solutions when possible. These conceptual representations of the process configure the process system model (Himmelblau and Bischoff, 1976). If defined with enough precision, the model can be studied with mathematical programming or algorithmic methods. In these cases, achieving the optimum design or optimum solution is guaranteed for given technical and economic conditions.

In order to simplify the handling of this mathematical model and to finish the technical details of the process system optimum design, the "information structure" of the process system merits study (Rudd and Watson, 1976).

5.2 SELECTING DESIGN VARIABLES

Food processing systems or lines usually involve a number of easily identifiable components or subsystems, such as evaporators, hot air drying units, and heat exchangers. These subsystems interact with each other to carry out a more complex function. Thus, the performance of one component, in great measure, depends on the performance of other components in the processing line. In effect, there is an information flow from one component to the next within the system.

5.2.1 Process Subsystems

5.2.1.1 Degrees of Freedom and Information Flow Diagram

It is difficult to achieve the optimum design of a process system because, initially, there are nonspecified variables that adopt different combinations of values. Theoretically, only one of these combinations will lead to an optimum design.

When a design for every subsystem is required, the first task is to identify the free design variables (decision variables in process equipment design). The number of variables will represent the "degrees of freedom" in the subsystem or processing equipment. To identify design variables it is necessary to tabulate the variables of the mathematical subsystem model. A list of relationships among these variables along with corresponding equations is prepared. These constitute the design relationships of the subsystem, expressed as R information sources on subsystem design, related to X_j variables ($j = 1, 2, \ldots, V$). Design relationships must be independent of each other, so any relationship derived from another must be removed.

Cases deduced from the structure of a subsystem include

a) Contradictory, $R > V$
   R = number of design relationships
   V = number of variables
b) No degrees of freedom, $R = V$
c) Optimization possibilities, $R < V$

In cases a and b, there is no possibility of optimization since the subsystem is determined (an equal or a greater number of equations than unknowns exist). In case c, there are more unknowns than equations or design relationships. In this case, some variables do not have specified values and can adopt different values, thus offering different design possibilities. In this way, the optimization problem used to find the optimum design alternative develops.

Design relationships (for a subsystem with V variables) include

$$R_j\,(d_j,\ s_k) = 0 \text{ with } i = 1, 2, \ldots, R \tag{5.1}$$

where
R = number of design relationships
d_j = design variables
s_k = state variables

and

j = 1, 2, …, $L = V–R$
L = $V–R$ = degrees of freedom
k = 1, 2, …, R
V = number of state variables

The s_k state variables are obtained once the values of d_j design variables are fixed by means of the solution of R available design relationships.

Generally, the number of degrees of freedom in a subsystem will be the difference between the number of variables and the number of independent design relationships.

Example: Calculate the degrees of freedom of a heat exchanger with fluids circulating in a counter flow, as indicated in Figure 5.1.

In this heat exchanger design, 13 state variables must be handled:

1. k = type of exchanger (shell and tube exchanger, concentric tube exchanger, etc.)
2. Q = transferring heat
3. A = heat-transfer area
4. U = overall coefficient of heat transfer
5. W_1 = hot liquid mass flow rate, in 1, at inlet of the heat exchanger
6. W_2 = hot liquid mass flow rate, in 2
7. W_3 = cold liquid mass flow rate, in 3
8. W_4 = cold liquid mass flow rate, in 4

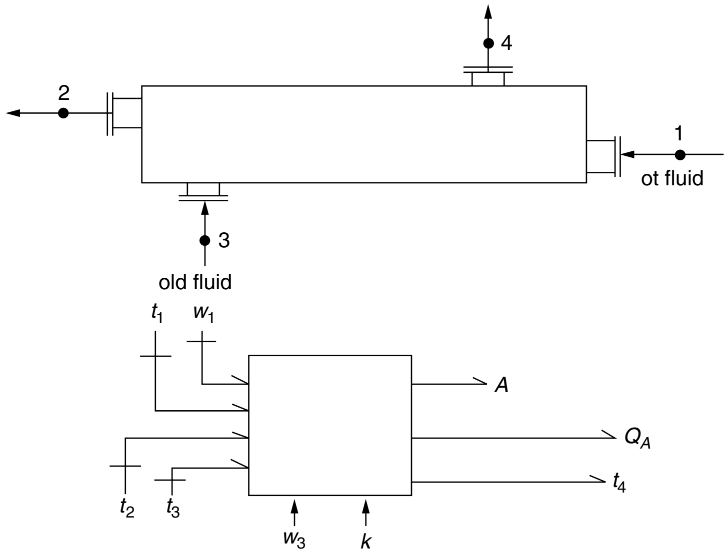

Figure 5.1 Data flowchart of a subsystem.

9. T_1 = hot fluid temperature, in 1
10. T_2 = hot fluid temperature, in 2
11. T_3 = cold fluid temperature, in 3
12. T_4 = cold fluid temperature, in 4
13. $(\Delta T)_{ml}$ = logarithmic-mean temperature difference between the heat exchanging fluids

$$V = 13$$

Design relationships that can be established between the 13 state variables:

1) $$Q = A \cdot U \cdot \left(\Delta T\right)_{ml} \tag{5.2}$$

2) $$\left(\Delta T\right)_{ml} = \frac{\left(T_1 - T_4\right) - \left(T_2 - T_3\right)}{\ln \dfrac{\left(T_1 - T_4\right)}{\left(T_2 - T_3\right)}}$$

3) $$W_1 = W_2$$

4) $$W_3 = W_4$$

5) $$Q = W_1 \cdot \hat{c}_{p1}\left(T_1 - T_2\right)$$

6) $$Q = W_3 \cdot \hat{c}_{p3}\left(T_4 - T_3\right)$$

7) $$U = U\,(W_1, \ldots, W_4, T_1, \ldots, T_4, k)$$

$$R = 7$$

The design relationship number 7 is empiric, indicating that the overall coefficient of heat exchange depends on the flow rates, temperatures, and physical state of the heat exchanging fluids, as well as the mechanical design of the heat exchanger.

The total degrees of freedom will be

$$L = V - R = 13 - 7 = 6 \tag{5.3}$$

If the heat exchanger is inserted into the food processing system as a subsystem with a technologically defined function, a number of degrees of freedom are consumed. For example, it is given that the exchanger must cool 2000 kg/h (W_1) of milk from a heating stage at T_1 = 90°C to T_2 = 40°C, using available cooling water at T_3 = 20°C. Thus, four of the six degrees of freedom are consumed.

The two design variables that remain, in this example the type of exchanger (k) and flow rate of cooling fluid (W_3), can be fitted by the engineer to achieve the optimum design. Once k and W_3 are fitted, the resulting equation system with an equal number of equations (design relationships) and unknown variables (state variables) can be solved.

Figure 5.1 shows a flow diagram of a heat exchanger in the example. The state variables specified, when considering the heat exchanger inserted into a process system (W_1, T_1, T_2, T_3), are indicated with crossed lines on corresponding arrows. Arrows with a complete head indicate design variables W_3 and k. Outlet arrows with incomplete heads represent the state variables deduced from design variables and design relationships.

5.2.1.2 Inversion of Information Flow

It has been proven that once the information flow diagram of a subsystem is established, reselection of the design variables may facilitate finding the solutions to different design relationships. These equations or design relationships cannot be solved simultaneously but in sequence.

Example: Calculate the extracting dissolvent flow rate and the type of dissolvent in a paprika oleoresin extracting installation (Figure 5.2a and Figure 5.2b) in order to maximize the following economic function:

Max [(extracted solute value) – (cost of extracting dissolvent)]

This can be expressed as follows:

$$Max\left[P_s \cdot Q_A\left(x_o - x_f\right) - c_d \cdot D\right] \qquad (5.4)$$
$$\left(d = A \text{ or } B\right)\left(D\right)$$

where

P_s = selling price of solute in extract phase (dollars/kg)
c_d = unit cost of extracting dissolvent (dollars/kg)
d = type of dissolvent, A or B (A = hexane; B = trichlorine-ethylene)
Q_A = feed flow rate to extractor; in this case, agglomerated paprika (kg/h)
x_o, x_f = initial and final solute concentration in agglomerated paprika
D = mass flow rate of dissolvent (kg/h)
y_f = solute concentration in extract phase

Design relationships will be

Solute balance (with y_f = solute concentration in the extract phase):

$$Q_A \cdot x_o = Q_A \cdot x_f + D \cdot y_f \qquad (5.5)$$

Equilibrium relationship between phases, depending on selected dissolvent (A or B):

$$f(x_f, y_f) = 0 \qquad (5.6)$$

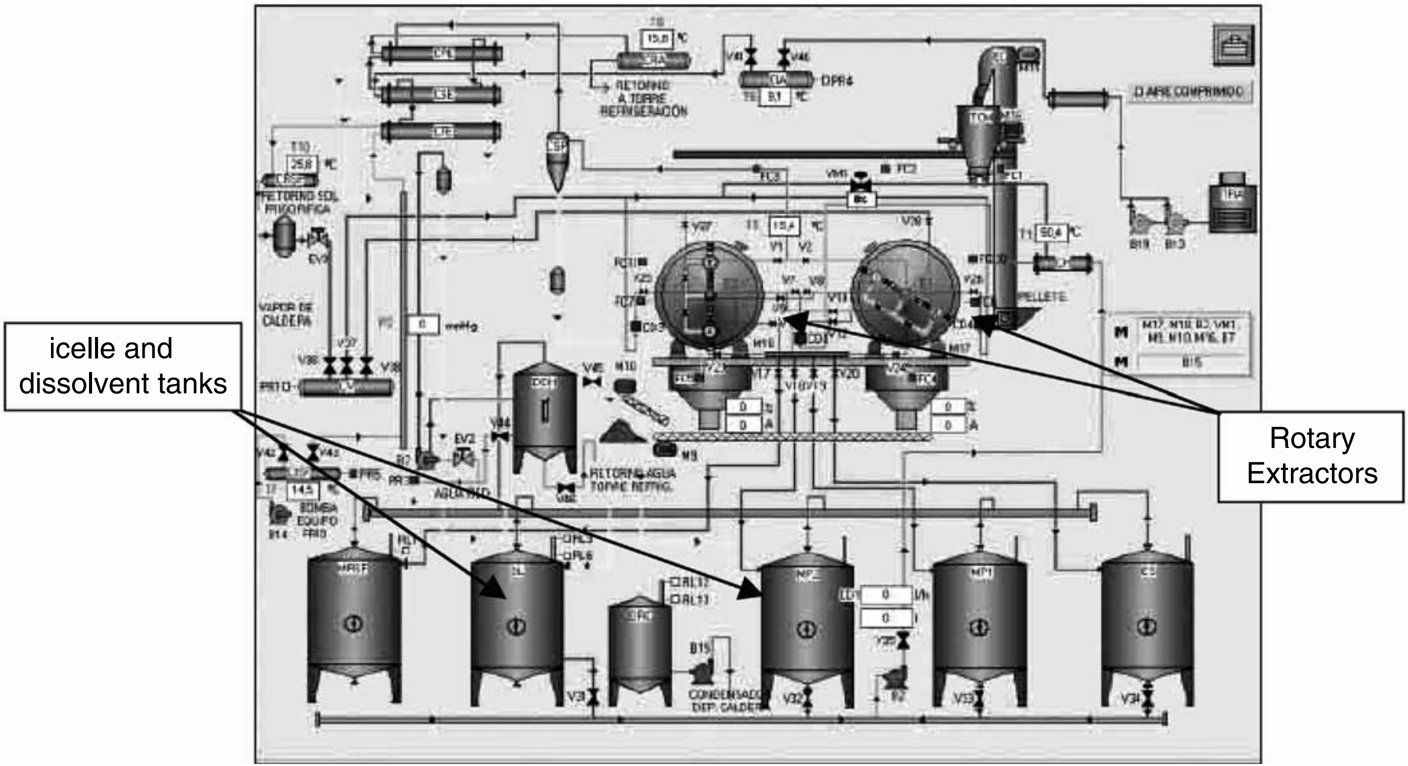

Figure 5.2a A paprika oleoresin-extracting installation, with two rotary extractors (courtesy of Indetec, S.L., www.grupovento.com).

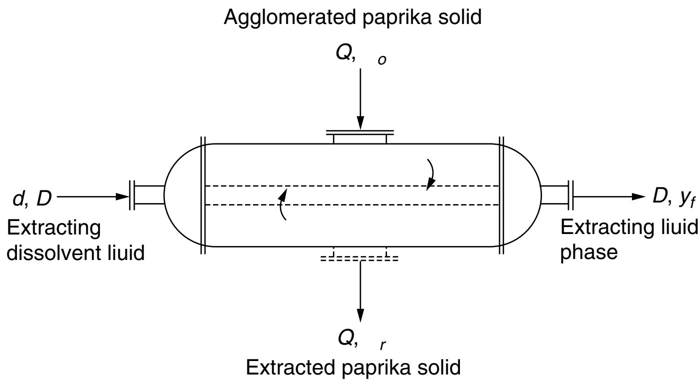

Figure 5.2b Flowchart of a paprika oleoresin rotary extractor.

where current Q_A (process capacity) and x_o (colorant matter content in the paprika) are specified.

There are six state variables (D, d, Q_A, x_o, x_f, y_f), two design relationships, and two specified variables (Q_A, x_o). Thus, degrees of freedom will be 6 – 2 – 2 = 2. So, if the type of dissolvent (A or B) and the value of the extracting dissolvent flow rate (D) are specified, the other variables can be calculated. In this case, if d and D are selected as design variables, both design relationships should be solved simultaneously to determine the other state variables. This selection of design variables makes the subsystem design difficult to solve, since the concentrations y_f and x_f (the equilibrium relation between phases) should be determined by means of an equation and a graphic relating the two variables.

If the concentration of solute x_f is chosen as a design variable instead of the extracting dissolvent flow rate, calculations are much simpler. The final concentration in the extract phase y_f can be determined first by means of the equilibrium diagram. The dissolvent flow rate D can then be directly solved from the corresponding mass balance.

Thus, it has been proven that inverting the information flow can simplify calculations, avoiding the simultaneous solutions of some design relationships.

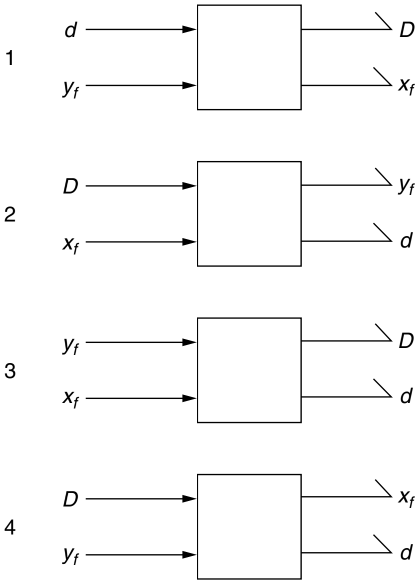

Figure 5.3 Other possibilities of the data flowchart.

Other possibilities of information flow diagrams or design variable selections are presented in Figure 5.3.

Case number one in Figure 5.3 facilitates calculations of the other state variable. However, cases two, three, and four would not be possible, because if the dissolvent type is not specified for each combination of design variables, two values of the remaining variables will be obtained, a situation that fails to solve the problem.

Consequently, a practical rule can be deduced: When a state variable is discrete and noncontinuous, it is appealing to select it as a design variable (for instance, type of heat exchanger, type of dissolvent, etc.).

5.2.1.3 Algorithms for Selecting Design Variables

When subsystems are simple, the degrees of freedom can be calculated by analyzing the structure of the information flow. Here, selecting the most suitable design variables for the solution of the subsystem becomes very straightforward. On

Table 5.1 Structural Distribution of a Heat Exchanger

		Initial state variables												
		K	Q	A	U	W_1	W_2	W_3	W_4	T_1	T_2	T_3	T_4	$(\Delta T)_{ml}$
Design relationships	1		X	X	X									X
	2									X	X	X	X	X
	3					X	X							
	4							X	X					
	5		X			X				X	X			
	6		X					X				X	X	
	7	X			X	X	X	X	X	X	X	X		

the contrary, when the subsystem presents a complex structure with many state variables and design relationships, it is more difficult to select the most suitable design variables (decision variables). The use of selection algorithms is interesting, as illustrated in the following example.

Example: Consider the heat exchanger analyzed in the above example (with fluids circulating at counter flow). The most suitable design variables that will make the heat exchanger design simpler are found as follows.

First, a table showing the structure of corresponding equations or design relationships must be prepared. This table establishes a structural arrangement. The state variables are presented in columns and the design relationships are shown in rows (Table 5.1).

Each state variable is related to the corresponding design relationship, indicated by an X at the cross point of the column and the row, as shown in Table 5.1.

Note that the variables whose values will be defined by process technology are circled. The specified variables are

$$W_1 = 2.000 \text{ kg/h};\ T_1 = 90°\text{C};\ T_2 = 40°\text{C};\ T_3 = 20°\text{C}$$

The variable k (type of heat exchanger) has also been selected as a design variable because of its discrete variability. In Table 5.1, it is in a square.

Table 5.2 Removal Order of the State Variables

Removal order of the state variables	State variable	Design relationship	DR number
1	A	$Q = AU\,(\Delta T)_{ml}$	1
2	U	$U = U\,(W_1, \ldots, W_4; T_1, T_4; k)$	7
3	$(\Delta T)_{ml}$	$(\Delta T)_{ml} = \dfrac{(T_1 - T_4) - (T_2 - T_3)}{In\,\dfrac{T_1 - T_4}{T_2 - T_3}}$	2
4	W_2	$W_1 = W_2$	3
5	T_4	$Q = W_3\,C_{p3}\,(T_4 - T_3)$	6
6	Q	$Q = W_1\,C_{p1}\,(T_1 - T_2)$	5
7	W_4	$W_3 = W_4$	4

Second, the algorithm to select the design variables is applied, determining the variable that will consume the only degree of freedom remaining in this problem. Here are the steps to follow:

a) Column containing only one X is found, and both the state variable and corresponding design relationship are crossed out.
b) Above stage is repeated until all design relationships have been removed.

By applying stages a) and b) repeatedly, not taking into account the specified variables, we arrive at a situation where only a few variables are not crossed out. These are the design variables. In the example, only W_3 remains.

The design relationships have been crossed out in the following sequence, presented in Table 5.2.

The order of successive evaluations of design relationships will be the inverse of that following their removal. In other words, relation number 4 is solved first, followed by 5, 6, 3, 2, 7, and 1. This order of priority in the successive resolution of the equations or design relationships can be expressed as shown in Figure 5.4, where the direction of the arrows shows the next equation to solve. The direction of the data flow through the different equations is indicated.

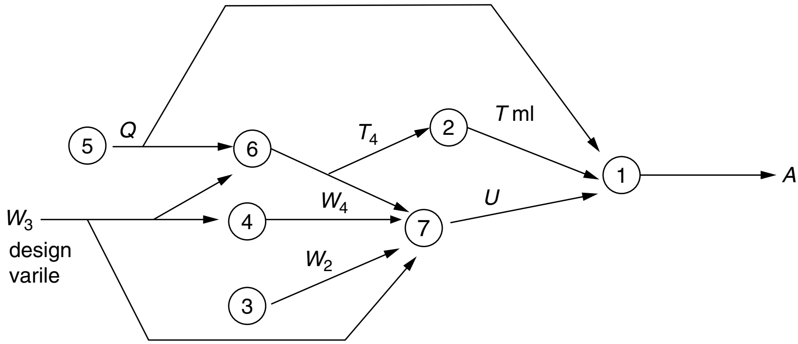

Figure 5.4 Order of priority in the successive resolution of equations.

In this manner, there is no need to solve the equations simultaneously. If after applying the algorithm some design relationships are not crossed out, these equations should be solved simultaneously. Selection of design variables should be completed with the knowledge of the degrees of freedom remaining in the subsystem, among the variables not crossed out.

The solution of the heat exchanger in the example shows that selecting the heat exchange area A as a design variable would not be appropriate, since calculations could be complicated due to the necessity of solving several design relationships simultaneously.

5.2.2 Process Systems

5.2.2.1 Information Flow through Subsystems

In previous sections, the process system was defined as a set of process units or pieces of equipment regularly interacting with one another. It seems logical that insertion of a subsystem into a system information flow structure would alter it. In other words, the degrees of freedom in the subsystem may vary.

Example: Evaluate the information flow through a given extraction system of paprika oleoresin (Figure 5.2a). This system operates as follows. Once the raw material is prepared (convenient agglomeration of paprika), it is introduced into a rotary extractor. This equipment is provided with all the necessary elements for raw materials collection, the addition of pure dissolvent, evaporation of residual dissolvent, and drying of any remaining extracted powder (for use as organic fertilizer or fodder). In this way, the extractor will also carry out the function of blending the dissolvent with the powder solid.

When equilibrium in the mixture is achieved, separation of the powder solid (refined phase) and extracting liquid dissolvent (solute with high content of colorant matter) is carried out. This is done by means of filters fitted inside the extractor.

For this example, it can be assumed that the extractor works at room temperature and requires extracting dissolvent (hexane or any other authorized organic dissolvent) at that temperature.

Next, the obtained mixture (dissolvent + solute) is introduced into the separating equipment by distillation, where the dissolvent is recovered, condensed, and cooled to room temperature. In this way, paprika oleoresin is obtained, which is a viscose, oil-like paprika liquid extract with an intense red color and the flavor of paprika.

Once the dissolvent cools up to 25°C, it is circulated toward the horizontal rotary extractor. There will be additional dissolvent to supply any losses during the process. In studying the structure of information flow, it can be assumed that it is carried out with only one dissolvent, for example, hexane.

In the paprika oleoresin extracting system with hexane there are four subsystems (Figure 5.5).

For every subsystem, there will be an information flow like that shown in Figure 5.5a.

5.2.2.1b *Distillation Equipment Variables*

- Mass flow rate of each component, temperature, pressure, and enthalpy of feed mixture; $C + 3 = 2 + 3 = 5$.
- Mass flow rate of each component and enthalpy of the vapor $= C + 1 = 2 + 1 = 3$.

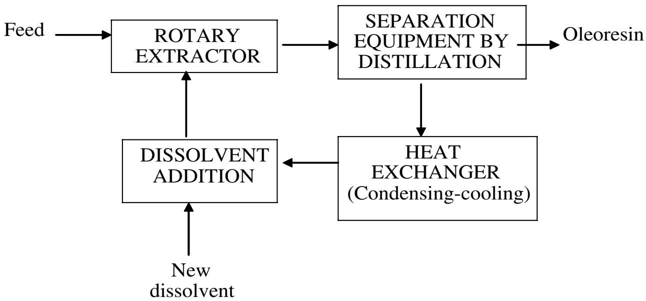

Figure 5.5 Subsystems in a paprika oleoresin extraction system.

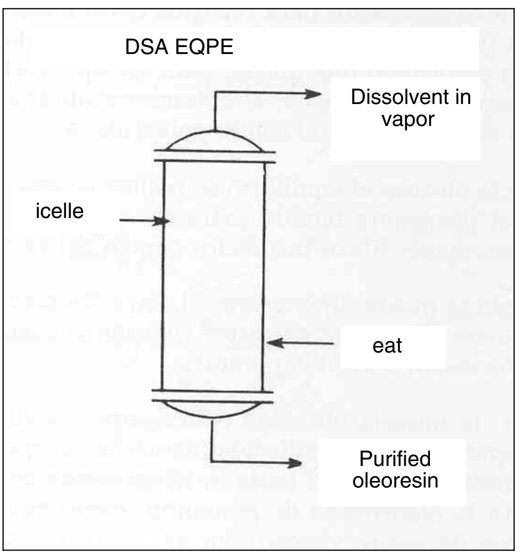

Figure 5.5a Distillation equipment.

- Mass flow rate of each component and enthalpy of oleoresin = $C + 1 = 2 + 1 = 3$.
- Distillation equipment: temperature, pressure, and hourly heat rate = 3.

TOTAL = 14

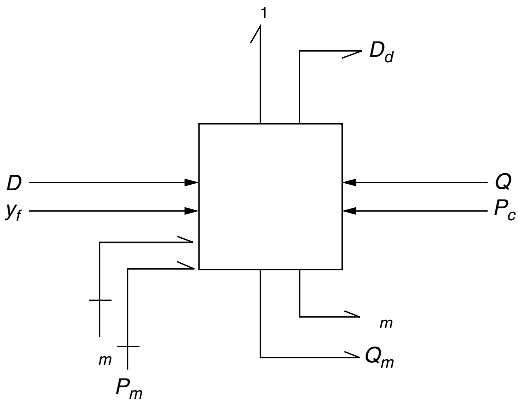

Figure 5.5b Flow diagram or data flowchart of distillation equipment.

Design Relationships

- If the temperature, pressure, and composition of any stream are known, their enthalpy can be calculated by thermodynamic methods. There is a design relationship for each one of the streams; 3
- For a given temperature and pressure, composition of the vapor and liquid for every component inside the distillation equipment can be calculated; that is, there is an equilibrium relationship between the vapor and liquid phases for each component; 2
- Mass balance of distillation equipment for every component; 2
- Energy balance of distillation equipment; 1

TOTAL = 8

Total degrees of freedom = 14 – 8 = 6

Usually, the mass flow of every component (2, dissolvent and solute) as well as the temperature and pressure of the mixture (2) are known, or can be determined by the extractor. Thus, only two degrees of freedom remain.

The distillation pressure and the intensity of additional heat can be modified. In addition, these parameters will be treated as design variables until the optimum economical

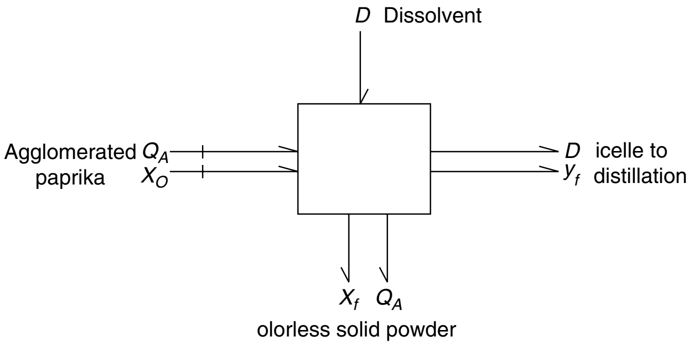

Figure 5.5c Flow data for the extractor.

separation of the components is achieved. The resulting information flow diagram appears in Figure 5.5b, where

D = mass flow rate of dissolvent + solute of mixture
y_f = solute concentration
T_m = temperature at inlet
P_m = pressure at inlet
T_1 = outlet temperature of vapor dissolvent
D_d = vapor dissolvent mass flow rate to condenser
x_m = oleoresin concentration in mixture at outlet
Q_m = purified oleoresin mass flow rate
P_c = pressure inside distillation boiler

Extractor

In analyzing the information flow structure of the extractor, two degrees of freedom are obtained. If the type of dissolvent is specified (e.g., hexane), one degree of freedom will remain, as indicated in Figure 5.5.c.

