CHAPTER 53
AIR HEATING

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53.1 AIR-HEATING PROCESSES

Air can be heated by burning fuel or by recovering waste heat from another process. In either case, the heat can be transferred to air directly or indirectly. *Indirect air heaters* are heat exchangers wherein the products of combustion never contact or mix with the air to be heated. In waste heat recovery, the heat exchanger is termed a *recuperator.*

Direct air heaters or *direct-fired air heaters* heat the air by intentionally mixing the products or combustion of waste gas with the air to be heated. They are most commonly used for ovens and dryers. It may be impractical to use them for space heating or for preheating combustion air because of lack of oxygen in the resulting mixture ("vitiated air"). In some cases, direct-fired air heating may be limited by codes and/or by presence of harmful matter of undesirable odors from the heating stream. Direct-fired air heaters have lower first cost and lower operating (fuel) cost than indirect air heaters.

Heat requirements for direct-fired air heating. Table 53.1 lists the gross Btu of fuel input required to heat one standard cubic foot of air from a given inlet temperature to a given outlet temperature. It is based on natural gas at 60°F, having 1000 gross Btu/ft^3, 910 net Btu/ft^3, and stoichiometric air/gas ratio of 9.4:1. The oxygen for combustion is supplied by the air that is being heated. The hot outlet "air" includes combustion products obtained from burning sufficient natural gas to raise the air to the indicated outlet temperature.

Recovered waste heat from another nearby heating process can be used for process heating, space heating, or for preheating combustion air (Ref. 4). If the waste stream is largely nitrogen, and if the temperatures of both streams are between 0 and 800°F, where specific heats are about 0.24, a simplified heat balance can be used to evaluate the mixing conditions:

heat content of the waste stream + heat content of the fresh air = heat content of the mixture or

$$W_w T_w + W_f T_f = W_m T_m = (W_w + W_f)\, T_m$$

where W = weight and T = temperature of waste gas, fresh air, and mixture (subscripts w, f, and m).

Example 53.1

If a 600°F waste gas stream flowing at 100 lb/hr is available to mix with 10°F fresh air and fuel, how many pounds per hour of 110°F makeup air can be produced?

Solution:

$$(100 \times 600) + 10W_f = (100 + W_f) \times (110)$$

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Table 53.1 Heat Requirements for Direct-Fired Air Heating, Gross Btu of Fuel Input per scf of Outlet "Air."

Inlet Air Temperature, °F	Outlet Air Temperature, °F														
	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
−20	2.39	4.43	6.51	8.63	10.8	13.0	15.2	17.5	19.9	22.2	24.7	27.1	29.7	32.2	34.9
0	2.00	4.04	6.11	8.23	10.4	12.6	14.8	17.1	19.5	21.8	24.3	26.7	29.3	31.8	34.4
+20	1.60	3.64	5.71	7.83	9.99	12.2	14.4	16.7	19.0	21.4	23.8	26.3	28.8	31.4	34.0
40	1.20	3.24	5.31	7.43	9.58	11.8	14.0	16.3	18.6	21.0	23.4	25.9	28.4	31.0	33.6
60	0.802	2.84	4.91	7.02	9.18	11.4	13.6	15.9	18.2	20.6	23.0	25.5	28.0	30.6	33.2
80	0.402	2.43	4.51	6.62	8.77	11.0	13.2	15.5	17.8	20.2	22.6	25.1	27.6	30.1	32.7
100		2.03	4.10	6.21	8.36	10.6	12.8	15.1	17.4	19.8	22.2	24.6	27.2	29.7	32.3
200			2.06	4.17	6.31	8.50	10.7	13.0	15.3	17.7	20.1	22.5	25.0	27.6	30.2
300				2.10	4.23	6.41	8.63	10.9	13.2	15.5	17.9	20.4	22.9	25.4	28.0
400					2.13	4.30	6.51	8.76	11.1	13.4	15.8	18.2	20.7	23.2	25.8
500						2.16	4.36	6.61	8.90	11.2	13.6	16.0	18.5	21.0	23.6
600							2.19	4.43	6.71	9.03	11.4	13.8	16.3	18.8	21.3
700								2.23	4.50	6.81	9.16	11.6	14.0	16.5	19.0
800									2.26	4.56	6.91	9.30	11.7	14.2	16.7
900										2.29	4.63	7.01	9.43	11.9	14.4
1000											2.32	4.69	7.11	9.57	12.1

Example: Find the amount of natural gas required to heat 1000 scfm of air from 400°F to 1400°F.