Addition Point of Dissolvent

There will be three variables and one design relationship (corresponding to the mass balance). Two degrees of freedom will remain (see Figure 5.5d), where D_p is the dissolvent mass flow rate added to the system to supply losses during the process.

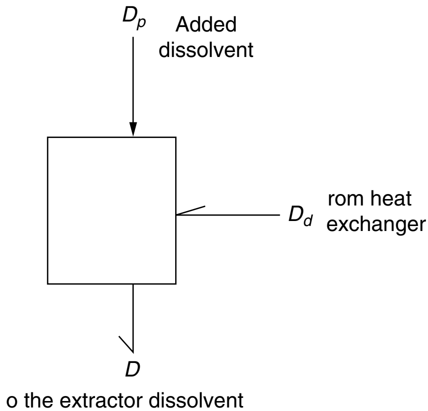

Figure 5.5d Flow data for the dissolvent addition point.

In principle, D_p is selected as a design variable.

Heat Exchanger

In the beginning, there were 13 variables and 7 design relationships, so there were 6 degrees of freedom. When the temperature of the refrigerant (T_3 = 20°C), as well as the temperature of the outlet dissolvent (T_2 = 30°C), are specified, however, there are only 4 degrees of freedom left. In principle, the type of exchanger k and the refrigerant flow W_3 are fixed as design variables, with the result shown in Figure 5.5e.

Finally, one local degree of freedom in the extractor, four local degrees of freedom in the distillation equipment, four local degrees of freedom in the heat exchanger, and two local degrees of freedom at the point of dissolvent addition have been obtained. Gathering and connecting all the information flow diagrams for every component results in an information flow diagram for the whole system, as shown in Figure 5.6.

Figure 5.6 demonstrates that the connections between the different elements are made by unspecified variables. The heat exchanger is not included in the recycling loop because its function will only be to condense and ensure a given temperature for the dissolvent.

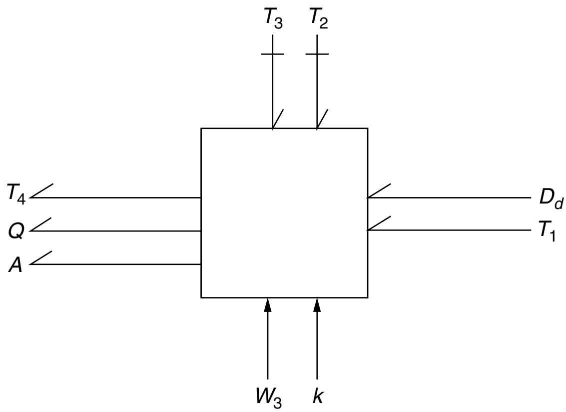

Figure 5.5e Flow data for the heat exchanger.

When the subsystems are connected to the process, the degrees of freedom are consumed and only 5 degrees of freedom remain, as can be seen in Figure 5.6. The sum of degrees of freedom was 11 in the beginning, so 6 degrees of freedom have been consumed.

Generally, the number of degrees of freedom for a system is equal to the sum of local degrees of freedom of L_i components minus the number of connections, or connection relationships, which are needed to arrange the whole system.

$$L_s = \sum_{i01}^{n} L_i \tag{5.7}$$

where
L_s = degrees of freedom of a system with n components
L_i = local degrees of freedom for each component
n_c = number of connections, or connection relationships

5.2.2.2 Inversion of Information Flow

In Figure 5.6, D_p, Q, P_c, W_3, and k are indicated as design variables, but other variables could be chosen in order to ease

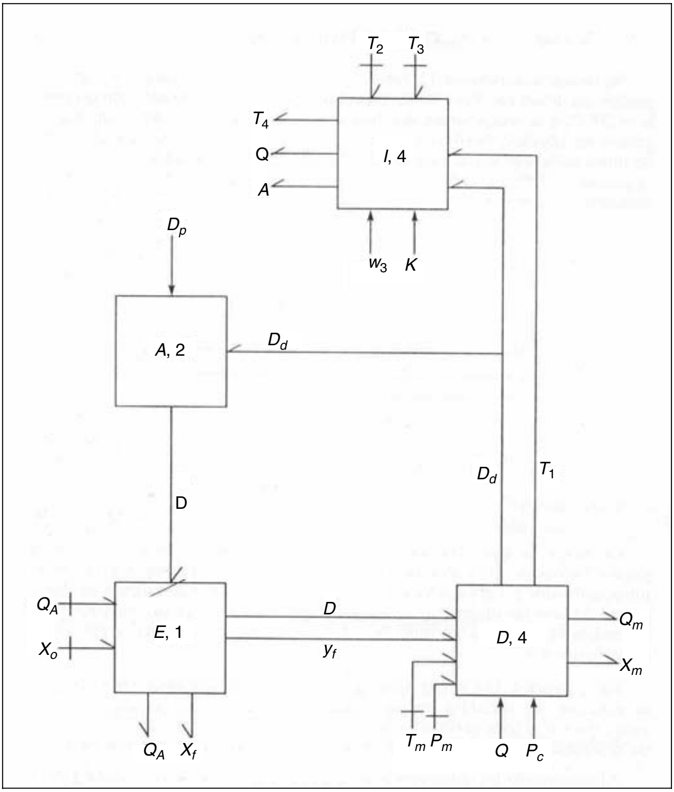

Figure 5.6 Flow data for a paprika oleoresin extraction system using hexane.

the resolution of the system with those characteristics. In a manner similar to Section 5.2.1.2, the information flow of the system can be inverted to design the system in a simpler form. For instance, in the paprika oleoresin extracting system, information about the variation in amount of pure dissolvent added to the recycled stream passes through the extractor, the distillation equipment, and the heat exchanger, and even returns to the point of variation. With this closed flow of information in the system design, all implicated subsystems must be solved simultaneously.

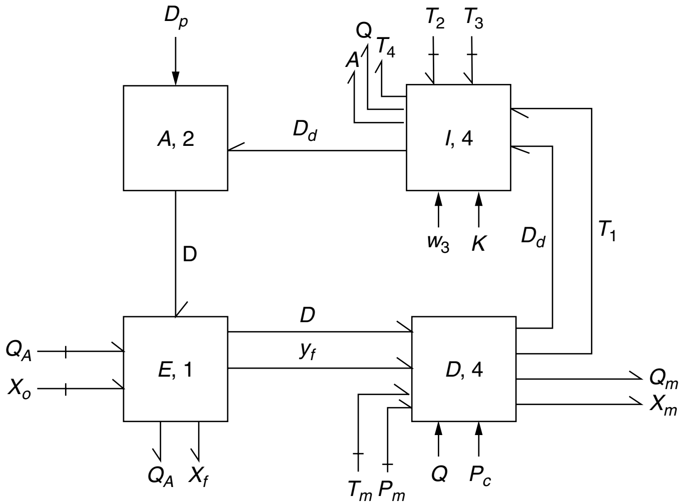

Figure 5.6a Initial data flowchart.

5.2.2.3 Algorithm for Selecting Design Variables

Fortunately, there are also less-complicated methods used to select the design variables of a system, beginning with different situations that depend on the information flow diagram of every subsystem.

As seen in the above example, a reselection of design variables (or decision variables) can modify a particular structure of information flow, avoiding iterative and complicated calculations in the resolution of a possible recycling loop.

The algorithm of design variable selection for a system will be described considering the above example (Figure 5.6) and using Figures 5.6a through 5.6f.

Design variables will be drawn, as explained above, by means of arrows with a complete head. State variables and specified variables will be represented as in the above information flow diagrams. In each subsystem, the incoming arrows indicate the entrance of information, while the exit arrows represent information obtained from entering state variables and design variables (determined by the engineer) through the corresponding design relationships.

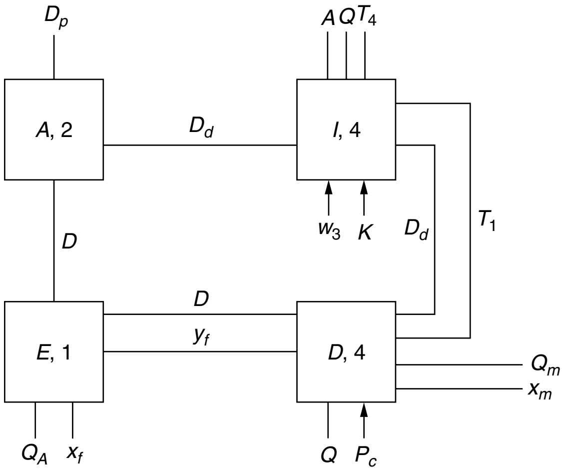

Figure 5.6b Removing specified variables and arrowheads.

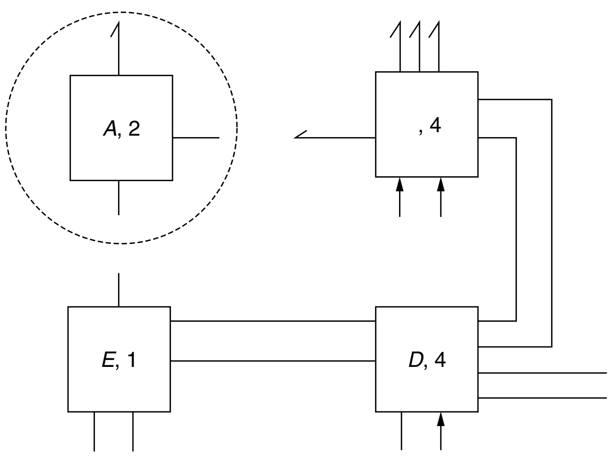

Figure 5.6c Assignment of exit arrows to variables of subsystem A. Removing the subsystem.

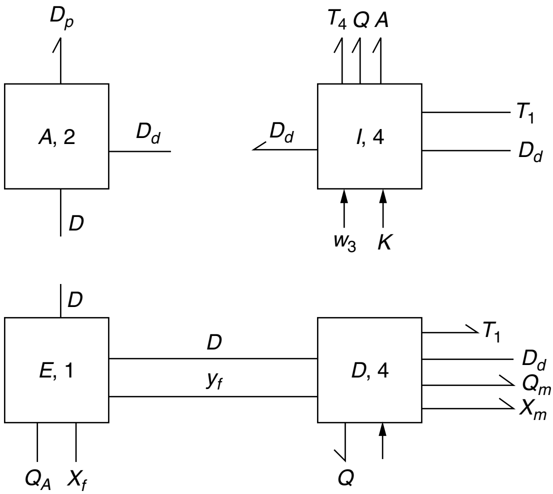

Figure 5.6d Assignment of exit arrows to variables of subsystem I. Removing the subsystem.

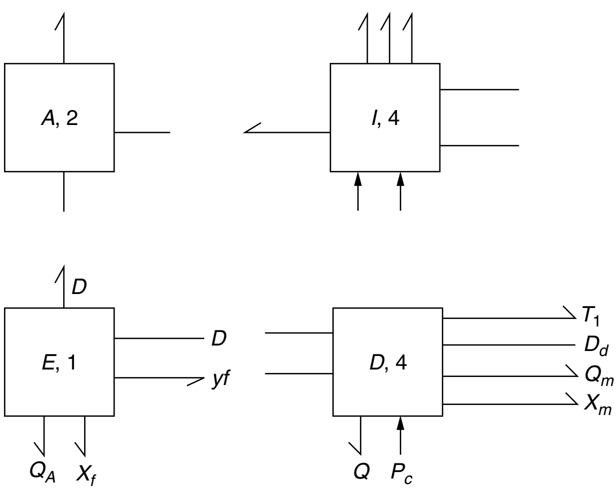

Figure 5.6e Assignment of exit arrows to variables of subsystems E and D.

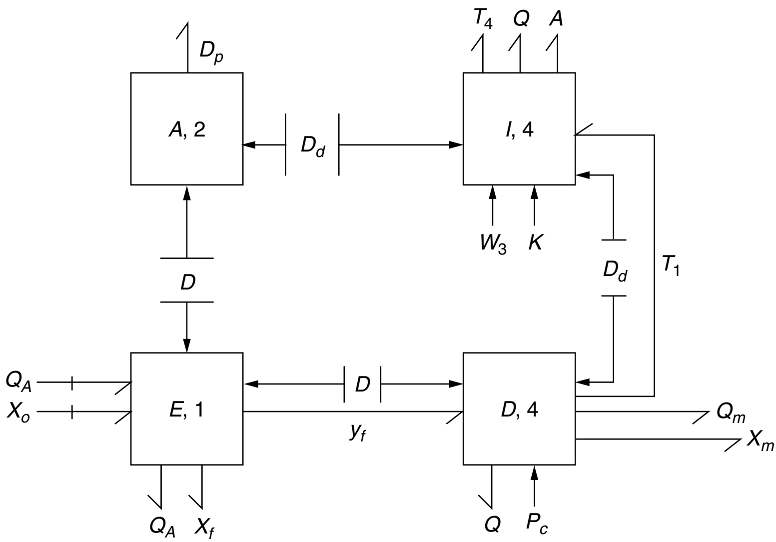

Figure 5.6f Final data flowchart.

Generally, the number of arrows entering a subsystem must be equal to the subsystem degrees of freedom, which are invariable during the application of the algorithm.

To determine every subsystem within an information flow diagram, like the one shown in Figure 5.6a, all subsystems involved in the recycling loop must be taken into account simultaneously in the calculations. This can become even more complicated when there are several simultaneous loops.

Application of the next algorithm avoids these recycling loops through an appropriate reselection of design variables. There are three steps:

1. Record the local degrees of freedom in the block for every component or subsystem and remove all arrowheads in the initial information flow diagram (Figure 5.6b).
2. Assign exit arrows to variables that do not connect components in the system. This assignment is repeated in each subsystem until the number of unassigned

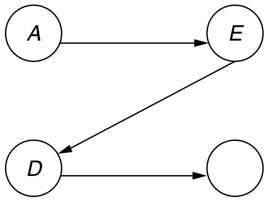

Figure 5.7 Solution order in subsystems.

variables is equal to the local degrees of freedom. This subsystem is then removed from the diagram (Figures 5.6c, 5.6d, and 5.6e).

3. Repeat step 2 in the reduced diagrams until it is no longer possible to remove any more subsystems. Using this method, the system design variables are obtained. These design variables correspond with the above-unassigned variables if there is no more information about them from another element or solved subsystem (Figure 5.6f).

Ordinarily, the application of this algorithm permits choosing the direction of the information flow among several possible alternatives. In this manner, the design engineer is able to assign flow directions according to personal preference criteria. Often several sets of design variables avoid recycling loops.

The algorithm application results in an information flow diagram like the one shown in Figure 5.6f. From this diagram, an order of precedence is easily deduced in solving the different subsystems. It can be expressed graphically, as shown in Figure 5.7 (given the values of D, D_d, W_3, k, and P_c).

Figure 5.6f shows a new information flow diagram for the system, indicating a reselection of design variables. It is easy to see that this new design variable selection leads to a situation where the units can be evaluated without taking into account the recycling flow, in the following order: (1) extractor; (2) addition block or reposition of dissolvent; (3) distillation equipment; (4) heat exchanger.

5.3 ALTERNATIVE ANALYSIS BY MEANS OF SIMULATION

When the different alternatives for the configuration of a food processing system are known, it is usually possible to build a corresponding mathematical or behavior model for each configuration alternative (see Section 2.6 of Chapter 2). In this model, we find numerous variables and the corresponding relationships between them: the equations or design relationships. In this manner, to solve a behavior model having more variables than equations, it is necessary to give values to the excess variables (the decision or design variables) to obtain the remaining variables (state variables) appearing in the model. Therefore, we can find the results for an alternative food processing system with a specific physical design operating in a particular way.

In previous sections, the information flow through process subsystems and the importance of correctly selecting the design variables are analyzed. This analysis has served as an exercise to understand the procedure and the methodology in food processing system simulation using a particular mathematical model.

The simulation algorithm (using specific computer software) determines information or data flow through a set of equations or relationships to explain system behavior, for example, the simulation algorithm of a drying operation in Chapter 2, Section 2.4.3.

To begin simulation of a unit operation with identified equipment, it is necessary to assign values to a set of variables that define the physical design and running conditions of the process equipment. These are the engineer's design or decision variables.

Whenever a simulation is running, an alternative analysis is done. If equipment running conditions change without altering the physical design, the alternative food processing system will change instead. Thus, there are various technological alternatives (altering operating conditions) and engineering alternatives (altering physical design, like size or type of process equipment) involved in processing a particular food.

It is important to note the changes that occur in the mathematical model with different types of equipment. For example, when using the continuous belt dryer and the rotary dryer (two engineering alternatives) to dry a food product, the mathematical or behavior models of the process will be different for each dryer.

Thus, to analyze different alternatives by means of simulation, the corresponding mathematical models for the various types of process equipment are needed.

5.4 DESIGN ECONOMIC CRITERIA

Through appropriate handling of information on raw materials, a series of possible technological and engineering alternatives for the processing system/processing line can be established for food products, process technology, process engineering, and auxiliary systems.

These alternatives must be analyzed both technically (per the above procedures) and economically, in order to select the process system corresponding to the optimum alternative. Therefore, appropriate economic criteria must be used.

Economic design criteria consist of any method commonly used in investment analysis or investment projects in the business field. Many books provide study of the different methods of investment analysis and alternatives (Romero, 1980; Peters and Timmerhaus, 1991). It is common to distinguish between static and dynamic analysis methods by considering the effect of money depreciation or appreciation, based on the particular moment in time.

5.4.1 Static Criteria

Groups of static criteria considered are (Tarrago, 1978):

1. Comparison of costs
2. Comparison of profits
3. Comparison of investment payback time

Criteria based on the comparison of costs involve (a) the mean annual total costs and (b) the unit cost. Total costs are calculated as the sum of the operating cost and amortization cost. Unit cost is determined by dividing the total cost by the volume of production. With these criteria, it is possible to determine the preferable alternative when money entries (from product sales) remain invariable with the independence of the considered process alternative.

Calculation of mean annual total costs:

$$C_{Tm} = \frac{\sum_{i=1}^{n} E_i}{n} + \frac{I_0\left(1 + n \cdot i\right)}{n} \tag{5.8}$$

where
C_{Tm} = mean annual total costs
E_i = running costs in year i
I_0 = initial investment
i = interest; $(I_0 \cdot i)$ is the interest to be paid in year i to make investment possible
n = estimated investment lifetime (in years)

Calculation of unit cost:

$$C_u = \frac{C_{Tm}}{V} \tag{5.9}$$

where
C_u = unit cost
V = mean annual production volume

Methods based on the evaluation and comparison of profits use the relationship between the foreseen profit and the financial capital necessary to obtain it as economic criteria. The most logical solution is to consider the mean profit and the net financial capital.

Calculation of mean annual profit:

$$B = \frac{\sum_{i=1}^{n} B_i}{n} \tag{5.10}$$

where
B_i = estimated profit in year i
n = lifetime of the investment

On the other hand, the financial capital is not constant and equal to the initial capital (I_0), but decreases as capital is recovered by means of amortization. As there is a residual value for the investment (I_R, the residual value of equipment, installations, tanks, buildings, etc., at end of investment lifetime), then the mean net financial capital (I_N) is evaluated by

$$\frac{I_0 - I_R}{2} = I_N \tag{5.11}$$

From the above expressions, it is deduced that

$$R = \frac{B}{I_N} \tag{5.12}$$

where R is profitability of the corresponding alternative, per unit.

Another way to evaluate profitability is to divide the foreseen mean annual profit by the initial investment I_0, or by the net financial capital ($I_0 - I_R$). This method offers a more closed approach to the concept of internal rent.

Another static economic criterion analyzes the payback period: time required by the company to recover the financial capital or investment corresponding to the investment project by means of the rent from the project. In principle, the alternatives with shorter payback periods are more appealing. This method calculates the cash flow of each year (difference between entries and payments, including taxes, but not considering amortization because it does not represent payment) and the cumulative cash flow of anterior years. In this manner, it is possible to perceive the moment at which the surplus equals the initial required investment for the corresponding alternative.

5.4.2 Dynamic Criteria

The most commonly used dynamic criteria for profitability evaluation include:

1. Net present worth
2. Net present worth/initial investment ratio or rate of return on investment

3. Pay out or payback period
4. Internal rent share

5.4.2.1 Net Present Worth

If asked whether they would rather have a dollar bill in the present than in the future, an economically aware person would probably choose the former. This is because the dollar today may not hold the same value as tomorrow. Its value will likely be of less magnitude; thus it is not valid to make sums with present-day dollars. The homogenization factor is the type of interest used to compute the value of money today. The present worth (or present value) of a future amount is the present principal plus interest, after it has been deposited at a fixed interest rate to yield a desired amount at some future date. In Equation 5.13, C represents the amount available after n interest periods if the initial principal is PV and the discrete compound-interest rate is i:

$$C = PV\left(1+i\right)^{n} \tag{5.13}$$

Therefore, the present worth can be determined by rearranging Equation 5.13 as follows:

$$PV = \frac{C}{\left(1+i\right)^{n}} \tag{5.14}$$

The factor $1/(1+i)^n$ is commonly referred to as the *discrete single-payment present-worth factor* (Peters and Timmerhaus, 1991).

The net present worth measures the expected global profit or net return on a given process system alternative. Calculations consist of actualizing all payments and recoveries in the project, and adding these amounts together. This way the net present worth (NPW) for this particular alternative is obtained. If it is positive for the chosen type of interest, the alternative becomes economically feasible.

The NPW is obtained as follows:

$$\text{NPW} = \frac{R_1}{(1+i)} + \frac{R_2}{(1+i)^2} + \ldots + \frac{R_n}{(1+i)^n} - I_0 \tag{5.15}$$

or

$$\text{NPW} = \sum_{j=1}^{n} \frac{R_j}{(1+i)^j} - I_0 \tag{5.16}$$

where
R_j = cash flow (difference between recoveries or entries and payments) in year i
I_0 = payment of the initial investment

5.4.2.2 Net Present Worth/Initial Investment Ratio

To obtain a ratio about relative profitability, divide the NPW generated by the alternative by the payment of the initial investment, as follows:

$$Q = \frac{\text{NPW}}{I_0} \tag{5.17}$$

In the case of fractional payment of the investment:

$$Q = \frac{\text{NPW}}{\sum_{j=0}^{m} \frac{I_j}{(1+i)^j}} \tag{5.18}$$

where
Q = profit/investment ratio
m = years of fractional payment of investment
I_j = payment fraction of initial investment in year j

5.4.2.3 Payback Period

The payback period is the number of years that have passed since the start-up of the food plant (in project), until the total sum of actualized recoveries equals the sum of actualized payments. In other words, the payout indicates the moment at which the NPW of the investment is zero.

The payback period evaluation consists in accumulating the actualized cash flow, year by year.

5.4.2.4 Internal Rent Share

It is also interesting to know the equivalent interest type that the investor would hypothetically recover during the life of the project if I_0 were considered as a loan to the process system alternative project.

This type of interest indicates the efficiency of the investment for the investor. If this interest is called r and there is no fractional payment of initial investment, it can be evaluated by

$$I_0 = \sum_{j=1}^{n} \frac{R_j}{\left(1+r\right)^j} \tag{5.19}$$

where r is the internal rent share.

It can be proven that the value of r in the above expression makes the NPW zero because:

$$\text{NPW} = \sum_{j=1}^{n} \frac{R_j}{\left(1+r\right)^j} - I_0 \tag{5.20}$$

Therefore, the type of interest t marks the limits of the viability zone for the investment. It is known that an investment alternative is noteworthy when r is greater than i. The value of i represents the current type of interest in the money market for industrial investments.

If the initial investment payment is fractionated during the first years of the investment lifetime, the previous expression is given by

$$\sum_{j=0}^{m} \frac{I_j}{\left(1+r\right)^t} = \sum_{j=1}^{n} \frac{R_j}{\left(1+r\right)^j} \tag{5.21}$$

5.5 COST ESTIMATION

The different criteria involved in the analysis of alternatives use parameters such as initial investment, costs-payments, and entries-recoveries, which must be determined.

5.5.1 Initial or Capital Investment Estimation

5.5.1.1 Cost Estimation of Food Processing Equipment

In principle, any alternative that solves the process system design should be detailed enough to list the equipment (subsystems), forming part of the corresponding process system. This is the list used to estimate the capital investment needed for the process system equipment.

This list must indicate the process equipment's work capacity and size. Generally, the auxiliary system components, such as pumps and screw conveyors, are not included. Sometimes the process equipment incorporates parts of the auxiliary systems, which are difficult to separate, like control systems, pumps, and feed systems. It is not customary to differentiate between these auxiliary systems in the budget of process equipment offered by commercial sources.

The capital investment needed for the process system will be easily determined if offers of both normalized and specialized design equipment are available from commercial companies.

Normalized design equipment has a patented design. It is common to find the technical specifications of different models in the corresponding trade bulletins, and prices can sometimes appear in special lists. In most cases, however, it is necessary to consult the manufacturers or distributors of normalized equipment. Examples of this type of equipment are the orange juice extractor, packaging machine, and plate filter.

Specially designed equipment is not available in stock. The equipment must be designed and manufactured for a food factory on a case-by-case basis. In turn, the manufacturer must be consulted regarding any corresponding cost, using drawings supplied by the design engineer (serving the equipment supplier or food factory company). In a relatively short time, the equipment manufacturer will offer a budget.

In some cases, it is possible to use empirical correlations to determine the acquisition cost for process equipment. In one method, Williams (1971) states that for some equipment the following is true:

$$I = a \cdot q^b \tag{5.22}$$

where

I = capital investment for a given piece of equipment
a, b = constants
q = main constructive characteristic of equipment, such as volume, surface, thermal or electric power, work capacity

In other words, for two similar types (equipment similar in form and construction material):

$$I_1 = a \cdot q_1^b \qquad \text{and} \qquad I_2 = a \cdot q_2^b \tag{5.23}$$

From these equations, it follows that

$$I_2 = I_1 \left(\frac{q_2}{q_1} \right)^b \tag{5.24}$$

In this manner, by knowing the equipment's value I_1 with a main constructive characteristic q_1, it is easy to evaluate the capital investment I_2 for similar equipment with a main constructive characteristic q_2.

The variation intervals of exponent b have been established for different types of process equipment in chemical engineering (Peters and Timmerhaus, 1991). According to Vian (1979) and Rudd and Watson (1976), for example, there are tables with values for b based on the type of equipment. In any case, a ratio of q_2/q_1 equaling less than 10 is recommended in order to obtain a result for I_2 with certain reliability. The value of costs I_2 may appear in tables as free on board cost (FOB) or cost at origin (point of manufacture) without the inclusion of transport cost. What is desired, however, is

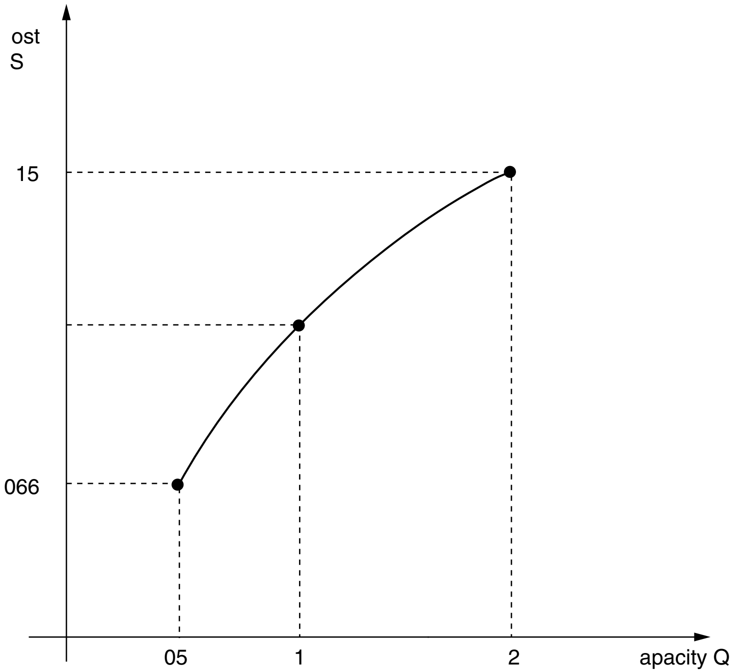

Figure 5.8 Relationship between process equipment cost and work capacity (adapted from Bartholomai, 1987).

the conversion of these costs into a real base, adding the equipment transport cost from the origin to the food factory (CIF destination cost), as well as the corresponding taxes and construction cost.

According to Bartholomai (1987), in the food industry it is customary to find a relationship between the capital investment I of a given process equipment and its capacity (kg/h or L/h). The plot of capacity versus equipment cost should be as shown in Figure 5.8. It can be observed that if normal capacity is doubled, the cost must be multiplied by 1.5, whereas if the work capacity is reduced to half, the cost is $0.66 \cdot I$, where I is the capital investment for normal capacity.

In this section, it is essential to mention the *factorial estimation method* used in chemical engineering for preliminary studies, in order to estimate the capital investment for a food processing plant (Peters and Timmerhaus, 1991). With this method, the capital investment for the plant, including project cost, contractor fee, construction, auxiliary systems, and necessary buildings, can be evaluated by means of the corresponding capital investment of the main elements in the process system.

In the chemical industry, it has been observed that the cost of other items needed to complete the process plant can be related to the required capital for the main process plant elements:

$$I_P = \left[I_E + \left(\sum_{i=1}^{k} f_i \cdot I_E \right) \right] \cdot f_I \tag{5.25}$$

where

I_p = capital investment for entire process plant
I_E = capital investment for process equipment
f_i = multiplying factors for auxiliary systems and buildings investments, always less than 1
f_I = multiplying factor for evaluation of indirect cost, mainly engineer and contractor fees

Peters and Timmerhaus (1991) also provide tables that show values of f_i and f_I for different types of chemical plants. However, there are no satisfactory similar coefficients for the food industry. As a reference, the coefficients f_i and f_I deduced from Bartholomai (1987) can be used; f_i and f_I may depend on the size of the process plant, further complicating the estimation.

The coefficient f_i that determines the necessary capital investment in auxiliary systems differs depending on food plant type (whether it mainly handles liquids, solids, or both).

Example: For food processing plants, the coefficients f_i can be obtained from the estimated cost of a recently installed plant by analyzing the different items involved in its budget. For example, according to the data offered by Bartholomai (1987) in reference to an apple processing plant:

Erected process equipment costs (I_E)	\$1,966,500
	f_i
Piping components	0.02
Solid materials transport system	0.02
Steam generation system	0.012
Water cooling system (cooling tower)	0.0025
Control system	0.0025
Quality control laboratory equipment	0.0010
Electrical substation	0.028
Water treatment system	0.0025
$\sum_i f_i =$	0.0885
Un-erected process equipment (I'_E)	\$1,911,500
Additional direct cost as a fraction of I'_E :	f'_i
Process equipment erection	0.028
Fire protection	0.013
Power wiring and control wiring	0.02
Piping installation	0.02
Civil works, buildings	0.325
$\sum_i f'_i =$	0.406
Indirect cost as a fraction of I'_E :	f''_i
Process equipment layout drawings	0.0026
Mechanical/electrical wiring, drawings, and specifications	0.026
Civil engineering	0.0156
Construction management	0.010
Project management	0.010
Start up and operation training services	0.005
$\sum_i f''_i =$	0.0692

In this case, the multiplying factor f_I can be calculated as

$$f_I = 1 + \sum_i f_i'' = 1.0692 \tag{5.26}$$

Then,

$$I_P = I_E + \sum_i f_i \cdot I_E + \sum_i f_i' \cdot I_E' + \sum_i f_i'' \cdot I_E' \tag{5.27}$$

However, if $I_E = I_E' \cdot 1.028$:

$$I_P = I_E' \left(1.028 + \sum_i f_i \cdot 1.028 + \sum_i f_i' + \sum_i f_i'' \right) \tag{5.28}$$

If

$$\sum_i f_i \cdot 1.028 + \sum_i f_i' = \sum_k f_k = 0.4969 \tag{5.29}$$

we obtain:

$$\begin{aligned} I_P &= I_E' \left(1.028 + \sum_k f_k \right) \cdot f_I \\ I_P &= I_E' \left(1.028 + 0.4969 \right) \cdot 1.0692 = I_E' \cdot 1.6305 \end{aligned} \tag{5.30}$$

From the above equations, it can be deduced that the necessary capital investment in the food processing plant can be evaluated as follows:

$$I_P = f_L \cdot I_E \tag{5.31}$$

where f_L is Lang's factor, evaluated as

$$f_L = \left(1 + \sum_i f_i \right) \cdot f_I \tag{5.32}$$

In this example, Lang's factor is 1.6305. Curiously, it has been proven that this factor is approximately 3 for a normal process in the chemical industry (Peters and Timmerhaus, 1991).

5.5.1.2 Auxiliary System Cost Estimation

It is possible to obtain capital investment for the auxiliary systems of a process system by means of the *factorial estimation method* described earlier.

To design a food processing system as part of a food plant in operation with existing auxiliary systems, the capital investment toward utilities is considered a proportion of the total available utilities, according to the foreseen consumption of the process system. In the chemical industry, data have been presented regarding the percentage of processing plant total costs represented by corresponding auxiliary systems (Rudd and Watson, 1976; Peters and Timmerhaus, 1991).

This investment can also be evaluated by knowing the auxiliary system needs, for example, the amount of steam in kg/h, at 7 bar, or the amount of kcal/h or kW of refrigeration at given conditions of storage room temperature, condensation temperature, etc.

In effect, there are rules established that can be used to evaluate steam system cost from the amount of steam to supply at a given pressure (kg_f/h or bar). Similar rules have been determined for calculating refrigeration installation cost per cubic meter of storage room space according to refrigeration power, evaporation and condensation pressure, temperature, the design or type of compressor, and so forth.

It is also possible to make a list of the auxiliary system main elements. By knowing the functional characteristics of each element (such as refrigeration power and steam flow supplied by the steam generator), the capital investment can be found by consulting prices in trade bulletins or information from manufacturers. From these main elements, the complete capital investment of the auxiliary system can be evaluated according to indexes and rules that manufacturers may supply.

5.5.2 Operating Cost Estimation

The food processing plant generates operating costs during operation, which can be evaluated by the expression

$$C_o = C_I + C_{PV} + C_{PL} \qquad (5.33)$$

where
C_o = total operating costs
C_I = costs depending on (or proportional to) capital investment
C_{PV} = costs proportional to production volume
C_{PL} = costs proportional to production labor

expressed as

$$C_o = a \cdot I_P + b \cdot P + c \cdot L \tag{5.34}$$

where
$a \cdot I_P = C_I$ with a = constant of proportionality
I_P = capital investment for whole food processing plant
$b \cdot P = C_{PV}$ with b = constant of proportionality
P = volume of production
$c \cdot L = C_{PL}$ with c = constant of proportionality
L = total production labor in food processing plant

Costs that are usually independent of the production volume and can be proportional to the capital investment include

Amortization of process plant
Maintenance of buildings and urbanized zones (gardens, roads, etc.)
Taxes on property
Insurance
Safety services (fire protection, vigilance, etc.)
Laboratory, amortization of food analysis instruments
Administrative services (office, accounting, legal, etc.)

If P_d is the design production capacity of the food processing plant, the coefficient of utilization C_u can be expressed as

$$C_u = \frac{P}{P_d} \tag{5.35}$$

This expression indicates the fraction of design capacity that is actually used in production. Costs proportional to production volume are

- Raw materials costs
- Auxiliary systems operating costs:
  - Fuel consumed in generators, kilns, and steam production
  - Electric energy
  - Maintenance of auxiliary systems
  - Process, cleaning, and steam production water
  - Products used in decalcification of water, wastewater treatment, and CIP cleaning systems
- Maintenance of process system equipment
- Additives and auxiliary materials (packages, tags, caps, antioxidants, etc.)
- Fungible materials (reagents, glass materials, etc.) used in quality control laboratories
- Royalties and patents

Costs proportional to operating labor are directly related to workers in one of the following departments:

- Management
- Production
  - Technical director and assistants
  - Skilled operators of process system equipment
  - Unskilled operators and forklift truck operators
- Maintenance
  - Technical director and assistants
  - Skilled operators of auxiliary systems
  - Maintenance mechanics/electricians
- Quality control
  - Technical director
  - Quality control assistants
- Commercial–sales/purchase
  - Director
  - Commercial assistants

To evaluate the annual cost in proportion to capital investment, multiplying factors are managed as follows:

- Maintenance of buildings and garden zones: 2% of corresponding capital investment
- Patents, insurance, security services, taxes, and administrative services: 4–14% of total capital investment

Amortization of buildings and garden zones: 4–5% of corresponding capital investment
Amortization of process system and utilities equipment: 10-20% per year of corresponding capital investment

Costs proportional to production volume can be evaluated using the mass and energy balances of the analyzed food processing system. Some cases, like electricity or steam consumption, must be considered factors of simultaneous consumption in running the different types of process equipment (not all will run simultaneously).

The price of raw materials in different countries can be found in various publications (e.g., raw matter market bulletins) or in the corresponding raw matter markets. Transport of raw materials to a factory must be included in the cost of raw materials.

Maintenance of food processing systems and auxiliary systems equipment is approximately 5% of the corresponding capital investment per year.

Example: Evaluate the annual operating cost of a vegetable canning factory, using the production plan shown in Table 5.3, corresponding to the production organization in Table 5.4.

The following raw material/product yield percentages are utilized to calculate the final product amount:

(1) Canned	
Asparagus	47%
Mushrooms	60%
Peaches	65%
Pears	60%
(2) Fruit creams	
Peach	65%
Plum	60%
Apricot	60%
Pear	60%
(3) Jam from fruit creams	160%
(4) Sugared juices from fruit creams	250%

Table 5.3 Production Planning in a Vegetable Cannery

Product	Raw Matter Consumption (kg/h)	Work Time (h/year)	Total Raw Matter (kg)	Elaborated Product (kg/h)	Total Elaborated (kg)	Packages of product (units)
Peach in syrup	3,000	66 d × 8/h/d = 528	1,584,000	1,950	1,029,600	cans ½ kg = 4,118,400
Pear in syrup	3,000	118 d × 8/h/d = 944	2,832,000	1,800	1,699,200	cans ½ kg = 6,796,800
Peach pulp	3,000	53 d × 8 h/d = 424	1,272,000	1,950	826,800	drums 220 kg = 3,758
Apricot pulp	3,000	26 d × 8 h/d = 208	624,000	1,800	374,400	drums 220 kg = 1702
Pear pulp	3,000	53 d × 8 h/d = 424	1,272,000	1,800	763,200	drums 220 kg = 3,489
Plum pulp	3,000	26 d × 8 h/d = 208	624,000	1,800	374,400	drums 220 kg = 1,702
Peach jam	1,000	52 d × 8 h/d = 414	413,400	1,600	662,400	jars 600 g = 1,558,588
Apricot jam	1,000	47 d × 8 h/d = 375	374,400	1,600	600,000	jars 600 g = 1,411,765
Plum jam	1,000	47 d × 8 h/d = 375	374,400	1,600	600,000	jars 600 g = 1,411,765
Peach nectar	1,000	52 d × 8 h/d = 414	413,400	2,500 L/h	1,033,500	1 L bottles = 1,033,500
Pear nectar	1,000	95 d × 8 h/d = 763	763,200	2,500 L/h	1,908,000	1 L bottles = 1,908,000
Asparagus	1,000	78 d × 8 h/d = 624	624,000	470	293,280	cans ½ kg = 1,173,120
Mushroom	1,000	286 d × 8 h/d = 2,288	2,288,000	600	1,372,800	cans ½ kg = 5,491,200

Table 5.4 Fabrication Scheduling in a Vegetable Cannery Factory

Product	January	February	March	April	May	June	July	August	September	October	November	December	working days
Jams													1 turn in 146 days
Nectars													1 turn in 146 days
Syrups													
Peach													1 turn in 66 days
Pear													1 turn in 118 days
Cream of fruit													
Peach													1 turn in 53 days
Apricot													1 turn in 26 days
Pear													1 turn in 53 day
Plum													1 turn in 26 day
Canned vegetables													
Asparagus													1 turn in 78 days
Mushroom													1 turn in 286 days

To evaluate the packages needed for different products, the dropping and net weight for each type of package is taken into account (according to quality standards):

1. For cans weighing 0.5 kg, the dropping weight must equal 250 g.
2. For glass jam jars weighing 600 g, the net weight must equal 425 g.

On the other hand, one-half of peach cream produced is used for jam manufacture and the other half for sugared fruit juices. All apricot and plum production is used to make jam, while pear cream is used entirely for sugared fruit juices. Canned fruits are packaged in 0.5 kg cans, as are mushrooms and asparagus.

The total capital investment in this cannery plant, excluding land:

Total civil works	\$463,300
Raw matter reception building	\$53,335
Process buildings	\$200,000
Storage buildings	\$105,550
Boiler building	\$20,000
Administration building	\$27,770
Roads, fencing, and gardening	\$55,550
Process system equipment	\$2,183,330
Canned peaches (3000 kg/h)	\$600,000
Canned pears (3000 kg/h)	\$216,665
Fruit creams (3000 kg/h), sugared fruit juices (1000 kg/h)	\$222,200
Fruit jams (1000 kg/h)	\$238,890
Canned asparagus (1000 kg/h)	\$377,780
Canned mushrooms (1000 kg/h)	\$277,780
Sterilization systems equipment	\$55,560
Seaming systems equipment	\$194,450
Auxiliary systems	\$431 845
Conveying system	\$115,180
Water distribution system	\$8,335
Compressed air generation and distribution	\$11,110
Wastewater treatment system	\$55,550

Steam generation and distribution	\$94,450
Electrical substation and power wiring	\$77,800
Refrigeration storage rooms	\$55,560
Quality control laboratory equipment	\$13,900
TOTAL INVESTMENT:	\$3,078,500

Operating Costs:

Labor

Permanent staff	
Plant manager	\$65,000
Production director	\$55,000
Quality control director	\$30,000
Administration director	\$20,000
Quality control assistant	\$15,000
Plant assistant	\$20,000
Maintenance mechanics	\$30,000
Administration assistants	\$60,000
Forklift truck drivers	\$30,000
Skilled operators	\$200,000
TOTAL	\$525,000

Social security and other social charges should be added to labor cost. For example, in Europe, these additional fees can represent 35% of labor cost.

In this example, 35% of \$525,000 = \$183,750. Thus, the total staff cost is \$708,750.

Eventual staff. In order to cover processing labor requirements, eventual staff will be employed. For example, the eventual labor cost in an agricultural region can amount to \$60 per working day (including some Sundays, feast days, bonus and holidays, and transportation). If the workday is 8 h, and wage is \$7.5/h, the eventual staff cost would be as follows:

Asparagus	40 Operators × \$7.5/h × 624 h/yr	\$187,200
Peach	45 Operators × \$7.5/h × 624 h/yr	\$210,600
Pear	20 Operators × \$7.5/h × 624 h/yr	\$93,600
Mushroom	15 Operators × \$7.5/h × 624 h/yr	\$70,200
	TOTAL	\$561,600

+ 35% Social charges	\$196,560
TOTAL Eventual staff	\$758,160

The amount of fuel (in kilograms) required to generate 1kg of steam is calculated as follows:

$$\text{kg fuel/kg steam} = \frac{L}{P_c \varepsilon_g} \qquad (5.36)$$

where

L = thermal energy (J) per kg of steam evaporated at the supplying steam pressure. It is the latent heat of vaporization in the steam generator operating conditions.

P_c = calorific power or heat content of fuel. For example, when one unit of fuel oil is used, P_c = 39590 kJ/kg.

ε_g = generator efficiency, using calorific power of fuel; usually around 0.8.

Costs proportional to production volume

Fuel oil

Asparagus	800 kg steam/h × 624 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 28,354 kg
Peach	1950 kg steam/h × 528 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 58,481 kg
Pear	(2.200 kg steam/h × 416 h/yr + 300 kg steam/h × 528 h/year) × 0.8 × 0.071 kg fuel oil/kg steam	= 60,844 kg
Fruit creams	400 kg/h × 1264 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 28,718 kg
Jams	1585 kg steam/h × 1164 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 104,792 kg
Sugared fruit juices	1000 kg steam/h × 1177 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 66,853 kg

Sterilization process	500 kg steam/h × 1976 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 56,118 kg
Mushrooms	220 kg steam/h × 2288 h/yr × 0.8 × 0.071 kg fuel oil/kg steam	= 28,590 kg
	Total kg of fuel oil	= 432,753 kg
	432,753 kg fuel oil × \$0.15/kg fuel oil	= \$64,913 per year

Electricity

Asparagus	(33 HP × 0.736) kW × 624 h/yr × 0.8 × \$0.06/kWh	= \$727
Peach	(84 HP × 0.736) kW × 528 h/yr × 0.8 × \$0.06/kWh	= \$1567
Pear	(26 HP × 0.736 × 528 + 45 HP × 0.736 × 416) kWh × 0.8 × \$0.06/kWh	= \$1139
Fruit creams	(28 HP × 0.736) kW × 1244 h/yr × 0.8 × \$0.06/kWh	= \$1250
Jams	(32 HP × 0.736) kW × 1164 h/yr × 0.8 × \$0.06/kWh	= \$1316
Sugared fruit juices	(15 HP × 0.736) kW × 1177 h/yr × 0.8 × \$0.06/kWh	= \$624
Mushrooms	(32 HP × 0.736) kW × 2288 h/yr × 0.8 × \$0.06/kWh	= \$2587
Auxiliary equipment	27.98 kW × 2288 h/yr × 0.8 × \$0.06/kWh	= \$1921
Steam generators	68.94 kW × 2288 h/yr × 0.7 × \$0.06/kWh	= \$6625
Refrigeration equipment	36.80 kW × 2000 h/yr × 0.7 × \$0.06/kWh	= \$3091
Lighting	30.02 kW × 2000 h/yr × 0.7 × \$0.06/kWh	= \$2520
	Total electricity	= \$26,903

Water

Asparagus	25 m^3/h × 624 h/yr × 0.8 × \$0.2/m^3	= \$2496
Peach	11 m^3/h × 528 h/yr × 0.8 × \$0.2/m^3	= \$929
Pear	(3.3 m^3/h × 528 + 9 m^3/h × 416) m^3 × 0.8 × \$0.2/m^3	= \$874
Fruit creams	3 m^3/h × 1264 h/yr × 0.8 × \$0.2/m^3	= \$607
Jams	10 m^3/h × 1164 h/yr × 0.8 × \$0.2/m^3	= \$1863
Sugared fruit juices	8 m^3/h × 1177 h/yr × 0.8 × \$0.2/m^3	= \$1507
Mushrooms	6 m^3/h × 2288 h/yr × 0.8 × \$0.2/m^3	= \$2197
Steam generators	5 m^3/h × 2288 h/yr × 0.8 × \$0.2/m^3	= \$1831
Sterilization	28.2 m^3/h × 2288 h/yr × 0.8 × \$0.2/m^3	= \$10,324
Administration buildings and other services	3 m^3/h × 2000 h/yr × 0.8 × \$0.2/m^3	= \$960
	Total water consumption	= \$23,585

Raw materials

Asparagus	624,000 kg × \$1.12/kg	= \$698,880
Mushrooms	2,228,000 kg × \$0.66/kg	= \$1,470,480
Apricots	624,000 kg × \$0.33/kg	= \$205,920
Plums	624,000 kg × \$0.28/kg	= \$174,720
Peaches	(1,528 000 + 1,272,000) kg × \$0.25/kg	= \$700,000
Pears	(1,832,000 + 1,272,000) kg × \$0.28/m^3	= \$869,120
	Total	= \$4,119,120

Packages and other auxiliary raw materials

Price per unit:

Glass jam jar, weight 600 g	= \$0.062
Caps for above jars	= \$0.031
Standard 1 L bottle for sugared fruit juice	= \$0.114

Bottle cap	= \$0.020
Metallic can, weight 0.5 kg	= \$0.083
Sugar	= \$0.627/kg
Pectin	= \$6.111/kg
Citric acid	= \$1.861/kg
Thickening agents	= \$4.722/kg
Other additives	= \$1.444/kg
Fructose	= \$1.611/kg
Liquid glucose 70 ºBrix	= \$0.389/kg

For raw materials:

- Packages

Glass jars and caps	4 382 118 units × \$0.093 /unit	= \$408,024
Glass bottles 1 L and caps	2 941 500 units × \$0.134/unit	= \$393,998
Cans, weight 0.5 kg:		
peaches	4 118 400 units × \$0.083/unit	= \$343,200
pears in syrup	6 796 800 units × \$0.083/unit	= \$566,389
asparagus	1 173 120 units × \$0.083/unit	= \$97,760
mushrooms	5 491 200 units × \$0.083/unit	= \$457,600
	TOTAL	= \$2,266,971

- Sugar

Peaches	4,118,400 (0.5 kg cans) × 0.25 kg syrup/can × 0.5 kg sugar/kg syrup × \$0.628/kg	= \$323,294
Pears	6,796,800 (0.5 kg cans) × 0.25 kg syrup/can × 0.5 kg sugar/kg syrup × \$0.628/kg	= \$533,549
Jams	1,862,400 kg × 0.625 kg sugar/kg jam × \$0.628/kg	= \$730,733
Sugared fruit juices	2,941,500 L × 0.5 L syrup (15ºBrix/L) × 0.15 kg sugar/L syrup × \$0.628/kg	= \$138,496

- Pectin

Jams 0.0026 kg pectin/kg jam × 1,862,400 kg jam × \$6.12/kg = \$29,635

- Other additives: \$55,560

TOTAL PACKAGES AND OTHER RAW MATERIALS = \$4,078,240

Maintenance of process equipment and utilities

Maintenance of process equipment and utilities is approximately 5% of corresponding capital investment:

$$\$2,615,167 \times 0.05 = \$130,758$$

Costs proportional to capital investment

Maintenance of buildings

Annual cost for building maintenance may range around 2% of building investment cost:

$$\$463,300 \times 0.02 = \$9,266$$

Safety and protection, taxes, and administrative cost

These costs can be evaluated as 2% of total capital investment:

$$\$3,078,500 \times 0.02 = \$61,570$$

Annual operating costs:

Operating labor cost	\$1,466,910
Fixed staff	\$708,750
Eventual staff	\$758,160
Cost proportional to production	\$8,443,519
Fuel oil	\$64,913
Water	\$23,585
Electricity	\$26,903
Raw materials	\$4,119,120
Packages and other auxiliary raw materials	\$4,078,240

Equipment maintenance	$130,758
Cost proportional to capital investment	$70,836
Building maintenance	$9,266
Safety and protection, taxes, and administrative cost	$61,570

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6

Experimentation in Pilot Plant

6.1 INTRODUCTION

As mentioned earlier in Section 3.4, Chapter 3, pilot plant studies are physical simulation studies (Blackhurst and Harker, 1973). The pilot plant is a physical model and should be a "copy" of the corresponding industrial unit, with equipment scaled down in size to approximately 1/100–1/10 of the modeled unit (Johnstone and Thring, 1957).

Pilot plant experiments serve to obtain more information and data in the following areas:

1. *Market survey*. A determined new product amount can be produced in the pilot plant, to test its acceptance and to decide whether it would be economically profitable.
2. *Design data*. The behavior of a given operation or unit process can be found under conditions impossible to duplicate in the laboratory. In other words, a pilot plant permits the acquisition of accurate data on processing system energy and mass balances. In some cases, pilot plants are used to determine the most suitable process technology.
3. *Products and raw materials*. A pilot plant is usually needed to characterize food products and to evaluate the development of certain raw materials into specific products.

4. *Optimization data of a running plant*. A pilot plant can be used to optimize running of equipment and food plants, in order to study possible modifications of the original food processing system deemed impracticable or uneconomical at the industrial level.