Solution: From the table, read 23.2 gross Btu/scf air. Then $\left(\frac{23.2 \text{ gross Btu}}{\text{scf air}} \times \frac{1000 \text{ scf air}}{\text{min}} \times \frac{60 \text{ min}}{1 \text{ hr}}\right) \div \frac{1000 \text{ gross Btu}}{\text{ft}^3 \text{ gas}} = 1392$ cfh gas.

The conventional formula derived from the specific heat equation is: $Q = wc\Delta T$; so Btu/hr = weight/hr × specific heat × temp rise = $\frac{\text{scf}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{0.076 \text{ lb}}{\text{ft}^3} \times \frac{0.24 \text{ Btu}}{\text{lb °F}} \times$ °rise = scfm × 1.1 × °rise.

The table above incorporates many refinements not considered in the conventional formulas: (a) % available heat which corrects for heat loss to dry flue gases and the heat loss due to heat of vaporization in the water formed by combustion, (b) the specific heats of the products of combustion (N_2, CO_2, and H_2O) are not the same as that of air, and (c) the specific heats of the combustion products change at higher temperatures.

For the example above, the rule of thumb would give 1000 scfm × 1.1 × (1400 − 400) = 1 100 000 gross Btu/hr: whereas the example finds 1392 × 1000 = 1 392 000 gross Btu/hr required. *Reminder:* The fuel being burned adds volume and weight to the stream being heated.

Solving, we find $W_f = 490$ lb/hr of fresh air can be heated to 110°F, but the 100 lb/hr of waste gas will be mixed with it; so the delivered stream, W_m will be $100 + 490 = 590$ lb/hr.

If "indirect" air heating is necessary, a heat exchanger (recuperator or regenerator) must be used. These may take many forms such as plate-type heat exchangers, shell and tube heat exchangers, double-pipe heat exchangers, heat-pipe exchangers, heat wheels, pebble heater recuperators, and refractory checkerworks. The supplier of the heat exchanger should be able to predict the air preheat temperature and the final waste gas temperature. The amount of heat recovered Q is then $Q = W c_p (T_2 - T_1)$, where W is the weight of air heated, c_p is the specific heat of air (0.24 when below 800°F), T_2 is the delivered hot air temperature, and T_1 is the cold air temperature entering the heat exchanger. Tables and graphs later in this chapter permit estimation of fuel savings and efficiencies for cases involving preheating of combustion air.

If a waste gas stream is only a few hundred degrees Fahrenheit hotter than the air stream temperature required for heating space, an oven, or a dryer, such uses of recovered heat are highly desirable. For higher waste gas stream temperatures, however, the second law of thermodynamics would say that we can make better use of the energy by stepping it down in smaller temperature increments, and preheating combustion air usually makes more sense. This also simplifies accounting, since it returns the recovered heat to the process that generated the hot waste stream.

Preheating combustion air is a very logical method for recycling waste energy from flue gases in direct-fired industrial heating processes such as melting, forming, ceramic firing, heat treating, chemical and petroprocess heaters, and boilers. (It is always wise, however, to check the economics of using flue gases to preheat the load or to make steam in a waste heat boiler.)

53.2 COSTS

In addition to the cost of the heat exchanger for preheating the combustion air, there are many other costs that have to be weighed. Retrofit or add-on recuperators or regenerators may have to be installed overhead to keep the length of heat-losing duct and pipe to a minimum; therefore, extra foundations and structural work may be needed. If the waste gas or air is hotter than about 800°F, carbon steel pipe and duct should be insulated on the inside. For small pipes or ducts where this would be impractical, it is necessary to use an alloy with strength and oxidation resistance at the higher temperature, and to insulate on the outside.

High-temperature air is much less dense; therefore, the flow passages of burners, valves, and pipe must be greater for the same input rate and pressure drop. Burners, valves, and piping must be constructed of better materials to withstand the hot air stream. The front face of the burner is exposed to more intense radiation because of the higher flame temperature resulting from preheated combustion air.

If the system is to be operated at a variety of firing rates, the output air temperature will vary; so temperature-compensating fuel/air ratio controls are essential to avoid wasting fuel. Also, to protect the investment in the heat exchanger, it is only logical that it be protected with high-limit temperature controls.

53.3 WARNINGS

Changing temperatures from end to end of high-temperature heat exchangers and from time to time during high-temperature furnace cycles cause great thermal stress, often resulting in leaks and shortened heat-exchanger life. Heat-transfer surfaces fixed at both ends (welded or rolled in) can force something to be overstressed. Recent developments in the form of high-temperature slip seal methods, combined with sensible location of such seals in cool air entrance sections, are opening a whole new era in recuperator reliability.