Experimentation in a pilot plant is very expensive, the reason why studies in laboratories aided by deep market surveys are recommended when acquiring necessary information and data for the process system design (Katzan, 1968; López et al., 1997).

6.2 SIZE AND STRUCTURE OF THE PILOT PLANT

6.2.1 Basic Principles of Scaling

The most important criterion in determining the size and form of a pilot plant is the principle of similarity, a principle first formulated by Newton.

If fluids are handled in the pilot plant, three types of similarities involved in fluid dynamics must be included:

1. *Geometric similarity.* Both the pilot plant and food processing plant should have the same physical form or at least the same geometric dimension relationships. This similarity can be partial. For example, the reduction in size of a geometric dimension can be completed by a scale factor of 100, while other defined dimensions can utilize a scale factor of one. Thus, when scaling down a food drying system, the drying bed height can remain (scale factor = 1), while the drying bed surface through which hot air passes can be reduced 100 times (scale factor = 100).
2. *Kinematic similarity.* The same velocity relationships should exist in both the pilot and food processing plants.
3. *Dynamic similarity.* In both the pilot and food processing plants, the same force relationships should exist. For example, the turbulence regime should be similar on both scales when fluids are handled.

If the process simulated in a pilot plant involves chemical or biochemical reactions, as frequently occurs in food processing systems, the following similarities apply:

1. *Thermal similarity.* In addition to geometric and kinematic similarity, the pilot and processing plants should present similar temperature differences among the various points in the system, simulated at both pilot plant and industrial levels.
2. *Chemical and biochemical similarity.* There should be parallel differences in concentration (of products or components in the studied system) in the pilot plant and food processing plant. In addition, the chemical or biochemical kinetics must be similar on both scales.

Generally, the thermal, chemical, and biochemical similarities (including kinetics) are complete at both pilot plant and industrial levels (with scale factor = 1). Therefore, the possible biochemical transformation processes occurring at both levels are the same (Iguaz et al., 2003; Arroqui et al., 2003).

6.2.2 Minimum and Maximum Size

Several factors can affect the size of a pilot plant. In general, the minimum size is set by the minimum product amount required for quality analytical control. For example, if the aim of pilot plant experimentation is to study the influence of process conditions on product quality, the minimum amount of processed product in the pilot plant should permit the necessary physical-chemical analysis to evaluate product quality. The maximum size of the pilot plant is set by the amount of processed product needed in order to test market acceptance.

In noncontinuous (batch) processes, a pilot plant design that reproduces small parts of the food processing system is relatively simple. In principle, a pilot plant is not needed for the entire food processing system. Continuous processes, however, require a more global experimental focus. Thus, if recycled

Figure 6.1 Single-stage dryer plant (courtesy of the National Drying Machinery Company, Aeroglide Corp., www.nationaldrying.com).

streams exist when the energy and mass balances are being studied, a pilot plant that includes these streams will be necessary. This pilot plant would be more complete than those reproducing batch processes.

6.3 TYPES AND APPLICATIONS

When product production in amounts large enough to conduct market acceptance tests is required, the pilot plant is called a semicommercial plant. Before building the semicommercial pilot plant, experimentation is customary in a smaller, scaled-down pilot plant in which the design data are refined.

If building repetitions of a food processing system are needed, it is sometimes common to build a prototype plant or system that reproduces (industrial scale) the technical behavior (Figure 6.1) (Campbell, 1968). This type of pilot plant also allows a more detailed design. In these cases, the cost of the plant is justified. In short, when a new process line is developed or new process equipment tested, it is common to use

Figure 6.2 Pilot plant or experimental installation to study the influence of cold storage conditions on hazelnut quality.

prototypes that permit an evolutionary design and a better definition at a more detailed engineering level.

In any case, reduced-scale pilot plant studies are the most often employed studies used to obtain information and data on production engineering (running of food processing plants) and design engineering (new food processing plants).

The most common applications of a pilot plant are as follows:

1. Product studies
   - Quality characterization
   - Influence of process conditions on product quality (Figure 6.2 and Figure 6.3)
   - Development of new products
   - Studies of market acceptance
2. Raw material studies
   - Raw material characterization
   - Evaluation of aptitude for industrialization of different raw materials

Figure 6.3 Closed boxes used to control the relative humidity and atmosphere (O_2 and CO_2) in hazelnut cold storage studies.

3. Process technology and engineering studies
   - Setting the most suitable process conditions from an economic point of view (cost minimization) and a product quality point of view (to obtain a product of given quality). Process technology is optimized.
   - Study of process equipment alternatives to carry out given food processing steps or unit operations.
   - Development of new process technology.
   - Development of new process engineering or process equipment.
4. Auxiliary system requirement studies
   - Reliable evaluation of mass and energy balances and food physical properties (Figure 6.4 and Figure 6.5)
   - Study of energy recovery possibilities in process systems
   - Improvement and evaluation of alternatives for control systems

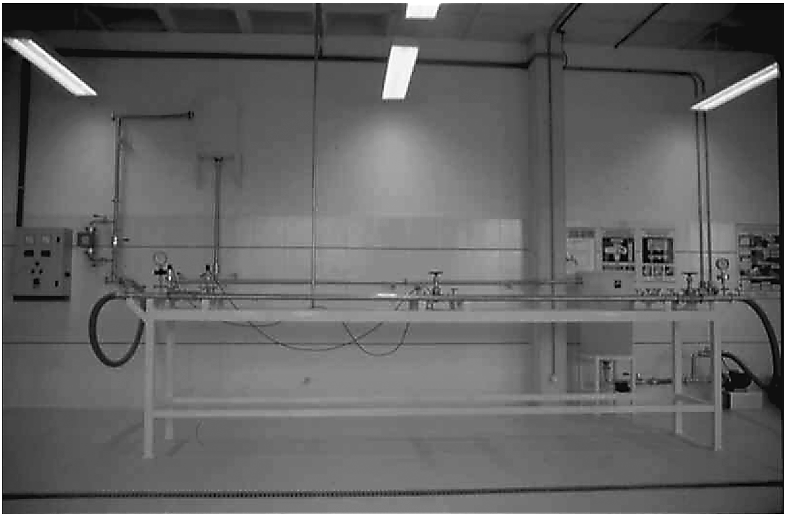


Figure 6.4 An experimental installation to study the flow characteristics of liquid foods.

Figure 6.5 An experimental installation to study the pneumatic transport of powder products.

Figure 6.6 Drying pilot plant (courtesy of the National Drying Machinery Company, Aeroglide Corp., www.nationaldrying.com).

6.4 PILOT PLANT DESIGN

An appropriate pilot plant design is essential in order to achieve reliable results during pilot plant experimental programs.

Taking into consideration the similarity principles, the factors that will be controlled or changed during experimentation are evaluated first.

Example: A study on drying fruits and vegetables with hot air crossing over the drying bed. Controlled factors are

- Air velocity between 0.2 and 3 m/s
- Air temperature between 50 and 100°C
- Load density of drying bed between 40 and 50 kg/m^2
- Air relative humidity between 20 and 100%
- Hot air recycling between 0% and 100%

Thus, the controlled factors are established as well as the interval of variation considered.

Using these data and the similarity principles, and by considering the required amount of product, the form and size of the pilot plant are deduced (Figure 6.6).

Other aspects to take into account in the design of a pilot plant are availability of auxiliary systems, raw materials, and specifications of the product. The construction materials needed and any auxiliary system requirements are deduced from the above data.

The location of the pilot plant usually depends on plant size, utilities, and laboratory requirements to assist in pilot plant operation. A relatively small pilot plant that requires few auxiliary systems but requires high laboratory assistance is normally installed near the research and development laboratory. On the contrary, if a pilot plant requires a large number of utilities, it is located near the industrial process plant.

6.5 EXPERIMENTATION STRATEGIES

Depending on the problem being solved in the pilot plant, a defined experimental program should be established. In each case, the time and cost spent on a program can be evaluated. The profits from experimentation in the plant should be greater than the costs. Thus, it is very important to establish an appropriate experimental design for the pilot plant, since it will save time and money.

The statistical design of the experimental program states the procedure used to conduct different experiments in the pilot plant. In this manner, by applying the appropriate statistical analysis, the results obtained will be reproducible and reliable (Hunter and Atkinson, 1966).

All controlled process parameters (experimental variables) are usually known as factors. The value of each factor is the variation level of the factor. A combination of factors used in a particular experimental run is called the treatment. The result of factor variation in an experimental run is designated as the effect. If the raw material used in experiments is limited in quantity, it may be necessary to use several batches of raw material that are similar but not identical in characteristics. Each batch is called a block and repetitions of the same experiment are known as replications.

For example, in reducing the time needed for germination in beer malt processing, the factors affecting the process are the additions of gibberellic acid, germination temperature, and grain moisture (intensity of previous steeping). At the same time, these factors can influence malt quality. Since the barley variety and growth area also affect the germination process, one possible experimental program could be the following (with factors and variation levels indicated):

Dose of gibberellic acid during germination (0, 0.05, and 0.1 ppm)
Germination temperature (13°C, 15°C, and 17°C)
Steeping intensity (40–44% moisture content in barley grain), prior to germination

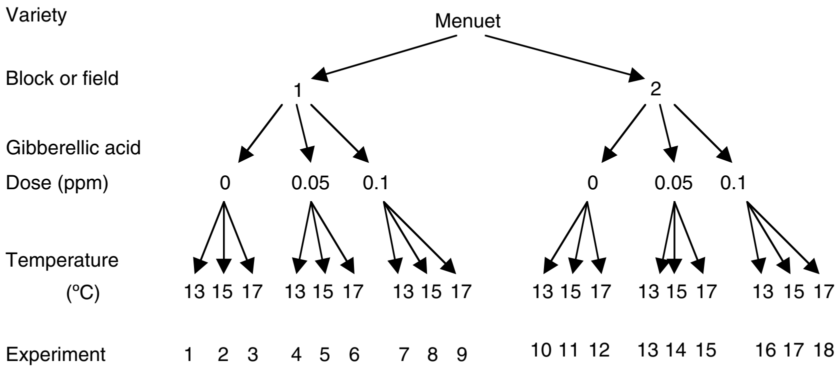
The experiments would be with a barley variety (e.g., Menuet) harvested in one zone and growth area. If only one variety is used but harvested from different growth areas, there would be a block of experiments in the pilot plant for each zone. It is common to complete four repetitions in each experiment, maintaining the level of each factor for the same variety and growth area (within same block) constant.

The effect of each factor on germination time and malt quality can be analyzed statistically. The different quality parameters (soluble protein, Hartong index, Kolbach index, etc.) are determined in the malt obtained from each experiment.

Factorial design requires an appropriate experimental design procedure in the pilot plant. It is useful in discovering the influence of different factors on process development or the final quality of the product. Once the effects of the different factors have been studied, a regression analysis can be completed to develop quantitative relationships among the different factors, process parameters, or product quality parameters.

Factorial design can be applied to the study of different factors and the variation levels of each factor. In preliminary studies, however, it is useful to select only two variation levels from each factor.

In the above study on the barley germination process to obtain beer malt, the factorial design states (for a 44% steeping level):



Consequently, there are 3 × 3 = 9 experiments in each block (2), since there are three variation levels for the gibberellic acid dose factor and three variation levels for the germination temperature factor. However, since four replicate runs must be made in every experiment, there are 4 × (2 × 9) experiments completed. The total number of experiments can be calculated as

$$N_1 \times N_2 \times B \times R \tag{6.1}$$

where
N_1 = variation levels of factor 1
N_2 = variation levels of factor 2
B = number of blocks
R = number of repetitions

Let's apply this expression to the example:

$$N_1 \times N_2 \times B \times R = 3 \times 3 \times 2 \times 4 = 72 \tag{6.2}$$

The result of each experiment is called the observation.

Statistical evaluation of the factorial design results is carried out by analyzing the variance. With this method, the significance of the effect of each factor on process and product quality parameters is deduced. Using the analysis of variance, interaction among the different factors under consideration can also be deduced.

Another experimental strategy used in pilot plants is the Box-Wilson design (Peters and Timmerhaus, 1991). This design is used to formulate behavior models of different physical processes, since it is well fitted to quadratic functions over a reasonable range of factor variability. For example, in a two-factor system, the commonly used model is

$$y = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{12}x_1x_2 + b_{22}x_2^2 \tag{6.3}$$

Similar equations can be formulated for models with more than two factors.

To construct these models, it is important to know that each factor varies at five levels over a reasonable factor range, depending on what is studied. After the experimental programs are completed, a regression analysis is carried out to determine the coefficients in the model. Using the corresponding analysis of variance and the F-test, the significance of the model fitting the data is determined.

The technique of "evolutionary operation" (Peters and Timmerhaus, 1991) involves the study of the effects of systematic, small changes in process factors during operation. The results are used to suggest further changes in the factors being studied. Thus, efforts are made to find the optimum operating conditions.

6.6 CAPITAL INVESTMENT AND OPERATION COST

The cost of experimentation in the pilot plant is determined as follows:

1. Capital investment costs for process equipment and auxiliary systems in the pilot plant, as well as unexpected expenses common during construction. For this reason, it is important to foresee the difficulties that could occur and their impact on capital costs. Possible residual value of the pilot plant after utilization must also be considered.
2. Cost of buildings and structures to construct and operate pilot plant.

3. Cost of raw materials and consumption of auxiliary systems, taking into account the total number of experiments completed in previously established experimental programs.
4. Cost of staff during experimentation, considering direct labor as well as supervision, analysis, and interpretation of results.
5. Cost of laboratory fungible material to control product quality and process.
6. Estimated cost of instrumental equipment use, needed to control process, product quality, and raw materials.

The total cost should be compared with the expected profits from experimentation in the pilot plant. Considering the implicit risks, experimentation in the pilot plant will be profitable when the benefits are greater than the costs.

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7

Materials for Construction of Food Equipment

7.1 CHARACTERISTICS OF SUITABLE CONSTRUCTION MATERIAL

Construction materials for food processing and auxiliary system equipment that are in contact with foods or cleaning agents should have certain characteristics (Jowitt, 1980):

a) *Resistance to corrosive action* of foods or chemicals (cleaning and sanitation agents) that may converge with exposed surfaces of construction materials. Corrosion can cause contamination of food and loss of quality, as well as flavor and aroma problems. An example of the detrimental effects of corrosion are color stability problems that occur in wine if the Fe content is greater than 15 ppm, resulting in ferric breakage and an undesirable red color. In any case, excessive corrosion reduces the shelf life of construction materials. In addition, corrosion can cause crevices to appear in the surfaces of construction materials. These altered surfaces are difficult to clean and sanitize, causing hygienic problems in food processing systems.

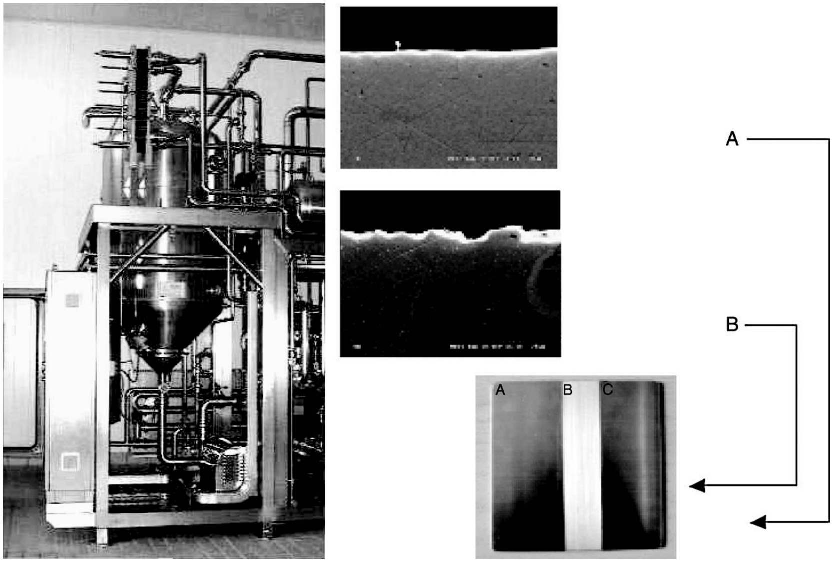


Figure 7.1 A good surface finish improves hygienic appearance and provides effective hygiene, as shown in photo (left) of juice deaeration equipment. The stainless steel sheet surface (right) presents certain rugosity, as shown in electron micrographs (right): 2B finish (zone A, Ra < 0.30 µm) and after welding partial polishing (zone B, Ra < 4 µm). Ra = mean rugosity.

b) *Suitable surface finish* to discourage buildup of dirt that can accumulate with excessive surface rugosity. A smooth finish can also improve external aesthetic and hygienic appearance of process equipment (Figure 7.1).

c) *Good mechanical behavior* according to performance of mechanical functions, such as structural strength, resistance to abrasion and physical or thermal shocks, and pressure charges. Process, cleaning, and maintenance operations determine these working conditions. On the other hand, mechanical characteristics of construction materials should permit

Possible fabrication of thin sheets to facilitate heat transfer in cooling or heating operations

Easy assemblage and fastening operations using common methods (screw threads, welding, etc.) and not requiring special techniques

Possible forming of materials into desired shapes, into undulated surface sheets (e.g., plate heat exchangers), sheets and plates, rods, pipes, elbows, etc.

In any case, the construction materials in contact with foods can be selected based on the aggressiveness (e.g., acid, alkaline, or neutral character) of the foods and the cleaning agents used. It would also be helpful to know whether there will be variations in the working temperature and the flow velocity of food on the material. Aspects such as thermal conductivity must also be taken into account if the materials will form part of a heat exchanger.

Materials not in contact with food or cleaning agents should meet many of the specifications required for machine construction, such as adequate rigidity and mechanical strength (Figure 7.2) (Baquero and Llorente, 1985).

7.2 TYPES OF MATERIALS AND APPLICATIONS

7.2.1 Stainless Steel

Stainless steel exhibits some of the most suitable characteristics of the construction materials used for food equipment. It is the most widely used material in direct contact with food found in the industry. Of the types available, AISI 304 stainless steel is the most commonly used (Figure 7.3).

Some plastics have many qualities that make them appropriate construction materials for process equipment in direct contact with food, but plastics rarely have the durability of stainless steel.

Before the generalized use of stainless steel, adequate corrosion resistance was provided using tin coating layers applied as a varnish over iron (e.g., inside tin cans) or copper (in construction of food processing tanks and pipes). This thin layer of tin has a very limited life, however, since it has low

Figure 7.2 Beer-making installation. Material in contact with the must and beer is stainless steel (courtesy of Dizio, www.dizio.it).

Figure 7.3 AISI 304 stainless steel is the most widely used construction material in the food industry. In this photo, AISI 304 is used for the tanks (courtesy of Dizio, www.dizio.it).

resistance to corrosive food products. In addition, after corrosion of the layer, the material is even more vulnerable to mechanical actions, such as abrasion and collisions during cleaning operations.

Table 7.1 shows the chemical composition of the main types of stainless steel (AISI 302, 304, 316, 416, and 440). AISI 302 exhibits better corrosion resistance than AISI 301, and is the most commonly used. AISI 304 is more corrosion resistant than AISI 302, but less so than AISI 316. Of all the stainless steel types, AISI 316 exhibits the best corrosion resistance to chemical agents. Due to their special qualities, AISI 416 and 416 Se are used for manufacture of mechanized parts, such as those of the helicoidal type.

Table 7.2 presents typical applications of various types of stainless steel used in the food industry (Francis, 2000).

7.2.1.1 Surface Finish

Sheets of stainless steel may exhibit different levels of surface polish or finish (Figure 7.1) depending on the application. According to the American Iron Steel Institute, there are the following polished and unpolished surfaces:

Unpolished Surfaces

- *No. 1 finish*. For industrial applications when heat or corrosion resistance is needed without surface polishing requirements.
- *No. 2D finish*. For surfaces that must be polished after construction and equipment assembly.
- *No. 2B finish*. For surfaces easier to polish than those requiring No.1 and No. 2D (Figure 7.1).

Polished Surfaces

- *No. 3 finish*. For surfaces further polished with more intensity. Polished with 100 mesh abrasives.
- *No. 4 finish*. For surface finishes commonly used on restoration equipment, in dairy industry, and food

Table 7.1 Composition of the Different Types of Stainless Steel

	C	Mn	P	S	Si	Cr	Ni	Mo	Se
AISI 302	0.15 max	2.00 max	0.045 max	0.030 max	1.00 max	17.00 19.00	8.00 10.00	—	—
AISI 304	0.08 max	2.00 max	0.045 max	0.030 max	1.00 max	18.00 20.00	8.00 12.00	—	—
AISI 316	0.08 max	2.00 max	0.045 max	0.030 max	1.00 max	16.00 18.00	10.00 14.00	2.00 3.00	—
AISI 416	0.15 max	1.25 max	0.0605 max	0.15 max	1.00 max	12.00 14.00	—	0.60 max	—
AISI 416Se	0.15 max	1.25 max	0.060 max	0.060 max	1.00 max	12.00 14.00	—	—	0.15 max
AISI 440	0.60 0.75	1.00 max	0.040 max	0.030 max	1.00 max	16.00 18.00	—	0.75 max	—

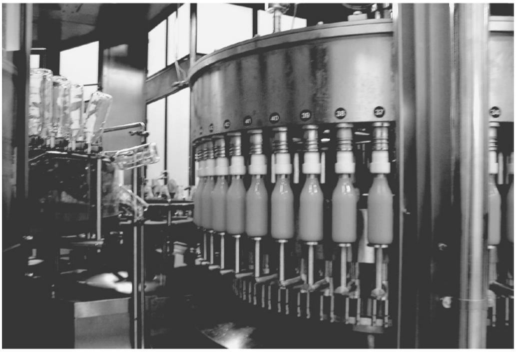
Table 7.2 Types and Characteristics of Stainless Steel and Their Uses

Identification	Chrome and Nickel Content	Characteristics	Most Common Uses
Series 200			
Not magnetic or lightly magnetic			
201	16–18%/3.5–5.5% 5.5–7.5% Manganese	Equivalent to 301	For surfaces not in continuous contact with product, except up to pH 7
202	17–19%/4.0–6.0% 7.6–10% Manganese	More resistant to corrosion than 201 Equivalent to 302	As indicated above
Series 300			
Not magnetic or lightly magnetic			
301	16–18%/6–8%	Good ductility Type within series 300 with minor resistance to corrosion mainly at high temperatures	Structural applications Bins and containers
302	17–19%/8%	Good corrosion resistance and mechanical properties	General purpose Heat exchangers, tanks, pipes, heaters, towers
304	18–20%/8–12%	Better corrosion resistance than 302	Type most used in food industry

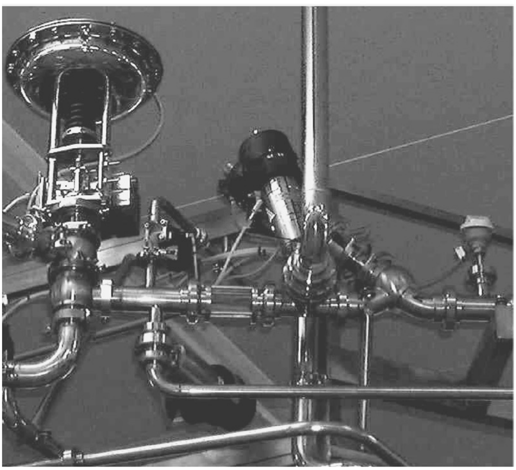
Table 7.2 (continued) Types and Characteristics of Stainless Steel and Their Uses

Identification	Chrome and Nickel Content	Characteristics	Most Common Uses
310	24–26%/19–22%	Good resistance characteristics at high temperatures	In applications at high operation temperatures
316	16–18%/10–14% with Molybdenum	Stainless steel with better corrosion resistance	In applications with special corrosion conditions
Series 400 magnetic			
410	11.5–13.5%/0.5% 0.15% Carbon	Lowest cost general purpose stainless steel	Wide use where corrosion is not severe: pump rods and valves, machine parts, turbine blades, freezers
416	12–14%/0% 0.15% Carbon	Sulfur added for free machining version of type 410	Valve stems, plugs, gates, useful for screw, bolts, nuts and other parts requiring considerable machining
430	14–18%/0%	Good corrosion resistance	External design of food equipment. Instrument parts and valve parts.
440	16–18%/0%	Not adequate with welded joints	Pump parts

Adapted from Hall and Farrall, 1986; and Peters and Timmerhaus, 1991.



a



b

Figure 7.4 A mirror finish is used to improve hygienic design of equipment.

industry in general. Polished with 120–150 mesh abrasives.

- *No. 6 finish*. For decorative elements, such as coatings for architectural components.
- *No. 7 finish*. Mainly for surfaces in architecture, but also for food equipment, pumps, and valves (Figure 7.4 and Figure 7.5). A mirror finish.
- *No. 8 finish*. For same applications as No. 7. A more intense mirror finish than No.7.

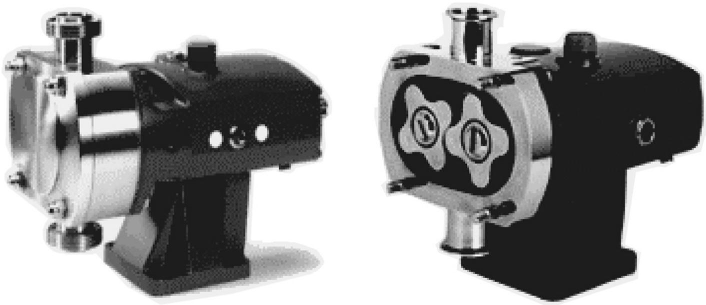


Figure 7.5 Internal surfaces of sanitary pumps and valves must have mirror finishes. This photo shows a closed sanitary lobe-rotor pump on left and one opened on right (courtesy of Alfa Laval, www.alfalaval.com).

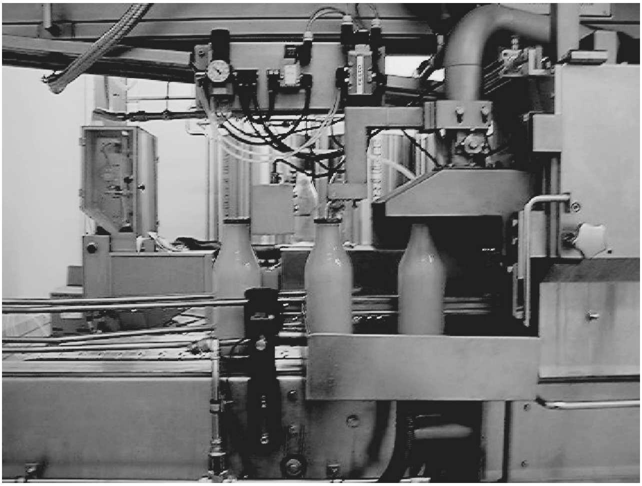


Figure 7.6 The No. 4 surface finish is the most widely used in the food industry.

The No. 4 surface finish is the most widely used type contacting food, since it allows easy cleaning and sanitation operation, as well as an appropriate hygienic level (Figure 7.6). It is also used as an external surface finish in tanks, in the external design of food process equipment and sanitary pumps, etc. Maintenance of the No. 7 surface finish is more difficult than the No. 4 finish, and is used for internal parts of auxiliary and food process equipment; it is easy to clean and sanitize.

7.2.1.2 Corrosion

Under special corrosion conditions, such as handling of acidic fluid foods or foods containing SO_2, AISI 316 or 316L stainless steel should be employed with preference over AISI 302 or AISI 304. AISI 302 stainless steel is used to improve the external design appearance of food equipment, but not equipment in contact with food or corrosive agents.

The corrosion resistance of stainless steel is due to the spontaneous formation of a layer of chromium oxide on the surface of the material (as a protective coating) when exposed to air. This layer can be formed artificially by treating the surface with nitric acid (20–30% at 60°C) for 30 minutes (Francis, 2000).

Stainless steel can be made to be corrosion resistant if a series of precautions are taken during manufacture and installation of the food equipment in the process system, equipment design, and operation and maintenance of equipment. In effect, when two different metals are used for the construction of equipment containing a conducting fluid (as a fluid food) in contact with both metals, an electric potential can be set up between the two metals. The resulting galvanic action can cause one of the metals to dissolve into the conducting fluid and deposit on the other metal (Peters and Timmerhaus, 1991). The different metals form an electrolytical pile, so that the current quantity or flow depends on the same metals and electrolyte (substances dissolved in conducting fluid) characteristics. It is very important to be able to recognize and avoid this effect in the design and construction of equipment. Deposits of foreign material on a stainless steel surface, such as food residues, cleaning agents, particles, and external gases, can help form corrosion electrolytical cellules (Henry et al., 1970).

Stainless steel can undergo five types of corrosion:

1. *General corrosion*. Indicates a more resistant stainless steel should be used.
2. *Intergranular corrosion.* Penetrates through the crystallized grains. Stainless steel with low carbon content should be used, for example AISI 316 L, instead of AISI 316 and 304 L substituting for AISI 304.
3. *Galvanic corrosion.* Occurs when two different metals are placed in contact; an electrical potential is created on the surface due to differences in concentration of conducting fluid. This can be solved using only one type of stainless steel in food equipment construction. Another solution is to ground the equipment.
4. *Corrosion forming spots.* Caused by metallic surface fouling. This can be avoided by maintaining clean surfaces. Contact of metallic surfaces with chlorine products for an excessive time may also cause corrosion and spots.
5. *Stress corrosion.* Caused by application of excessive mechanical stress to certain areas. For example, the brace disposition over a stainless steel surface may cause stress corrosion in this area.

The aggressiveness of food on equipment construction materials will depend on temperature, pH, food rugosity (abrasiveness), flow velocity, and contact duration. Once these aspects are known, the corrosion of stainless steel, from chlorides for example, can be reduced by delaying the addition of salt during heating (as much as possible) to the jacketed tank heated by steam, which is used to process sauce containing salt. Maintenance of brine pH between 7.5 and 8.0 is also recommended; if a different pH is sustained, corrosion will appear.

The most corrosive products are those containing vinegar and salt. In these cases, including more acidic products like lemon juice and sweet pickled cucumbers (pH=3), AISI 316 stainless steel is the most suitable material. The most corrosive chemical products are hypochlorines, but there is no danger of stainless steel corrosion in typical concentrations.

7.2.2 Aluminum

Aluminum has a high thermal conductivity, around 217 W/m.K or 187 kcal/h.m.°C, and a specific weight of 2700 kg/m^3. It is corrosion resistant under normal conditions during the distillation of water, fruit juice, milk, and SO_2. It does not, however, resist attack by hydrochloric and hydrofluoric acid, or caustic solutions. For this reason, alkali products must not be used with this material. Acid cleaning agents, on the other hand, are appropriate for aluminum.

Currently, aluminum is used in the construction of some parts of food process equipment. It is not as corrosion resistant as stainless steel, and it is not as resistant to abrasion from cleaning and sanitization products and foodstuffs. This is the main reason why aluminum, once widely used, is now seldom used. Even beer barrels are currently made of stainless steel, since it has better mechanical resistance and does not require a protective coating, an aspect that reduces maintenance cost.

7.2.3 Nickel and Monel

Pure nickel and monel (an alloy with 67% nickel, 28% copper, and the remainder iron and manganese) were widely used in preference over nude or tinned copper for food equipment until stainless steel proved to be the more satisfactory material.

In the beginning, pure nickel was used to construct milk pasteurization equipment and jacketed vessels heated by steam for soup processing. Some jacketed vessels are still in operation after more than 50 years due to the high overall coefficient of heat transfer obtained from these vessels manufactured with nickel. From experimental data on heating water with jacketed vessels made of nickel, an overall coefficient of heat transfer of 1715 kcal/h.m.°C at the heating stage, and 3300 kcal/h.m.°C when boiling, were obtained. On the other hand, when jacketed vessels were manufactured with stainless steel, only 1200 kcal/h.m.°C and 2450 kcal/h.m.°C were obtained during heating and boiling of water, respectively.

A negative characteristic of nickel is that it is sensitive to sulfur products. To solve this problem, jacketed vessels have been constructed using nickel only in the jacketed area and stainless steel over the liquid level when the damage from sulfur products is severe.

Monel was initially used in ice cream processing and other applications, but has been replaced by stainless steel. An alloy of nickel, zinc, and copper has been used in casting pieces for valves, mainly for closing devices, since it exhibits better mechanical abrasion resistance than nickel or stainless steel. This alloy must not contact food, however, since zinc and tin are toxic.

Monel is the preferred material for common salt processing systems since it exhibits even better corrosion resistance than stainless steel. It is also employed in pumps that handle alcohol, brines, vegetal oils, and fruit juices.

Other metallic materials used for food industry equipment are copper and bronze, which are mainly used in processing beer, alcohol, some calcium brines (with pH near 8), ketchup, citric acid, fatty acids and vegetal oils, distillate water, wine, whisky, and other distillates. In many cases, however, these materials have been replaced by stainless steel.

7.2.4 Plastic Materials

Plastic materials are used in harvesting and transporting agricultural raw materials to the food processing plant, in food packaging of solid and liquid foods, and even in food process equipment (mainly processing tanks). The most important plastics are (Robledo and Martin, 1981):

- *Polypropylene*. Used for hampers and large trays in harvesting and transporting agricultural raw materials to factories, for example, hampers made of polypropylene in grapevine harvesting.
- *High density polyethylene*. Most commonly used material for boxes in fruit harvesting, since it's more durable and lower in maintenance cost than wood. Polyethylene (PET) is used for packaging milk, beer, and juices. Harvesting nets for olives and almonds are also made of polyethylene and polypropylene.
- *Rigid PVC*. Used for packages in collecting and shipping small fruits and vegetables (strawberries,

Figure 7.7 Carbon steel stirring tanks with chemical resistant epoxy lining for citrus juice aseptic storage (see www.enerfab.com). Tanks can range up to 4.000 m^3 capacity.

cherries, grapes, raspberries, radishes, etc.), along with polystyrene. Also used in packaging edible oils, wine, vinegar, mineral water without gas, etc.

- *Polyester*. Commonly used, when reinforced with fiberglass, for tanks in olive lactic fermentation, substituting the traditional wood hogshead of 400 kg capacity. Polyester is alkali (caustic soda 4ºBé), acidic (pH = 4), and chloride resistant. Also used for storage of olive oil. Tanks made with polyester exhibit good mechanical resistance, acceptable durability, no metallic contamination in food products, and easy cleaning characteristics. Tanks are also used in production and storage of wine. In these cases, tanks range up to 500 m^3 capacity, with 10 m diameter.
- *Epoxy resins*. Used for lining of cement and carbon steel tanks to avoid corrosion in wine and juice processing and storage, simplifying cleaning and sanitizing, and improving surface finishes in contact with food and cleaning/sanitizing products (Figure 7.7 and Figure 7.8).

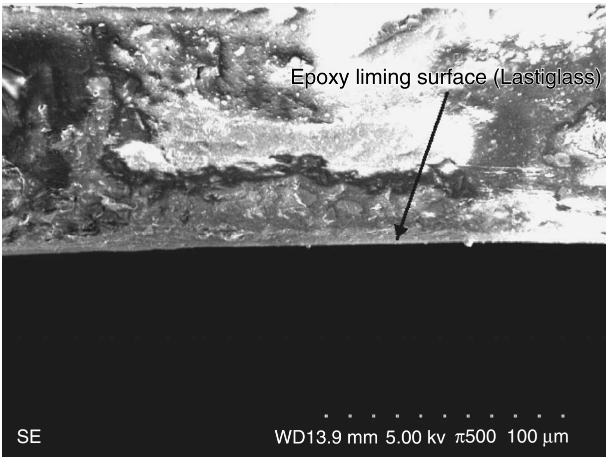


Figure 7.8 Electron micrograph of surface finish for carbon steel epoxy lining (Ra < 0, 40 µm).

In flexible pipes, natural or synthetic rubber was commonly used in the past. However, PVC, polyethylene, nylon, and propylene are more widely used today.

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8

Hygienic Design of Processing Systems and Auxiliary Systems

8.1 BASIC PRINCIPLES FOR HYGIENIC DESIGN OF FOOD EQUIPMENT

The following basic principles were derived from the FMF/FMA Joint Technical Committee (1976) and reviewed by Jowitt (1980); and then standardized by several organizations as the European Hygienic Engineering and Design Group, www.ededg.org, and the American National Standard Institute (ANSI) www.ansi.org:

a) All materials in contact with foods must be inert under operating conditions. Material must not migrate to food, causing toxicity problems or product quality modification.
b) All surfaces in contact with foods must be smooth, polished, and nonporous to avoid buildup of small food particles, bacteria, and insect eggs in surface crevices. Food residuals must not be observed in surface microscopic analysis. Dirt residuals become difficult to remove and are potential sources of contamination and infection of food. Sterilization cannot be achieved with common cleaning and sanitizing operations unless surface sterilization treatments are carried out. The objective is to achieve

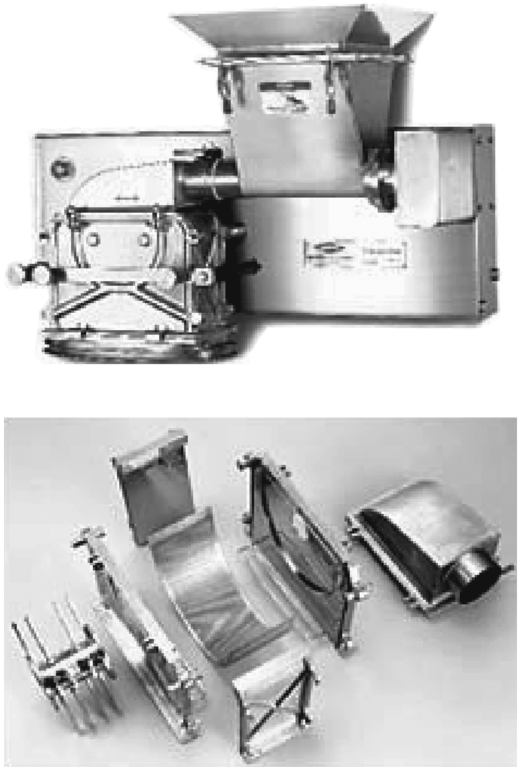


Figure 8.1 Readily disassembled mill for inspection, cleaning, and sanitizing (courtesy of Fitzpatrick Co., www.fitzmill.com).

acceptable cleaning and sanitization levels according to food product and operation conditions.

c) All surfaces in contact with foods must be visible or accessible for inspection. Equipment must be readily accessible for disassembly and inspection (Figure 8.1), or demonstrated that routine cleaning procedures can achieve acceptable levels of hygiene, cleanliness, and sanitization without bacterial or insect contamination. In this respect, all surfaces in contact with food must be readily accessible for manual cleaning, or, if automatic cleaning techniques are used, results achieved must be equivalent to those in manual procedures.

d) All interior zones of equipment in contact with foods must accommodate easy self-draining of liquid foods and cleaning/sanitizing chemicals. This is important since accumulation of food or cleaning products in defined internal zones of processing equipment may result in microorganisms and subsequent food contamination, creating hygiene problems in processes.

e) Food equipment must be designed to protect food contents (in processing stage) from external contamination. External surfaces and those normally not in contact with foods should be arranged to avoid dirt accumulation and to permit easy cleaning. Consequently, all equipment components should be accessible for ready cleaning, and designed to permit complete self-draining of cleaning agents to avoid accumulation of such products or rinsing water.

The designer must not only take into consideration the compatibility of the equipment and the food product, but also must bear in mind the cleaning and sanitization processes used to resolve any compatibility problems with equipment and cleaning agents, and thus achieve a design that permits appropriate hygienic process conditions. It is important to remember that unless aseptic packages and storage are required, there is no need for an aseptic design. The process design must be carried out to achieve *acceptable contamination conditions*. Acceptable contamination levels will be different, for instance, in liquid milk processing and winemaking processes. In other words, different process systems and food products may require different standards of hygiene. In any case, the design must ensure acceptable cleaning and hygiene conditions.

In order to achieve the desired hygienic design, inert construction materials with suitable stability and mechanical characteristics should be used. These materials should have surface finishes according to the hygienic conditions of the plant (No. 4 is used for surfaces in contact with food) and should be stable at working conditions. The equipment assembly should also fulfill certain conditions. For pipe fittings in permanent contact with food, for example, a welded fitting (with similar resistance and surface finish to the metal secured) is preferable to a screw fitting, since pipe fittings sometimes create zones that are rather difficult to clean. On the other hand, if O-ring fittings are used, inert materials with adequate corrosion resistance and surface finish should be chosen (natural or synthetic rubber, chlorineprenstyrene, buthadien-acrylonitryle, or silicone).

As mentioned in Chapter 7, AISI 304 stainless steel is the most widely preferred construction material in the food industry, from a hygienic point of view, and AISI 316 is favored in extremely corrosive conditions. Other metallic materials or plastics, however, can also be used.

Materials, including zinc (e.g., galvanized steel), can only be used for pipes that carry water at pH 7. Lead can only be utilized in welding, not exceeding 5% in composition. Cd and Sb are not suitable components of material for food equipment construction. Plastic materials containing free phenol and formaldehyde groups must not be used, and wood should be avoided due to difficulties in cleaning.

8.2 HYGIENIC DESIGN OF AUXILIARY SYSTEMS IN CONTACT WITH FOODS

8.2.1 Tanks

Design of process and storage tanks for liquid foods must take into consideration the ease of cleaning and method of cleaning, whether manual or automatic (Kessler, 1981). For hand cleaning, the diameter of horizontal tanks and the height of vertical tanks should allow access for manual cleaning of all zones in the tank. If a clean-in-place (CIP) system is used, tank design will take into consideration the spray or distribution system of cleaning agents (Figure 8.2).

Internal surfaces of tanks should have a No. 4 finish or equivalent. Construction materials should meet all the above mentioned requirements (Figure 8.2).

Design of tanks should avoid external contamination of food during processing or storage. The disassembly accesses should therefore ensure good closure. It is recommended that

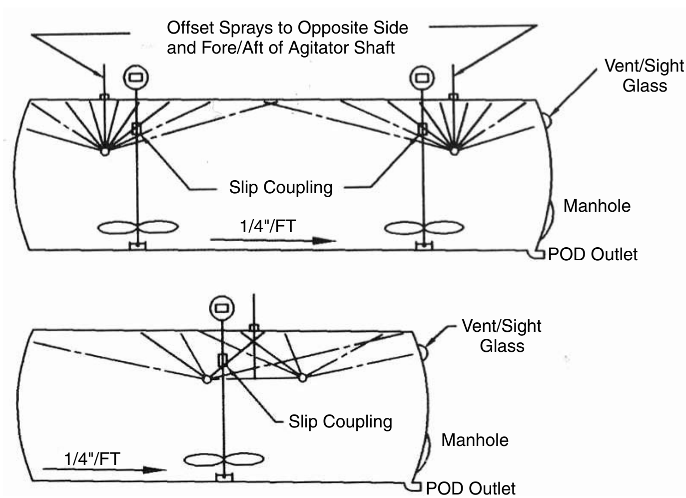
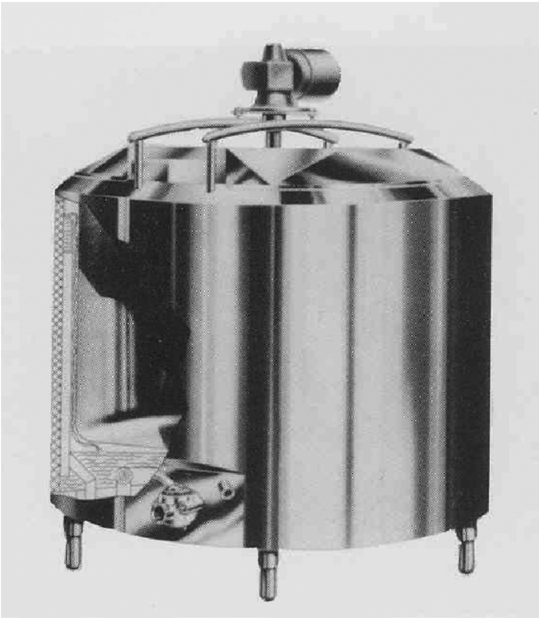


Figure 8.2 Process tanks connected to CIP system (courtesy of D. Seiberling, www.seiberling4cip.com).

tanks include lids for inspection and cleaning. At the same time, it is essential that tank mouths or lids not cause drainage into the tank when opened. Agitators and coils to heat or cool inside the tank are necessary in some cases. The internal



(a)

Figure 8.3 Hygienic design of process tanks: the legs have sphere ends (a) or flat ends (b).

arrangement of these devices should allow adequate cleaning and inspection and should be easy to disassemble.

For ease of cleaning and sanitizing of tank interior zones, construction that forms right or pointed angles must be avoided. All internal corners of wall-floor and wall-ceiling intersections in the tank should be arranged with a minimum radius of 2 in. to facilitate tank cleaning and sanitizing. It is also advisable to avoid overlapped, soldered joints where possible. If overlapped welding is used, however, it should be made with a generous welding fillet radius. All stainless steel welding joints should be continuous with welding material of similar composition (Hall and Farrall, 1986).

(b)

Figure 8.3 (continued)

The necessary wall thickness of tanks must be adequately calculated in order to avoid stress corrosion in the construction material. Mechanical evaluation should take into account the agitators and other internal tank equipment, and their design and position in the tank should be through hygienic seals to prevent food contamination by mechanisms, lubricating oils, and other external foreign materials.

It is advisable to avoid acute angles and other possible dirt harbors in the leg-floor joints of the tank. Sphere-ending legs (Figure 8.3) are preferable, but flat-ending legs are sometimes necessary and must be fixed to the floor over a plate. The tank legs must be arranged with a minimum of 20 cm height from the floor to simplify cleaning under the tank. In addition, the tank-wall and tank-ceiling separations should be large enough to allow access to cleaning operations (Figure 8.2 and Figure 8.3) (Hall and Davis, 1979; Leveau and Bouix, 1999).

8.2.2 Pumps

Pumps are standard design equipment. Some types of pumps, such as sanitary and aseptic pumps, exhibit special hygienic designs, but most only have hydraulic and mechanical design criteria. Nonetheless, it can be observed that some types of pumps are inherently more hygienic. It is possible, therefore, to state an order of precedence in selecting pumps based on hygienic design criteria. The following pumps can be ordered at high to low hygienic levels:

1. Peristaltic pump
2. Diaphragm pump
3. Centrifugal pumps with open impeller
4. Centrifugal pumps with closed impeller
5. Positive displacement rotary pumps: (a) flexible simple lobe-rotor pump; (b) screw pump with flexible stator; (c) double lobe-rotor pump
6. Reciprocating pumps: (a) single-piston pump with external valves; (b) multipiston pump with external valves; (c) single-piston pump with internal valves; (d) multipiston pump with internal valves; (e) double-acting piston pump with external valves; (f) double-acting piston pump with internal valves

Selection of the pump should involve economic, mechanical, and hygienic design criteria. If the pump is going to displace a high flow rate of liquid and have low head losses, centrifugal pumps (Figure 8.4 and Figure 8.5) or positive displacement pumps such as the screw pump should be chosen. If the required amount of fluid pumped is small or moderate, and the head losses in meters is high, a positive displacement pump such as the screw pump (Figure 8.6) or double lobe-rotor (Figure 8.7) should be selected. If the viscosity of the fluid is high, a positive displacement pump, such

Figure 8.4 Sanitary centrifugal pump constructed in stainless steel, with a mirror surface finish (courtesy of Alfa Laval, www.alfalaval.com).

as the double effect pump with a rigid piston (Figure 8.7) should be chosen.

The surfaces of fluid passing zones within the pump should be smooth and adequately polished. If flow through the pump is very turbulent, corrosion problems could arise. Dead flow zones should be avoided wherever dirt accumulation is possible.

Usually, an easy-to-assemble sanitary pump is readily accessible for cleaning and has a minimal number of parts (Figures 8.5, 8.6, and 8.7), which increases the rapidity of disassembling. Screw threads in contact with food should be avoided. Bearings should be located outside the food product zone and should be sealed to separate both areas and prevent contamination. Pumps designed to be readily drained of a product (food or cleaning agents) are also worthy of note. In other words, the automatic draining and filling of pumps should be convenient. All external parts of the motor-pump group should also be easy to clean. Sanitary pumps in which the motor is covered by stainless steel, converting it to a very suitable hygienic design (Figure 8.8), are good solutions.

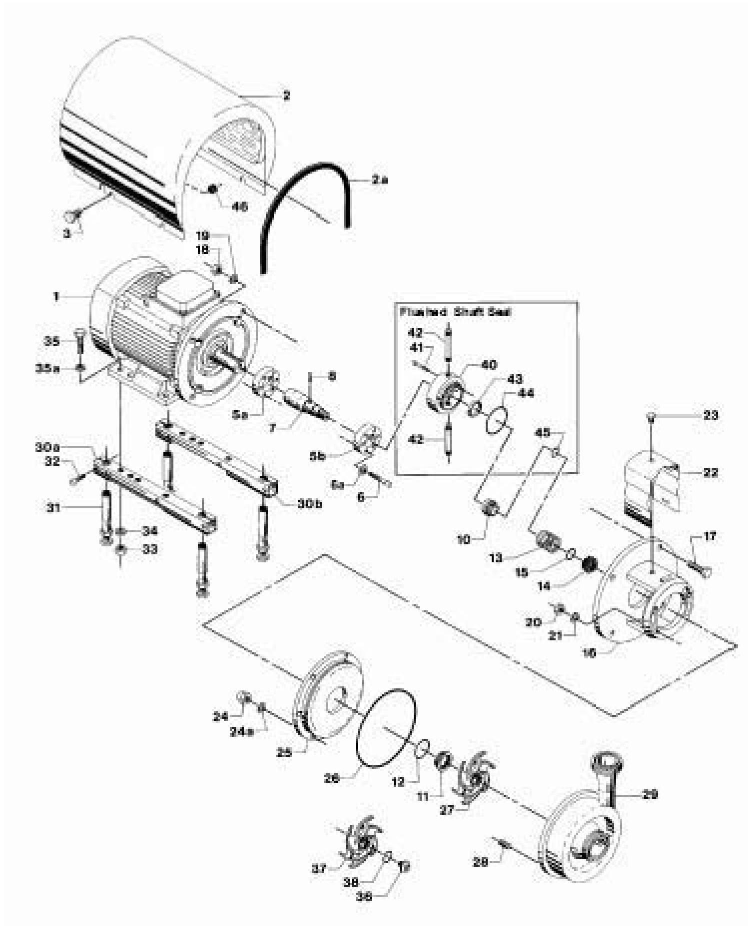


Figure 8.5 Construction details for a sanitary centrifugal pump with open impeller and mirror surface finish (courtesy of Alfa Laval, www.alfalaval.com).

Both portable and fixed pumps should be supported on legs (Figure 8.8) that are conveniently polished, avoid screw-nails, and have round ends for easy cleaning access, including under the motor-pump group.

Finally, if the power transmission system is connected to the high pressure side of the screw pump, it will not be

Figure 8.6 Positive displacement rotary pump with screw rotor, constructed in stainless steel and stator in plastic material (courtesy of Alfa Laval, www.alfalaval.com).

possible for external air and contaminants to enter the food product pumping zone, because liquid will leave at higher than atmospheric pressure.

In the aseptic version pumps, live steam or sterilizing solution is circulated to ports, the cover, and product seal areas, where bacteria might enter (Figure 8.9).

8.2.3 Valves

Valves can also be classified according to design and type in decreasing order from the hygienic design point of view:

1. Flexible seat and closing plug valves, such as pinch cock valves (mechanically, hydraulically, or pneumatically operated) and diaphragm valves
2. Butterfly valves
3. Ball and seat valves
4. Globe valves
5. Gate valves
6. Needle valves, etc.

According to this classification, the most hygienic valves are the types with mechanisms that do not contact liquid food. This is why the sealing procedure is very important in avoiding the entrance of external contaminants. There are different types of efficient seals, including the diaphragm, O-ring, and packed gland seals.

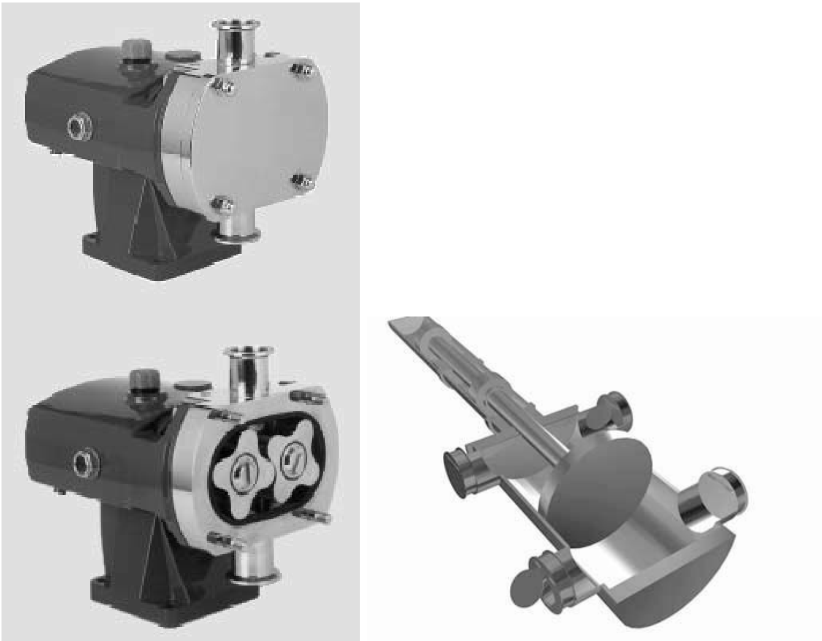


Figure 8.7 Positive displacement rotary pump with lobe-rotor (left) (courtesy of Alfa Laval, www.alfalaval.com); (right) Double effect pump with a rigid piston, especially designed to delicately pump particulate products and shear sensitive products (for handling whole fruits and vegetables, slices and dices of fruit; in aseptic construction the separation chamber is steam sealed; courtesy of HRS-Spiratube, www.hrs-spiratube.com).

A valve must be self-drained to be considered hygienic, so that no remnants of dirt such as food or cleaning product residuals remain. In addition, the valve construction materials in contact with food must be corrosion resistant and have a suitable surface finish.

The most hygienic valves are the pinch types or diaphragm valves, but they are inconveniently of limited use due to the flexible diaphragm, a relatively short-lived component. The diaphragm material also limits the temperature and pressure operating conditions. Cleaning products must also

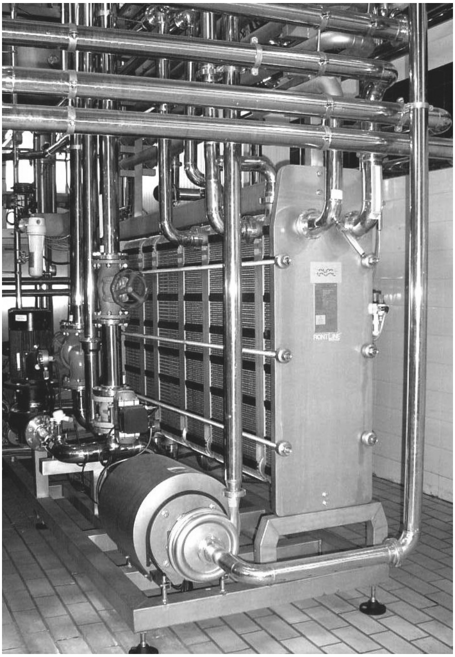


Figure 8.8 Engine pump group with sanitary centrifugal pump and engine lined with stainless steel sheets.

be carefully selected according to the diaphragm material. These valves are especially suitable for automatic operation with pneumatic or electromagnetic control (Figure 8.10).

The butterfly valve is not subject to limitations of temperature and pressure because its parts are all metal; it also incorporates good hygienic design (Figure 8.11).

The seat valve is the most widely used in the food industry because it is easily disassembled, cleaned, and reassembled. It is possible, however, for the product to remain between the plug and the valve body. The traditional design of globe valves and gate valves presents hygiene problems due to the accumulation of food in the valve body. There are, however, modified designs that solve this problem by incorporating an adequate hygienic design (Figure 8.12 and Figure 8.13).

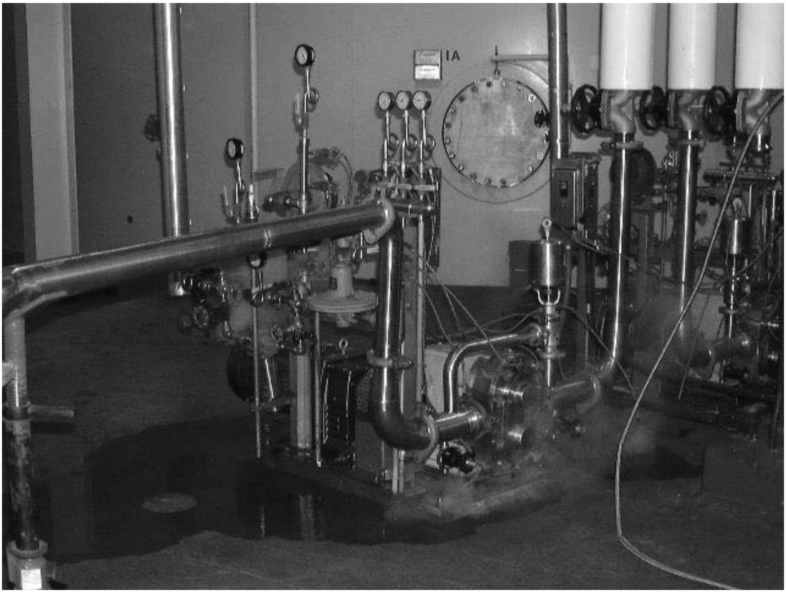


Figure 8.9 Aseptic pump with steam barriers.

For CIP systems and the product aseptic circuit, these hygienic valves must also guarantee an adequate seal to prevent food contamination (Figure 8.11, Figure 8.12, and Figure 8.13).

The design of the aseptic valve chamber in Figure 8.14 eliminates dead legs and isolates the product from the environment by using either PTFE or metal bellows. The aseptic design is also complemented by a high surface finish and bellows materials that reject soil adhesion. These features, combined with the ability to steam the internals of the valve at high sterilization temperatures, result in absolute operational security.

8.2.4 Pipes

The following items deserve special scrutiny in the hygienic design of pipes:

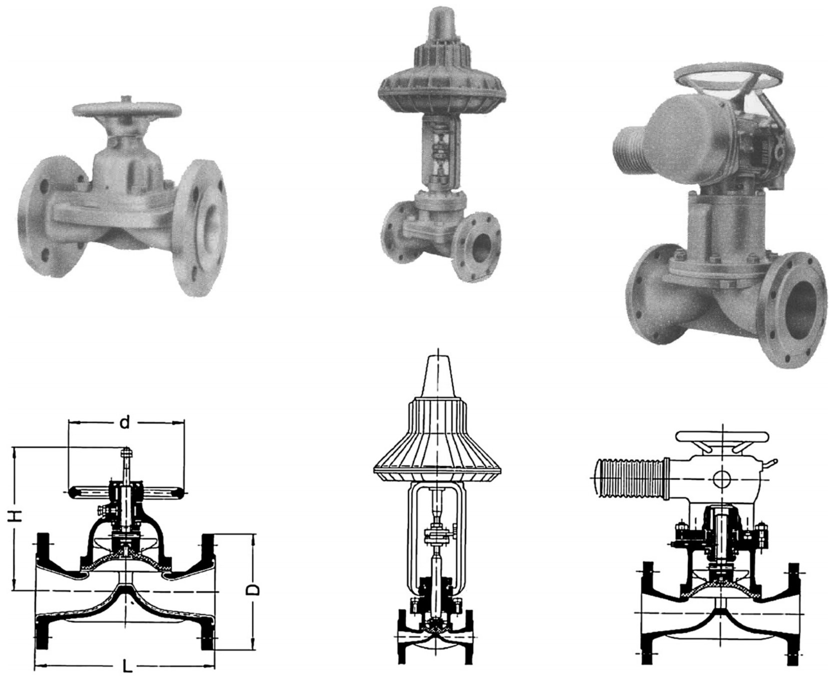


Figure 8.10 Diaphragm valves with manual, pneumatic, and engineered actuators.

a) *Pipe fittings*. Internal pipe surfaces must be polished at joint points. This means that pipes must be joined by welding or by using the easily assembled sanitary fittings. Screw fittings present hygienic problems. The surface finish of the weld should be polished so that it is similar to the rest of the internal pipe surface. Easy-to-assemble sanitary fittings solve this problem with a suitable level of hygiene (Figure 8.15 and Figure 8.16). The design of aseptic fittings in Figure 8.15 eliminates any crevices, and the use of metal-to-metal contact protects the gasket from over compression during steaming cycles and at other times during high temperatures. These aseptic fittings also

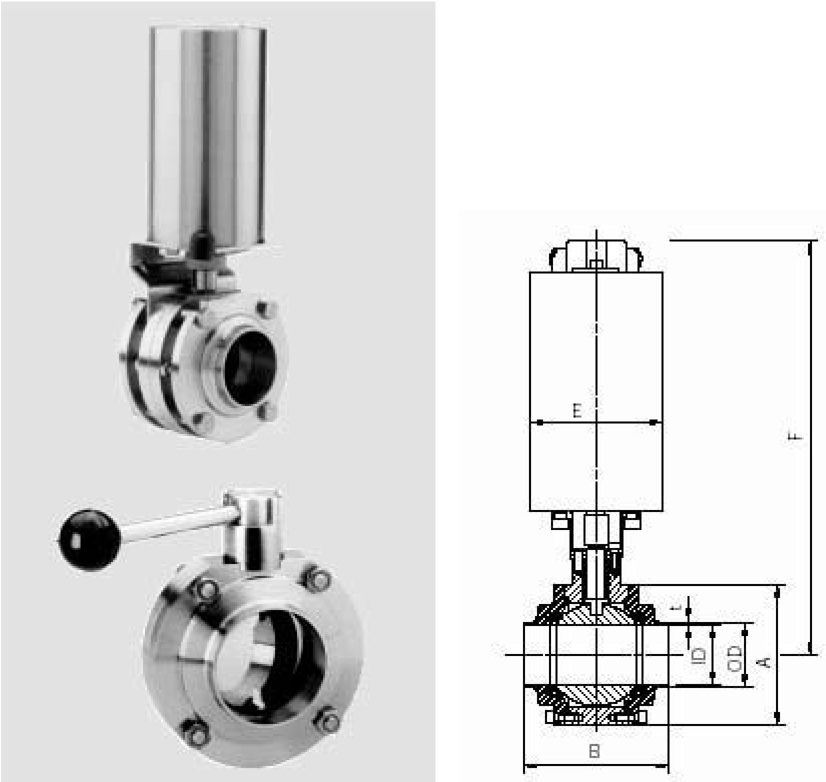


Figure 8.11 Sanitary butterfly (left) and ball (right) valves (courtesy of Alfa Laval, www.alfalaval.com).

benefit from a self-centering design that ensures perfect alignment of the gasket and fitting components every time.

b) *Construction and surface finish materials*. If stainless steel is employed, AISI 304 or AISI 316 is used, and a No. 4 surface finish will be required, always depending on the properties of the liquid food being processed. For fixed or disassembling rigid pipes, glass and plastic materials (PVC, polyethylene, etc.) may be used for food handling in addition to stainless steel. In the construction of flexible pipes or hose, PVC, polyethylene, nylon,

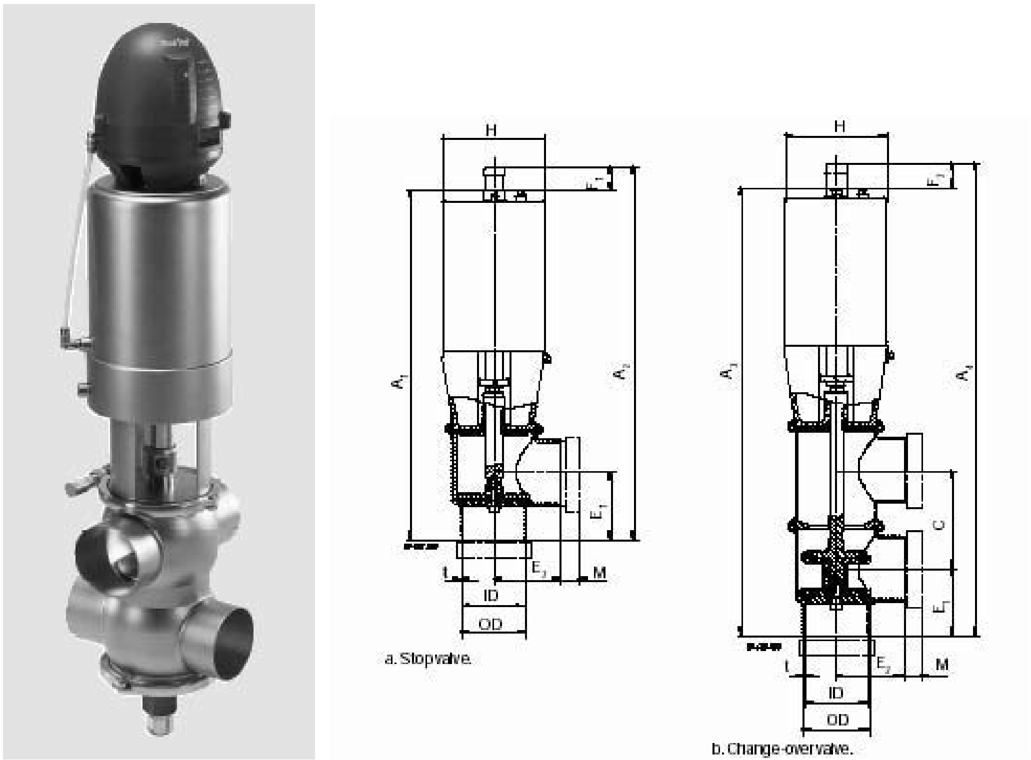


Figure 8.12 Double-seat mix proof valves (at left). At right, single (stop valve) and double-body (change-over air operated valves (courtesy of Alfa Laval, www.alfalaval.com).

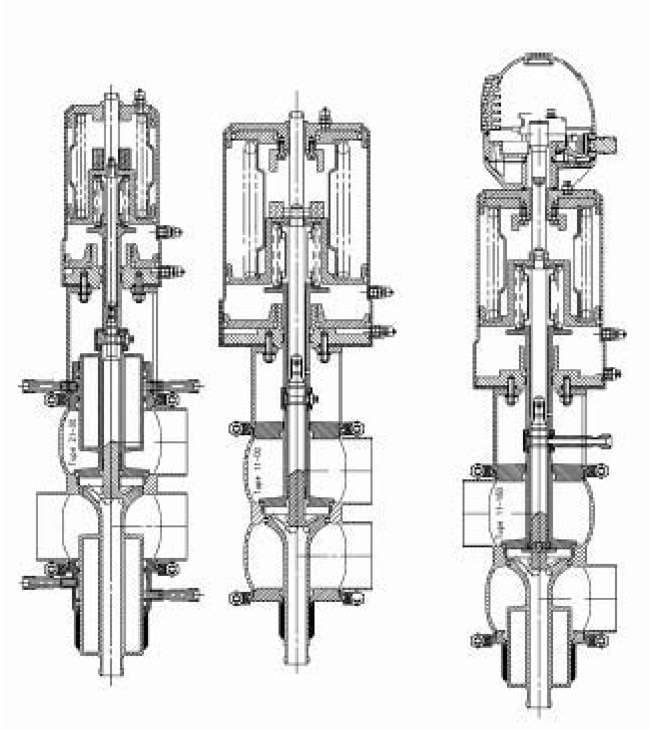


Figure 8.13 Mix proof valves. The aseptic valve is equipped with steam connections to form a steam barrier to the atmosphere (courtesy of Alfa Laval, www.alfalaval.com).

and polypropylene are used. In any case, the internal surface finish must be similar to stainless steel No. 4 in order to permit a satisfactory manual or automatic (CIP) cleaning process.

c) *Fixed pipes arrangement*. Piping should be arranged so that easy and complete self-draining can be achieved while avoiding accumulation of food and cleaning products. A minimum slope of 0.4% toward the draining points is recommended. Pipes should be accessible for inspection and maintenance.

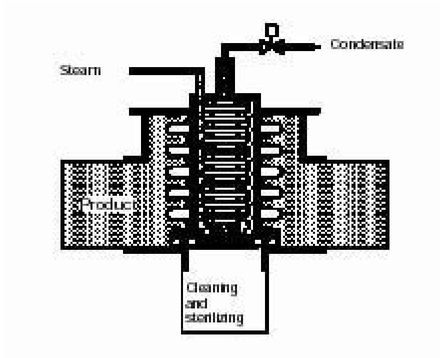


Figure 8.14 Aseptic valves with steam barrier (courtesy of Alfa Laval, www.alfalaval.com).

8.3 EXTERNAL DESIGN OF PROCESSING EQUIPMENT AND AUXILIARY SYSTEMS

All motors should be effectively enclosed if there is the possibility of being contaminated by nearby food or cleaning products. The outer surface or shell of the motor is usually made of stainless steel or plastic material with a good surface finish to permit easy cleaning (Figure 8.8). An appropriate distance between the support base and motor is also necessary.

Power transmission between electric motors and pumps or action mechanisms (screw conveyor axe, driving cylinder in conveyor belts, etc.) should be designed so that contamination of food during processing or transport is not possible. Direct drive is the simplest form of power transmission that passes through the motor shell, which can be conveniently sealed. Other driving forms include the V-belt drive, gear train, and chains. These also can be conveniently sealed to prevent food contamination and facilitate external cleaning.

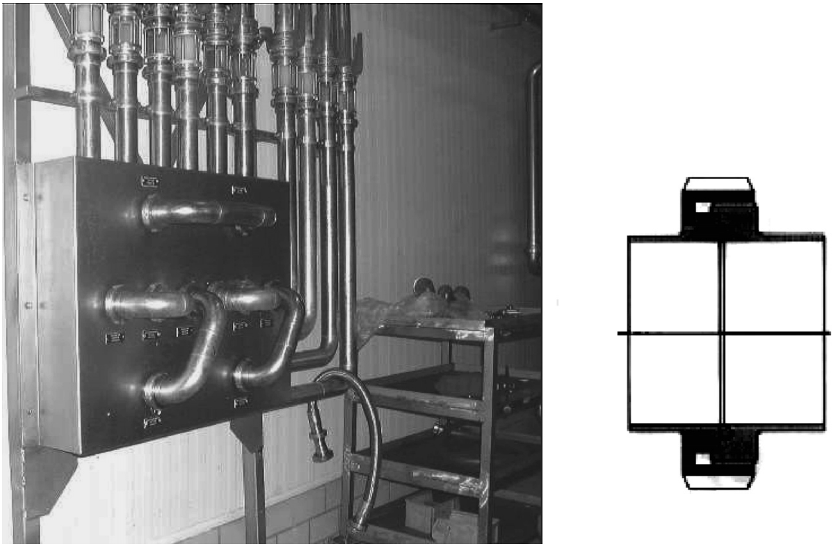


Figure 8.15 A swing bend or transfer panel for manual change between different lines (left), with aseptic fittings (right).

Figure 8.16 Sanitary unions in stainless steel pipes (courtesy of Alfa Laval).

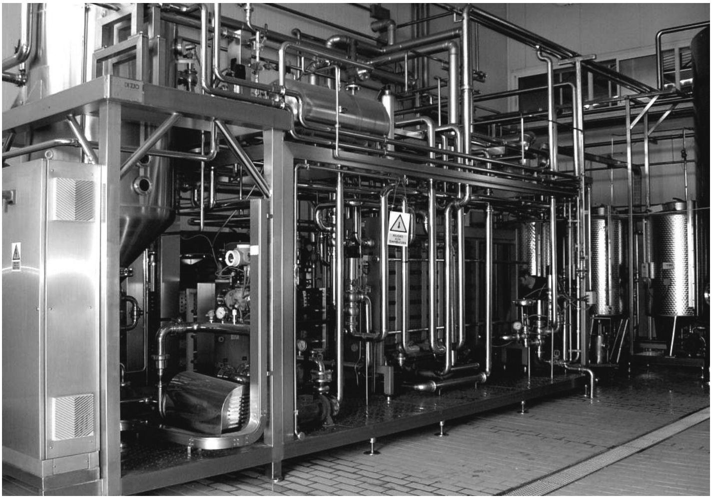


Figure 8.17 An external hygienic design of food processing equipment.

In principle, processing equipment must be designed to avoid sprinkling of the exterior with food. In any case, there should be as little soiling of processing equipment in nearby areas as possible; equipment should appear aesthetically pleasing, be well finished (Figure 8.17) and clean, and avoid creating inaccessible spaces where dirt could accumulate. One solution would be to sufficiently separate (as necessary) the motor and drive, as well as equipment components difficult to clean from the "dirty" areas of food production and where cleanup should be intensified. Enclosing the equipment with an adequately fitted or hermetic shield would also improve the external hygienic design, thus simplifying cleaning. In this case, it is necessary to separate the equipment from the support base at a sufficient distance in order to conduct cleaning operations (Figure 8.18).

8.4 CIP (CLEAN-IN-PLACE) SYSTEM DESIGN

Internal cleaning of food equipment can be manual or automatic. In hand cleaning, equipment should be designed to

Figure 8.18 An external design of citrus juice processing line.

facilitate disassembling for cleaning and subsequent reassembling (Farrall, 1976, 1979). Manual cleaning, however, requires a great deal of time and labor. On the other hand, automatic cleaning is carried out without disassembling the equipment, resulting in great savings in cleanup labor cost and time. This procedure is referred to as a clean-in-place (CIP) system. When applying a CIP system, a series of items should be considered (Seiberling, 1979, 1986, 1992, 1997):

a) The food processing plant in which the CIP system is installed must exhibit hygienic design. The design solution for equipment, including construction materials, should permit the installation of this system. In other words, if the CIP system is installed in a running process plant, it must be assumed that similar or better hygienic levels will be achieved.

b) Careful selection of cleaning products in conjunction with type of soil removed and materials used to construct food equipment.
c) Impact of the CIP system installation on total cost must be estimated, since supplementary capital investment and other operation cost will be needed. Installation of the CIP system must be profitable and economically feasible.

As explained above, CIP systems are automatic systems, a characteristic that leads to labor cost savings and enhanced safety, since personnel are not in contact with chemicals (caustics), and the recovery of cleaning agents makes their reuse possible.

There is a different CIP system design applicable to each food processing system and food plant, according to its size and arrangement. Two different basic CIP systems can be distinguished, however: one that uses cleaning agents only once (single-use CIP systems), and one that recovers and reuses cleaning agents and water as much as possible (multiple-use CIP systems).

8.4.1 Single-Use or Single-Tank Systems

A single-use CIP technique is implemented when the reuse of cleaning agents is not convenient or not possible. For example, with high soil levels, occurring in must and wine clarification tanks, the reuse of cleaning products is not recommended.

In general, single-use systems are small units with a relatively simple design, normally placed near the food equipment to be cleaned. The main components follow (Figure 8.19):

- One cleaning product tank where different components are formulated (cleaning agent, wetting product, water, stabilizing agents, etc.). It might include level indicators and automatic dosage systems for water and cleaning products, as well as an automatically controlled heating system.
- One centrifugal pump, usually a sanitary pump
- The piping system which is usually nondisassembling and made of stainless steel

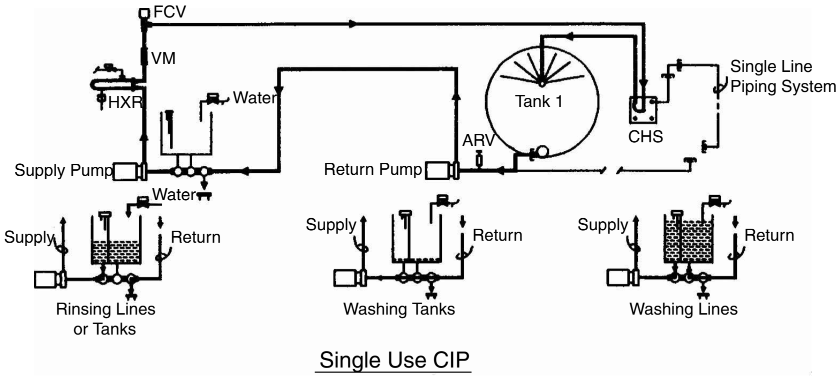


Figure 8.19 Single-tank CIP system (courtesy of Dale A. Seiberling, www.seiberling4cip.com).

Because there is continuous application of the cleaning product for a certain period, not only are the pumps and a cleaning agent application circuit required, but a return line to the unique tank of the CIP system is also necessary (Figure 8.20). One or several pumps for the returning line will frequently be necessary. In any case, since the centrifugal pump's impeller suffers the abrasive effects of the insoluble solids in suspension, it is advisable to install a cartridge filter, in stainless steel, in the aspiration zone of the return pump.

A possible variation of the single-tank system would be to recover the water from the last rinse, which would have a low content of soil and detergents. Here, an additional tank for the recovered rinse water is needed.

As the containing liquid is circulated for a certain period, these tanks can be designed to contain 1.2 times the volume of the most unfavorable circuit capacity. For a tank cleaning, it is important to take into account the minimum amount of liquid remaining on the tank bottom that must be pumped

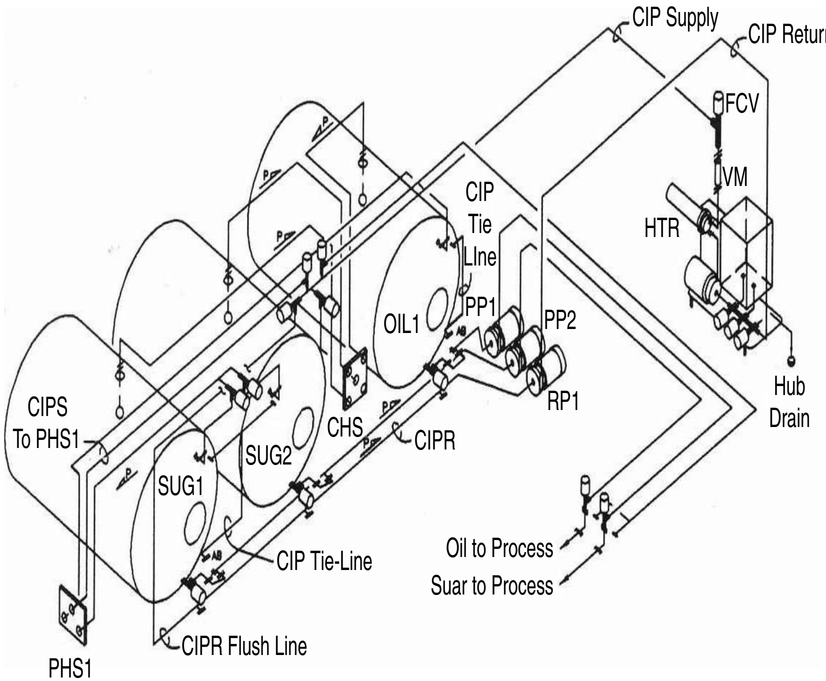


Figure 8.20 Single-use CIP system flowchart (courtesy of Dale A. Seiberling, www.seiberling4cip.com).

through the return line. The cleaning products and recovered water tanks have a capacity of between 1 and 2 m^3.

For example, a typical cleaning program for a liquid food processing tank would include these steps:

1. Three pre-rinses with water for 20 seconds with switch-off intervals of about 40 seconds each, to remove the gross soil. A CIP return pump discharges the water from the tank into a wastewater collector channel. To improve the efficiency of this step, the pre-rinse may be carried out using water recovered from the final rinse.
2. Application of cleaning agents with a given formula/concentration, and at a defined temperature achieved

through steam injection into the circuit (at the pump outlet) or through a heating system fitted inside the cleaning product tank. This stage is maintained by recycling the cleaning product for about 10 to 12 minutes, after which the spent chemicals are discharged into a drain channel.

3. Two intermediate rinses with cold water for 20 seconds with a switch-off interval of 40 seconds each, discharged into either a drain channel or a water recovery tank.
4. Final application of a sanitizing product for a few minutes.

8.4.2 Multiple-Use or Multitank Systems

When process systems are cleaned frequently, as in dairy plants, the soil removed from food processing equipment is relatively light. In addition, if a pre-cleaning phase exists during the cleaning process, the detergents and cleaning products will not become very contaminated. Therefore, in these cases, it is beneficial to recover and reuse the cleaning products as much as possible in order to reduce expenses and diminish contamination levels in the wastewater.

Essential components of a multiple-use CIP plant are (Figures 8.21, 8.22, 8.23, and 8.24):

- Alkali and acid detergent tanks and a sanitizing tank (each product in process is contained in a separate tank). These tanks are equipped with level probes and concentration control instruments (usually by conductivity), which control the dosage-reposition of any losses of cleaning or sanitizing products.
- Rinse water tank, optional
- Water and cleaning product heating system, using either direct injection of steam into the impulsion pipe, a heating steam coil fitted inside the tanks, or plate heat exchangers installed in the impulsion pipe, usually including a heat recovery body for returning liquids
- Sanitary centrifugal pumps for impulsion and return

- Connecting pipes, normally forming a fixed network with remote controlled automatic valves
- Filters
- Central control unit to apply automatic cleaning programs, ensuring the automatic sequence of different cleaning phases. This unit will activate and inactivate remote controlled valves (electromagnetic or pneumatic valves) and pumps by a preestablished cleaning plan.

The multiple-use CIP plants exhibit different layouts (Figures 8.21, 8.22, and 8.23). For example, one layout contains two alkali detergents with different concentrations. The lower concentration is used to clean the tanks and pipelines, the higher concentration to clean the plate heat exchangers. Neutralization tanks with automatically adjusted pH can even be provided to neutralize cleaning effluents.

For example, a typical multitank CIP program for tank cleaning would be as follows:

1. Pre-rinsing with water at net temperature, 3–5 minutes
2. Applying 1% caustic soda at room temperature or heated, 5–15 minutes
3. Intermediate rinsing with water, 3 minutes
4. Applying an acid cleaning product, 0.5–1%, at room temperature or heated, 5–15 minutes
5. Final water rinsing
6. Sanitizing

The pretreated rinse water must be recovered whenever possible. For example, the intermediate rinse water carries the detergent solution to the corresponding recovery tank, but when the water stream has a low detergent content (detected by conductivity), it must be pumped towards the water tank. The pre-rinse water is usually discharged into the wastewater drain.

8.4.3 Compact Systems and Foam-Cleaning Systems

Combining the features of multiple-use and single-use systems, a compact CIP system has a modular and completely

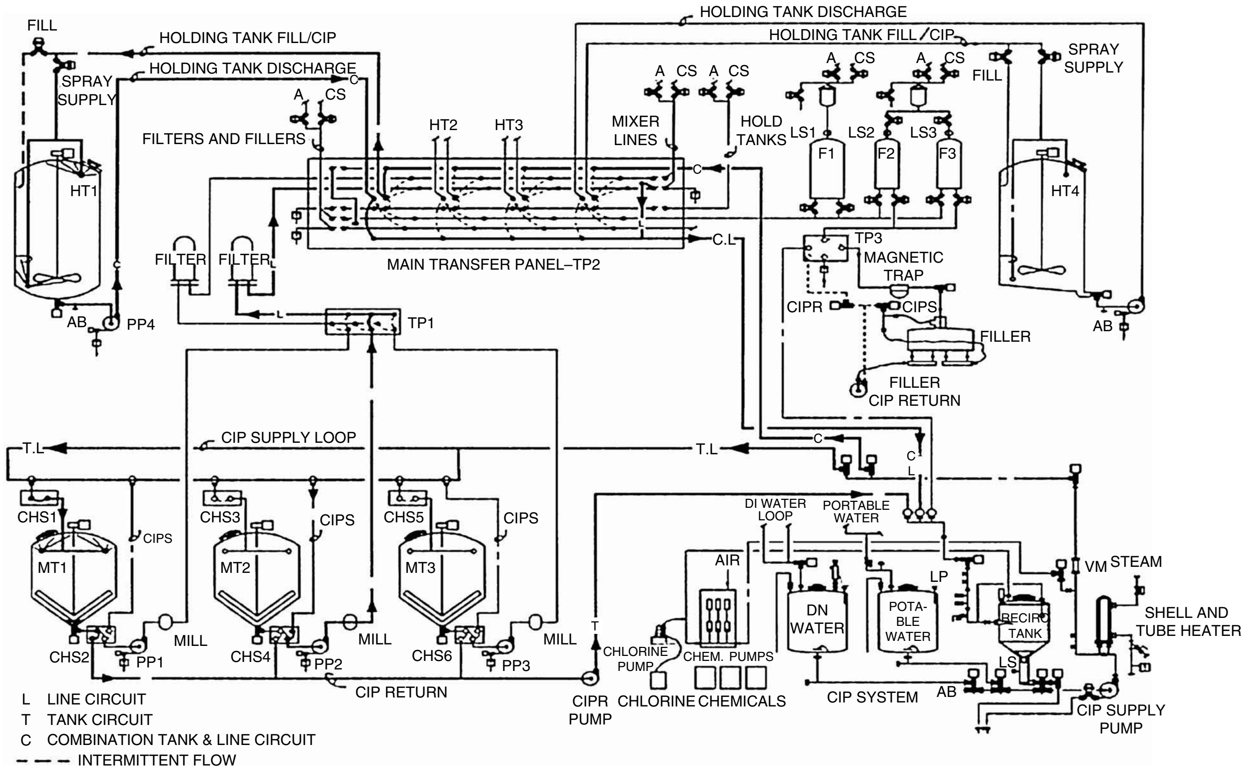


Figure 8.21 Multiple-use CIP system flowchart (www.seiberling4cip.com).

Figure 8.22 Multitank CIP system.

versatile configuration. It can have tanks for different cleaning chemicals and water recovery, with an associated impulsion pump, connection and distribution piping, and a heat exchanger, all assembled in one block. Some single-tank systems exhibit this compact design, which has the advantage of being portable and usable in different parts of the food processing plant (Figure 8.25, right).

Another type of CIP system generally used for cleaning and sanitizing the food equipment's external surfaces is shown in Figure 8.25. This foam-cleaning system is based on an innovative technology that makes high-pressure jet application obsolete. Using low-pressure foam technology, surface cleaning and disinfecting no longer requires violent mechanical action. This technique of combining detergents, water, and compressed air guarantees an optimal foam structure, ensuring sufficient contact time for loosening all soil from processing equipment external surfaces, work benches, walls, and floors. Too much foam is difficult to rinse away. If the

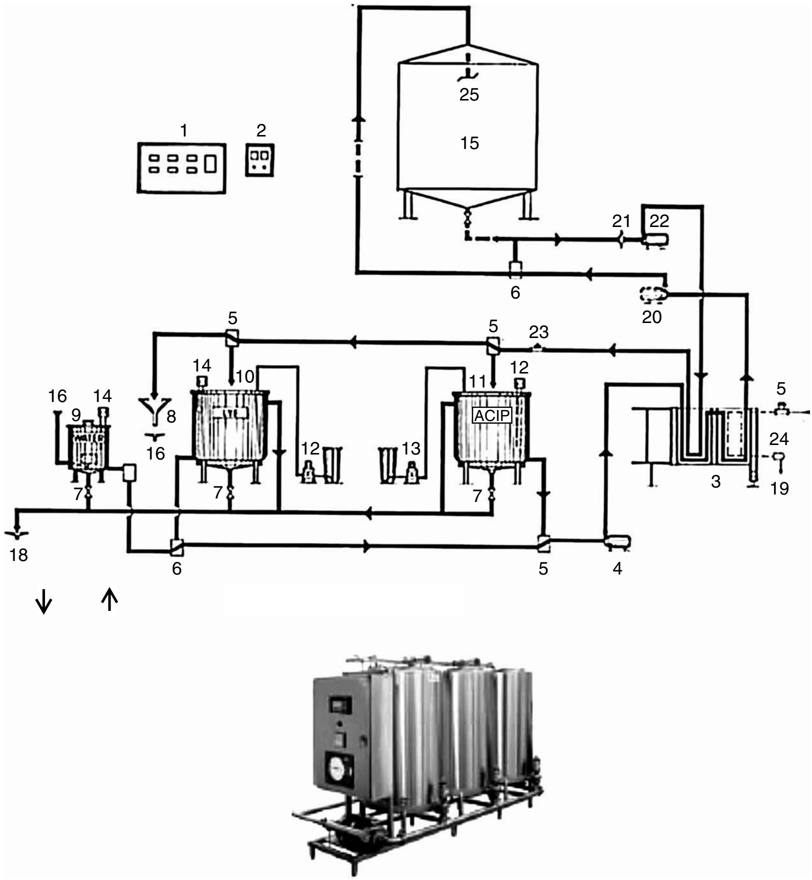


Figure 8.23 Detailed flowchart of multitank CIP systems for cleaning tanks (courtesy of Alfa-Laval) (top). Multitank CIP plant (bottom).

foam layer is very thick, or too wet, it will rinse off too quickly, causing inefficient product consumption. Foam produced by this system, however, has an optimal consistency and ideal structure that consists of millions of tiny bubbles. As these bubbles burst, they allow a slow release of detergent solution onto the soiled surface. Following this action, the foam and loosened soil are easily rinsed away. Another very significant advantage is that due to this new low pressure foam technology,

Figure 8.24 Multitank CIP system with concentration control instruments (by conductivity) and dosage-pumps to control the reposition of cleaning products.

soil and bacteria are no longer redistributed throughout the plant (Levean and Bouix, 1999).

Several satellites from this system, placed in different departments of a plant, can be connected together. Rinsing, cleaning, and disinfecting can be carried out simultaneously, with cleaning and sanitizing performed using different products at varied concentrations for each satellite location.

8.4.4 CIP System Design Details

CIP systems are designed according to the soil characteristics (nature, composition, and quantity), the most suitable cleaning frequency, and the equipment being cleaned: process or storage tanks, pipes, pumps or food processing equipment, such as heat exchangers and evaporators. Thus, the cleaning program to apply, the most adequate cleaning and sanitizing

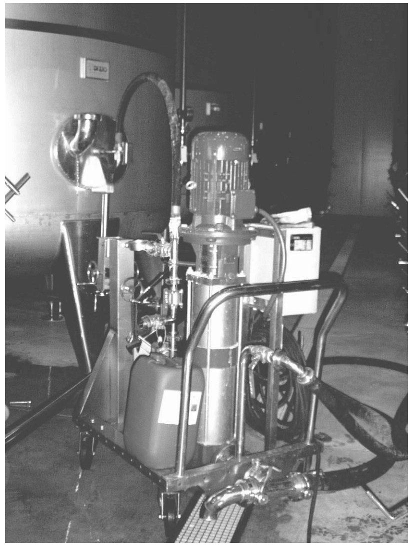


Figure 8.25 A foam-cleaning system (left); and a portable CIP system (right).

agents, and the frequency of application are determined (McKenna, 1984; Troller, 1983). The temperatures of the detergents and sanitizing agents and their mass flow rates will determine the size of the necessary heat exchanger. The selection of the best distribution system (spray-balls, rotating jets, etc.) depends on how the equipment will be cleaned.

8.4.4.1 Spray Distribution Devices

The main function of these devices is to distribute the cleaning agent uniformly over the entire surface being cleaned. Different types of spray distribution devices are used.

The fixed spray-ball (Figure 8.26) has a large number of advantages over rotating or oscillating jets:

- No moving parts
- Can be entirely made of stainless steel
- Not highly affected by variations in pressure (within certain limits)

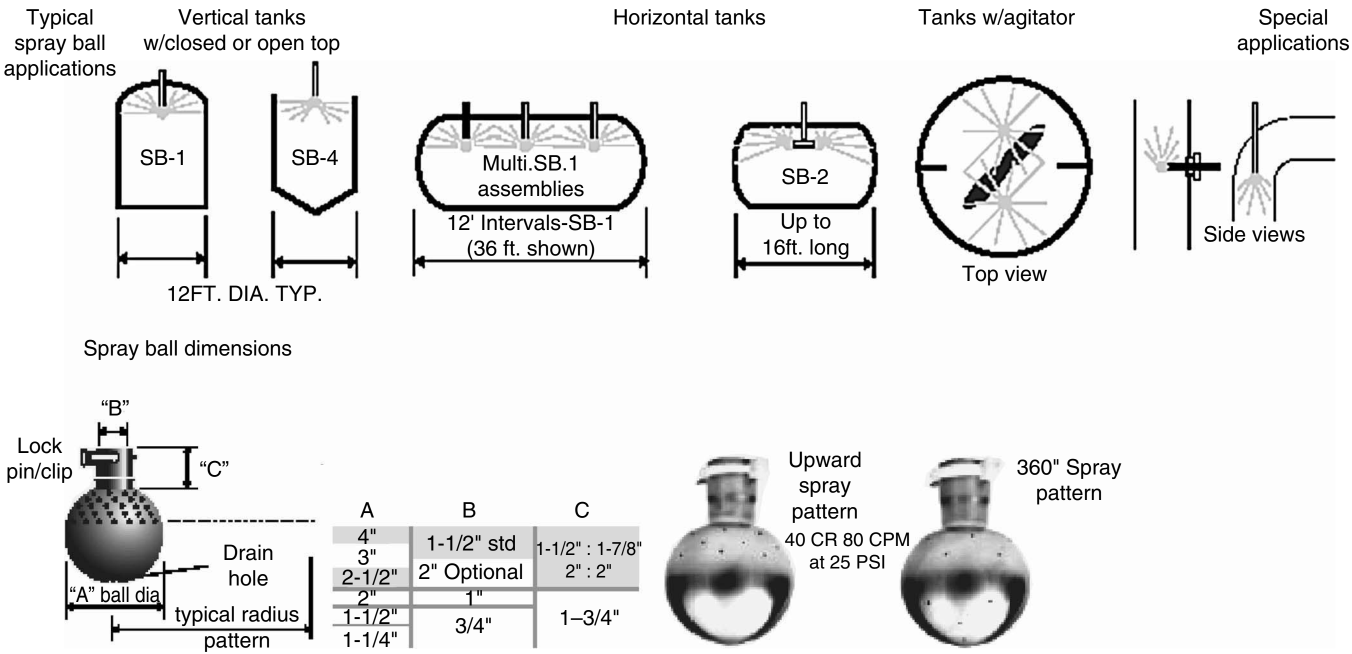


Figure 8.26 Spray-ball characteristics and applications (Sani-matic CIP Systems, www.sani-matic.com).

- Can operate with low flow
- Has an acceptable radial reach, providing continuous (not intermittent) surface wetting during the entire cleaning product application period

It has been proven experimentally that cylindrical and rectangular tanks can be properly cleaned by spray-balls with 0.64-2.04 l/s and m^2 of internal surface. Silo tanks require spray-balls with 0.52-0.62 l/s and a linear meter of circumference length. In this type of tank, however, spray discs are recommended for their wider radial reach (Figure 8.27).

Other designs for cleaning product distribution devices are spray rings and spray cane, used in evaporators, dryers, vacuum chambers, and other equipment of irregular design. All of these distribution devices, including spray-balls, allow the cleaning of more or less difficult points (Seiberling, 1997).

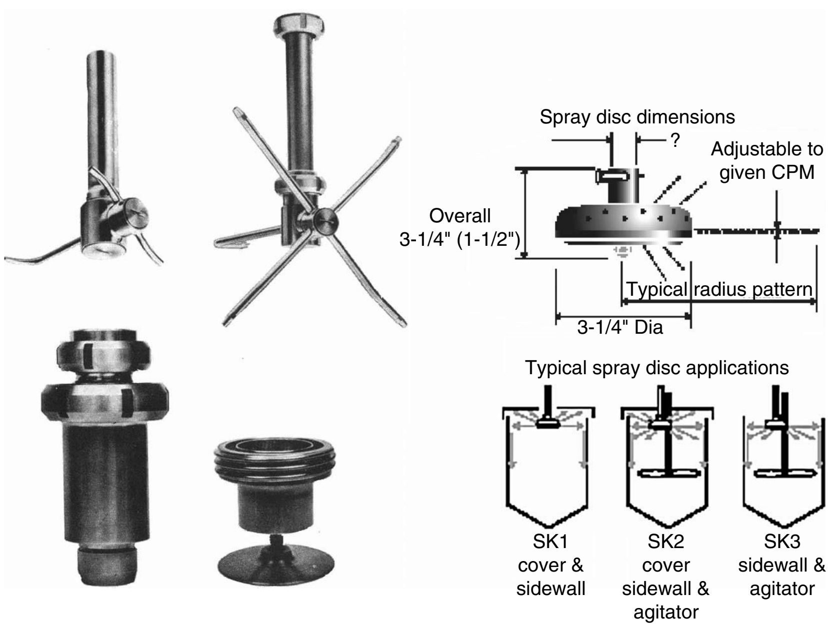


Figure 8.27 Different spray devices for distributing detergent products from a CIP system (courtesy of Alfa-Laval, and Sani-matic CIP Systems, www.sani-matic.com).

During the tank-cleaning process, it is convenient to apply water or cleaning products for 15–20 seconds three or more times; the tank should be completely drained between applications. This procedure is more efficient than continuous application and saves on water and detergents.

8.4.4.2 Pumps, Heat Exchangers, and Valves

The use of centrifugal pumps is recommended in CIP systems. In the impulsion circuit, high-velocity pumps are preferred (3000–3600 rpm) since they are able to move large amounts of product. Low-velocity pumps (1500–1800 rpm) will work best in the return circuit for filter feeding. If positive displacement pumps are used in CIP systems, lobe-rotor pumps are preferred.

For food pipeline cleanup, the pump must be designed to provide a circulating velocity of approximately 1.5 to 3 m/s to force cleaning agents through the pipes. Whenever the flow velocity is higher, the turbulence and the mechanical cleaning effect will be greater. Along CIP pipe circuits, the flow velocity should be 1.5 m/s since there is no cleaning action in these areas.

The most widely used heat exchangers used in CIP systems are plate heat exchangers, which feature easy cleaning and inspection. Shell and tube exchanger types are rarely used in the heating of cleaning agents and heat recovery, but do function well to steam-heat water.

In order to guarantee closure in the CIP circuit, special two- or three-way mix-proof valves are frequently used (Figures 8.12, 8.13, and 8.14). They guarantee that no contact exists between food and CIP chemicals, thus avoiding undesirable contamination. These valves are usually automatic with pneumatic mechanisms.

Two-way diaphragm valves have also been used in CIP systems, but they present cleaning and maintenance problems. These valves must be carefully selected according to the working conditions, temperature, and properties of the cleaning agents.

All remaining valve types can also be used, wherever they can accomplish minimum hygienic requirements, in those cases where a complete and sure enclosure is not required.

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9

Food Processing Plant Design Considerations

9.1 DESIGNING THE FOOD PLANT

A food processing plant consists of the food processing systems, auxiliary systems, and necessary buildings. These buildings mainly provide a controlled environment for the food processing and auxiliary systems. The buildings therefore house the systems that make the production function of the factory possible. The buildings are designed to permit adequate working conditions for comfort, safety, functionality, and hygiene (Ingram, 1979; Clark, 2000).

The design of buildings must be subordinate to lodging of the food processing systems and auxiliary systems, but it is also necessary to take into account that a building is usually one of the largest capital investments in the construction budget of a new food plant. The building budget can comprise more than 50% of the total investment needed for the food processing equipment.

Lack of attention to building design may result in the following:

1. Excessive and frequent maintenance requirements
2. Large capital investment, in the case of a disproportionate building budget, with negative influence on product unit costs

3. Conditions such as improper temperature control, insufficient ventilation, null expansion possibilities by building enlargement, irrational distribution, and inconvenient work
4. Legal problems caused by a failure to abide by building standards, safety standards, or corresponding food processing standards

9.1.1 Legal Aspects

Legal requirements will establish the following:

1. Where the food plant can be installed, which is normally regulated by:
   - Standards regarding annoying, noxious, insalubrious, and dangerous activities
   - Town-planning standards
   - Specific standards according to the activity of the food plant
2. Actions to take in order to counteract the negative influence a food plant may have on the environment, such as wastewater and waste product treatment, handling excessive noise, etc. In some cases, direct spillage into natural riverbeds or city sewers may be possible, but prior wastewater treatment is frequently required. It is therefore important to know the main features of the food factory's wastewater to determine if treatment is necessary.
3. Food plant layout (Slade, 1967; Loiseau and Moulhan-Dallies, 1999). In most cases, the distribution of different food processing and auxiliary systems rooms or zones are established by law in order to achieve suitable hygienic and safe working conditions in the food plant. It is common to separate dirty and clean zones (Figure 9.1). For example, in slaughterhouses and by-product processing plants, standards will set the layout limitations of dirty and clean zones, restricting the circulation of people and transport vehicles and materials. All of these regulations are

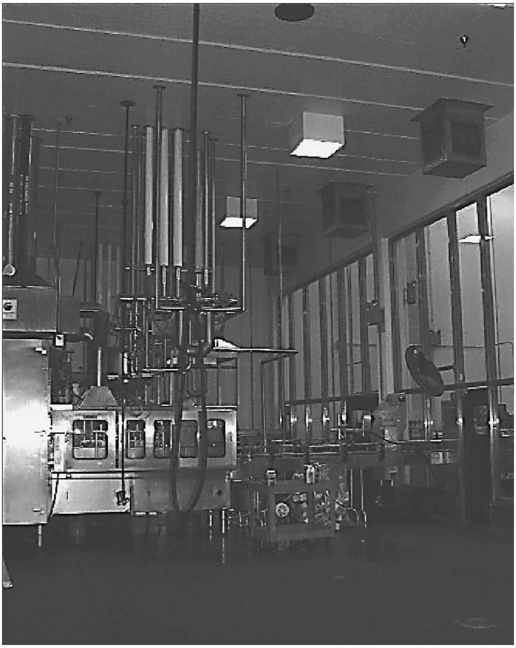

Figure 9.1 In a citrus juice factory, the juice packaging room is a separate zone that is overpressurized with filtered air.

detailed in standards established for specific food processing activities.

4. Hygienic design details of the buildings. For example, the standards established for slaughterhouses determine the building factors affecting the hygienic design of floors, walls, and ceilings. The nature of meeting points or joints between the floor-walls or wall-ceiling intersections is also determined.
5. General aspects of building construction, as published in Basic Standards for Building.
6. Aspects of work safety and hygiene, concerning ventilation conditions, lighting in different work zones, etc.

7. Site and design of building housing auxiliary systems. Standards include
   - Refrigeration installation
   - Electrical installations and power transformers
   - Steam generation and distribution installations
   - Reception, storage, and supply of fuel for boilers
   - Site and design of pressure vessels
   - Storage of potable water
   - Treatment and spillage of wastewater

9.1.2 Functional Aspects

Buildings should be functional in the full sense of the word, forming an integral set with the food processing and auxiliary systems. For this reason, design of food processing systems, auxiliary systems, and buildings must be completed in an interactive manner. The overall design should be completed by one individual or a technical team, since problems can arise if the three designs are created in an unrelated manner.

Building designers must bear in mind that, in the food industry, the food processing system distribution is often accomplished in a straight line or in L, U, or Z layouts (Figure 9.2 and Figure 9.3). In short, it is necessary to design a rational layout for the food processing and auxiliary systems, and the building and zone distribution must follow this design (García-Vaquero, 1979).

Generally, the ceiling height of the building is based on its function to house the food processing and auxiliary systems. If there are processing and storage tanks above where human circulation is required, the ceiling height should be 2 m above the tanks' maximum heights. In the storage zone, the height depends on the loading and unloading system. If forklifts are used, the ceiling height should be the maximum height reached by the forklift plus approximately 0.5 m.

On the other hand, if later food plant expansions are possible, the layout of the food processing systems, auxiliary systems, and buildings should allow for such expansions without requiring too many modifications in the future. In this case, the interior layout and the position of buildings on the land must be taken into account.

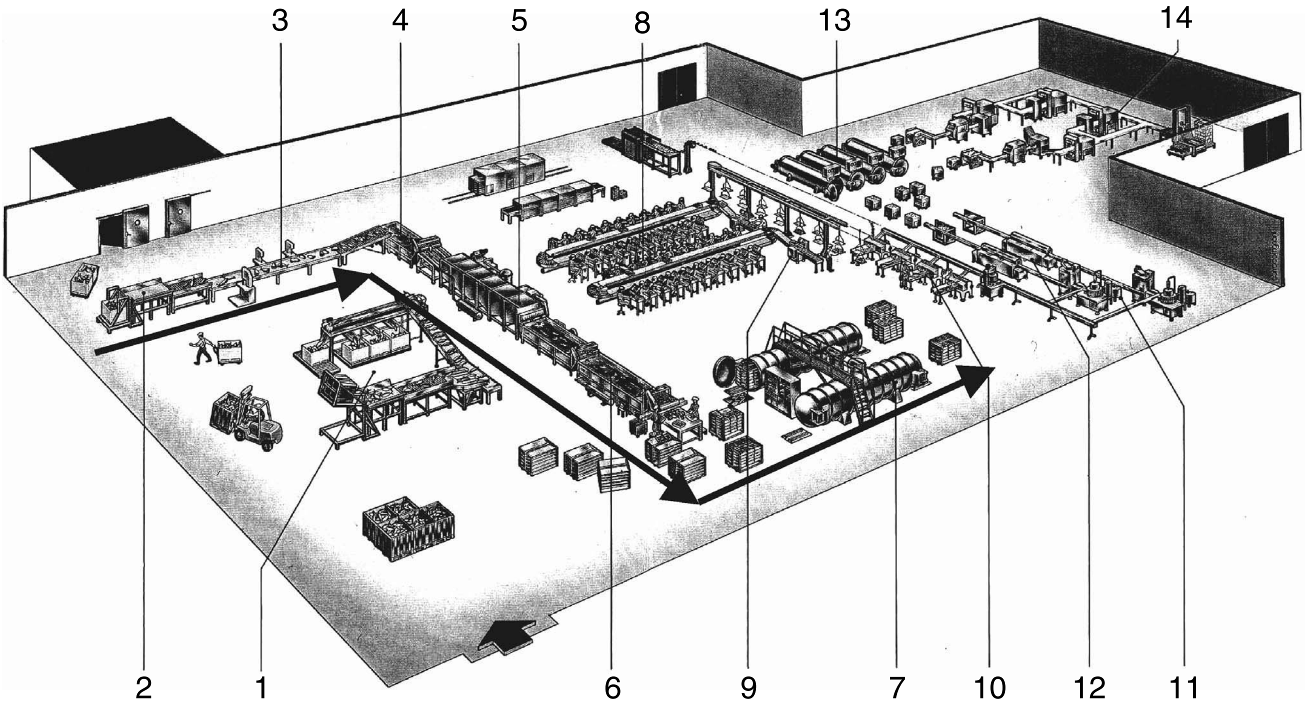

Figure 9.2 General layout of a tuna processing plant (courtesy of FMC Food Tech). Food processing system distribution according to a Z design.

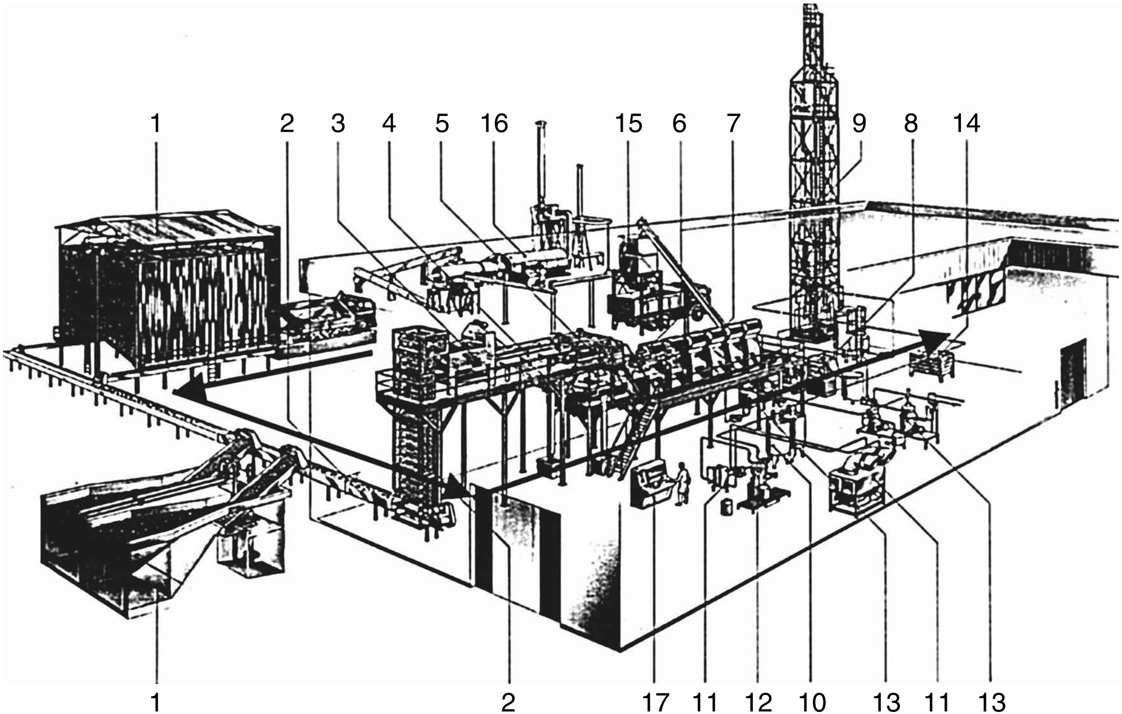

Figure 9.3 General layout of a citrus processing plant (courtesy of FMC Food Tech). Food processing system distribution according to a U design.

9.1.3 Plant Layout

Work scheduling in the food processing plant must be as logical as possible. All functions and operations should be carried out in a simple manner, using the least amount of time necessary to minimize operation costs (Michel, 1978; López, 1990).

Functions of the food processing plant include the following:

a) *Reception and storage,* for a specified time, of raw and auxiliary materials such as fruits, packages, sugar, salt, etc. In some cases, "raw materials" are pigs, calves, lambs, or chickens.
b) *Processing and packing*. By-products, waste products, and wastewater products are removed. At the same time, auxiliary systems and materials are consumed (components of product formulation, packages, etc.).
c) *Quality control*
d) *Storage and shipment of final products*

To minimize operation costs, these functions must not interfere with one another. An example of a rational and straight-line layout of functions and zones is shown in Figure 9.4. Expansion possibilities should not be limited by the corresponding buildings (Figures 9.5, 9.6, and 9.7). Dirty zones (reception and storage of raw materials, empty packages, and storage of packed products) and clean zones (processing and packaging zones, where hygienic conditions have special importance) should be delineated as well. It is always suitable to maintain minimum distances between the receiving of raw materials and the first processing step, and between the storage of empty packages and filling equipment, as well as between auxiliary systems (steam or water, cold or hot) and the processing equipment using such, mainly when a centralized layout is adopted (Figure 9.7).

In some cases, such as relatively small refrigeration chambers, the use of individualized and compact refrigeration equipment within each chamber is recommended. In other cases, however, the use of a centralized compressors room may be preferable.

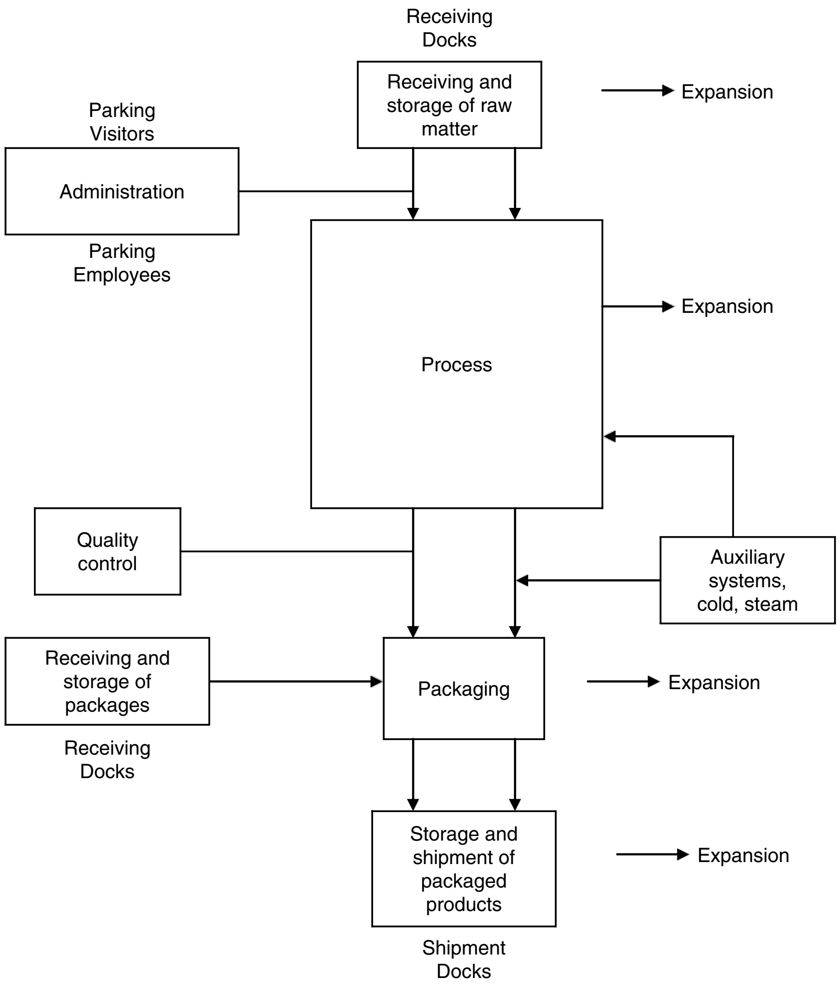

Figure 9.4 Rational distributions of functions in a food processing plant.

Steam generation and distribution installations are normally centralized, in which case the boiler room should be placed as near to the points of steam consumption as possible (Figure 9.7).

Figure 9.5 Shipment docks at a citrus juice factory. They are located at the end of the packaging and storage zones inside the factory.

Figure 9.6 Administration building at a citrus juice factory (courtesy of Agrumexport, S.A). It is relatively separate from the main factory buildings, with gardening and wheeled accesses.

Figure 9.7 Centralized refrigeration and boiler rooms building in a food factory. It is relatively near the processing rooms.

9.2 SELECTING FOOD PLANT SITE

9.2.1 Land Conditions and Location

Gentle topography, level land, or even slightly sloped land is adequate. Building layout on a site profiting from the slope of the land is desirable: raw materials can then enter at the higher site point and products can exit at the lower point. In this case, since the food plant is erected on a completely flat surface, the docks are built at the lower site zone.

The soil must possess enough mechanical strength to keep the buildings erect. Pools of water close to the food factory are not convenient because permanent puddles can form, resulting in insect proliferation leading to contamination.

The building site should be located in a zone with good access and communication, and near to roads and rail services for the supply of raw materials and shipment of final products. Accessibility to a water supply, electricity, and phone lines is also necessary.

The plant construction site should be large enough to permit foreseen expansions. It is common to anticipate expansions that double or triple the initial building site surface. Moreover, the site should be as remote in distance as possible from wastewater and waste product treatment, or incineration plants.

9.2.2 Distribution of Zones at the Site

On-site building layout should provide adequate expansion space, always maintaining the necessary distance between buildings and site borders. Town planning and land laws will determine these distances and the building conditions. Whenever possible, building location should provide wheeled access to all four sides of a building, facilitating firefighting and equipment installation.

At the building site, vehicle corridors must be designed to prevent interference between the raw materials reception zone and the final product shipment zone. In some situations, the relatively dirty access zone of raw materials should be completely separate from the final product shipment zone. Independent, connected vehicle paths that form the site outlet will define a relatively clean zone. A room for cleaning and sanitizing trucks and packages for raw materials transport (from the slaughterhouses) is needed in by-product processing plants.

Paved vehicle pathways with sidewalks are common in the food industry for transporting raw materials and final products. In this manner, if rainwater drainage systems are provided, a clean environment can be achieved around the food processing plant, avoiding the accumulation of rainwater and formation of puddles (Figure 9.7).

Wastewater treatment plants are located near the spillage points and relatively far from the processing or clean zones of the food plant.

9.3 HYGIENIC DESIGN OF THE FOOD PROCESSING PLANT

As mentioned earlier, a food processing plant layout must exhibit clear separation between the clean and dirty zones. In food processing rooms, where a high standard of hygiene is required, the floors, walls, ceilings, and wastewater drainage systems must be designed to allow total cleaning. In rooms within the dirty zones, where floors are infrequently washed, the basic requirement is to prevent dust formation and accumulation on floors. This dust usually comes from the disintegration of floor concrete. To avoid this problem, floors must be formed using concrete with hardening additives to improve their resistance to abrasion from rolling traffic (Ingram, 1979; Loiseau and Moulhon-Dallies, 1999).

9.3.1 Resistant Structure

Any building structure could be valid from the hygienic point of view. Cost would be the main limitation factor. The following alternatives can be used:

- Prefabricated covering structures of reinforced concrete on masonry loading walls, or on pillars and reinforced concrete beams
- Metallic covering structures on masonry loading walls or reinforced concrete pillars, or metallic pillars and beams
- Structure fabricated "in situ" with reinforced concrete

In short, the resistance elements of the structure are constructed with reinforced concrete (prefabricated or not), but steel is used more frequently. Selection will depend on the loads the structure will support, span between pillars, and cost in each case.

9.3.2 Building Enclosure and Interior Divisions

Walls are normally made of concrete masonry blocks or brick masonry, but walls fabricated "in situ" with reinforced concrete,

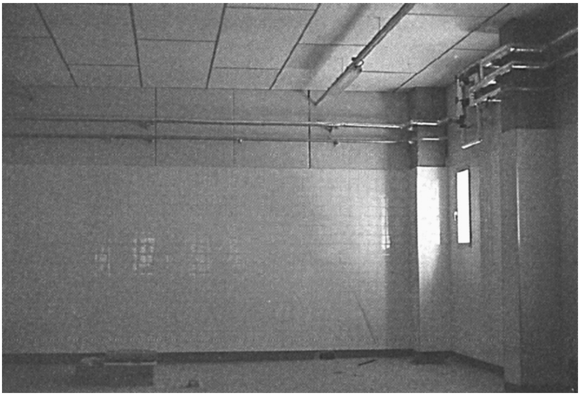

Figure 9.8 Processing room with walls lined with ceramic tiles, and an external enclosure with prefabricated panels of reinforced concrete.

and prefabricated panels of reinforced concrete with an interior layer of insulation material (imitating sandwich panels used normally in cold storage), are also common. In a tall building (10 to 15 m), walls based on polyurethane sandwich panels or prefabricated panels of reinforced concrete seem to yield good results (Figure 9.8).

Wall surface finishes in food processing rooms must permit washing. In these zones, an adequate design would be to line walls with polished ceramic tiles, bonded with concrete and leaving 1 cm width joints (Figure 9.8). These joints must be filled with concrete made of cement and epoxy resin to achieve smooth surfaces that are easy to clean. In this manner, the walls are waterproof and relatively resistant to acid products.

Epoxy and other wall surfaces, such as fiberglass boards or plastic material sheets on polyurethane sandwich panel, are also good solutions (Figure 9.9, Figure 9.10, and Figure 9.11). They are less aesthetically pleasing but more economical than ceramic tiles. These plastic panels are readily installed, in some cases with silicone paste only.

A wall's hygienic lining height is sometimes defined by legislation; however, 3 to 3.5 m is the most common height.

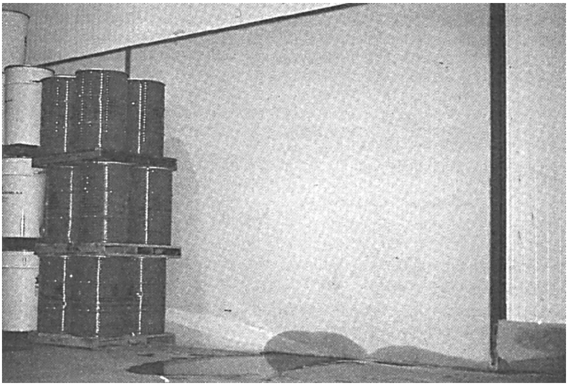

Figure 9.9 Enclosure constructed of sandwich panels with reinforced walls in a storage zone.

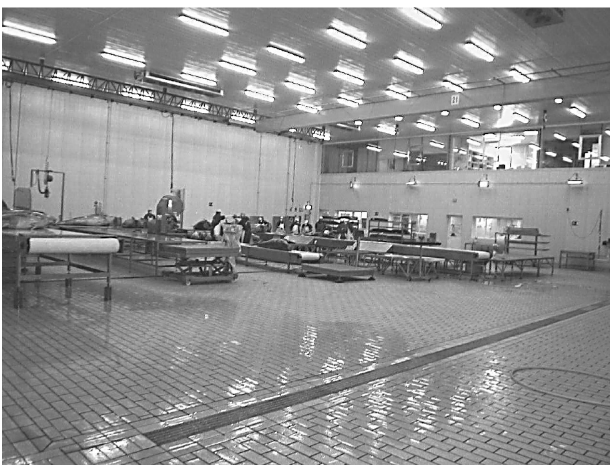

Figure 9.10 Enclosure constructed of sandwich panels in a tuna processing room.

Some cases require that wall lining be extended to the ceiling, with rounded joints for the ceiling-wall and wall-floor junctions (Figures 9.11 and 9.12). Thus, a very hygienic design is achieved.

Figure 9.11 Packaging room construction with polyurethane sandwich panel walls and ceiling.

Figure 9.12 Cold storage construction with ceiling made of polyurethane sandwich panels.

Figure 9.13 Cold storage construction with metallic structure and stone layer floors over 20 cm thick.

9.3.3 Floors

Floors are usually fabricated using reinforced concrete (15 to 20 cm thick) over a 15 to 20 cm thick stone layer as the ground floor (see Figure 9.13). For a high floor, or a floor over an air chamber, construction will be of reinforced concrete.

In ground-level storage buildings, the floors are usually fabricated by lining the reinforced concrete layer with cement and a hardening additive to avoid the formation of dust (Figure 9.14).

Because of the need for acid-proof, abrasion resistant, nonskid, and waterproof floors in food processing rooms, some type of lining is required on the reinforced concrete layer. Ceramic tile lining is the most aesthetic and durable floor

Figure 9.14 Construction of cold storage metallic structure.

available to the food industry today. Tiles are bonded with cement to the bedding system. Cement with epoxy resin is later grouted into the 1 cm open joints. Quarry tiles 1.27 to 1.90 cm thick should be used only in areas subjected to light or foot traffic. Tiles 3 cm thick are suitable in heavy traffic areas (Figure 9.10, Figure 9.15, and Figure 9.16).

Continuous floors are available lined with cement and additives, making the floors acid-proof, abrasion resistant, non-skid, and waterproof (Hall and Farrall, 1986) (Figure 9.17). Protective coatings of polyester and epoxy resins, applied directly to the concrete layer, are only useful in nontraffic areas (except for cleaning operations) since they lack mechanical resistance and break easily with large temperature changes.

Even if floors are tiled and constructed over a reinforced concrete slab in the food processing rooms, it is appropriate

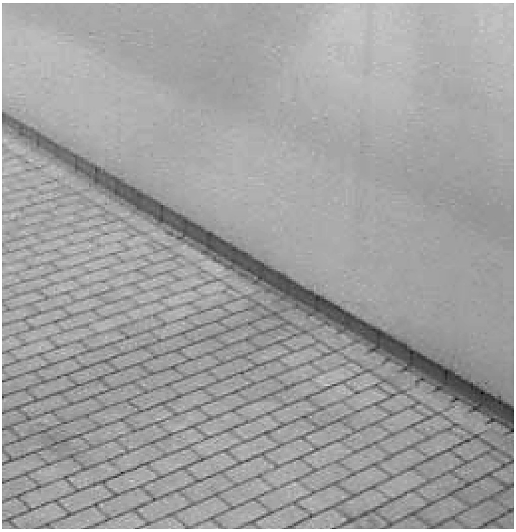

Figure 9.15 Floor lined with ceramic tiles in a food factory, with rounded joints for the wall-floor junctions.

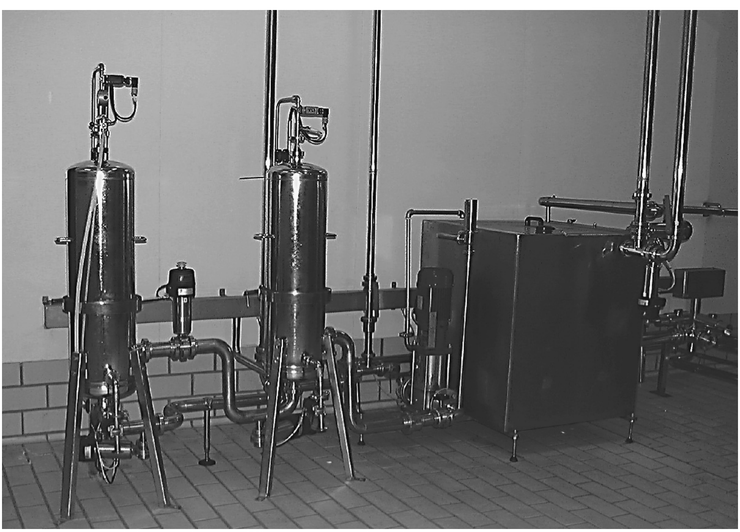

Figure 9.16 Floor lined with ceramic tiles in a juice packaging room.

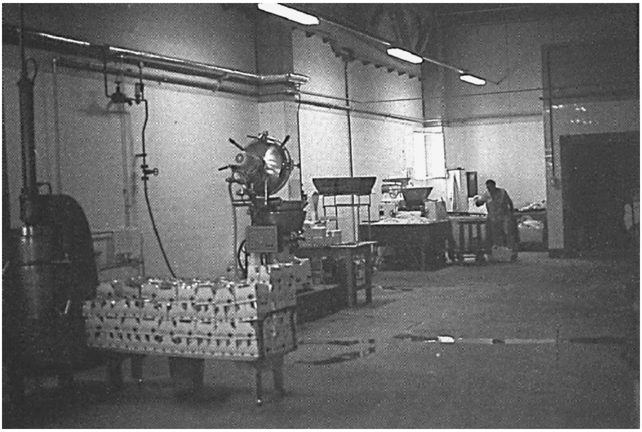

Figure 9.17 Continuous floor, both anti-acid and waterproof, made of cement and additives.

to apply a layer of asphalt over the concrete slab. The tile is thus bonded to the asphalt bed, resulting in a waterproof floor.

Dilatation joints are necessary for any kind of floor. In food processing rooms, the most commonly used backup material is polyethylene foam in sheets, with a sealant based on silicone or an epoxy resin.

Floors in processing areas should have enough slope (0.5–1%) to drain wastewater. Floor drains made of stainless steel (Figure 9.18) can be installed every 45 to 50 m^2 of floor. Connections from floor drains to the general wastewater collector should be resistant to the corrosive action of different cleaning products. These connections are usually made of PVC or stainless steel (Figure 9.19), but never concrete.

Floor drain channels are also available covered with stainless steel grids to collect cleaning products (Figure 9.20). The drain channels are usually made of bricks lined with cement and epoxy resin; the most suitable solution, however, would be to install drain channels made of stainless steel (Figure 9.20). These channels carry wastewater to the general sewage collector.

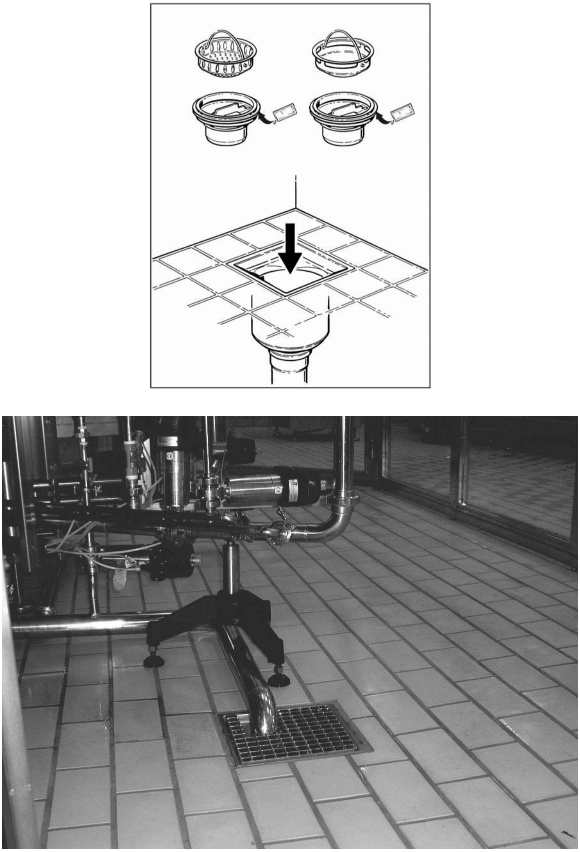

Figure 9.18 Floor drains made of stainless steel.

Figure 9.19 Wastewater collector tubes of stainless steel (courtesy of Blücher, www.blucher.com).

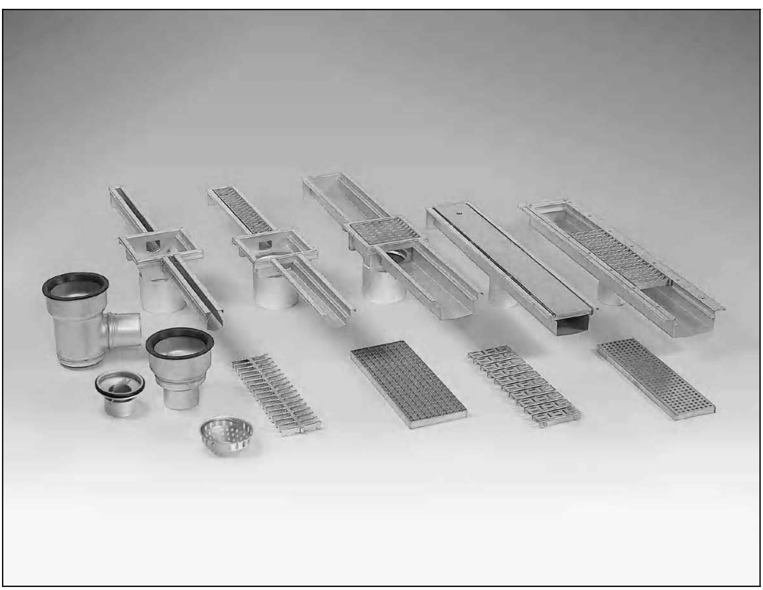

Figure 9.20 Floor drain channel made of stainless steel (courtesy of Blücher, www.blucher.com).

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