Corrosion, fouling, and condensation problems continue to limit the applications of heat-recovery equipment of all kinds. Heat-transfer surfaces in air heaters are never as well cooled as those in water heaters and waste heat boilers; therefore, they must exist in a more hostile environment. However, they may experience fewer problems from acid-dew-point condensation. If corrosives, particulates, or condensables are emitted by the heating process at limited times, perhaps some temporary bypassing arrangement can be instituted. High waste gas design velocities may be used to keep particulates and condensed droplets in suspension until they reach an area where they can be safely dropped out.

Figure 53.1 shows recommended minimum temperatures to avoid "acid rain" in the heat exchanger.[2] Although a low final waste gas temperature is desirable from an efficiency standpoint, the shortened equipment life seldom warrants it. Acid forms from combination of water vapor with SO_3, SO_2, or CO_2 in the flue gases.

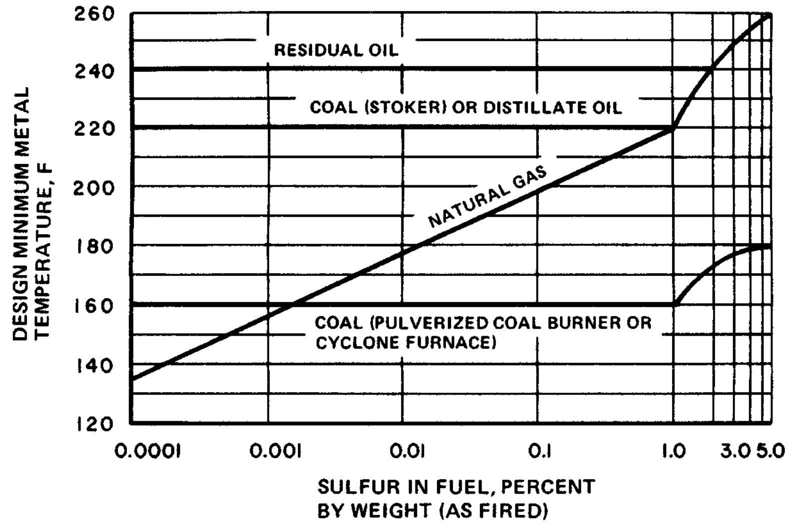

Fig. 53.1 Recommended minimum temperatures to avoid "acid rain" in heat exchangers.

53.4 BENEFITS

Despite all the costs and warnings listed above, combustion air preheating systems *do* pay. As fuel costs rise, the payback is more rewarding, even for small installations. Figure 53.2 shows percent available heat[3] (best possible efficiency) with various amounts of air preheat and a variety of furnace exit (flue) temperatures. All curves for hot air are based on 10% excess air.* The percentage of fuel saved by addition of combustion air preheating equipment can be calculated by the formula

$$\%\text{ fuel saved} = 100 \times \left(1 - \frac{\%\text{ available heat before}}{\%\text{ available heat after}}\right)$$

Table 53.2 lists fuel savings calculated by this method.[4]

Preheating combustion air raises the flame temperature and thereby enhances radiation heat transfer in the furnace, which should lower the exit gas temperature and further improve fuel efficiency. Table 53.3 and the x-intercepts of Fig. 53.2 show adiabatic flame temperatures when operating with 10% excess air,† but it is difficult to quantify the resultant saving from this effect.

Preheating combustion air has some lesser benefits. Flame stability is enhanced by the faster flame velocity and broader flammability limits. If downstream pollution control equipment is required (scrubber, baghouse), such equipment can be smaller and of less costly materials because the heat exchanger will have cooled the waste gas stream before it reaches such equipment.

*It is advisable to tune a combustion system for closer to stoichiometric air/fuel ratio *before* attempting to preheat combustion air. This is not only a quicker and less costly fuel conservation measure, but it then allows use of smaller heat-exchange equipment.

†Although 0% excess air (stoichiometric air/fuel ratio) is ideal, practical considerations usually dictate operation with 5–10% excess air. During changes in firing rate, time lag in valve operation may result in smoke formation if some excess air is not available prior to the change. Heat exchangers made of 300 series stainless steels may be damaged by alternate oxidation and reduction (particularly in the presence of sulfur). For these reasons, it is wise to have an accurate air/fuel ratio controller with very limited time-delay deviation from air/fuel ratio setpoint.

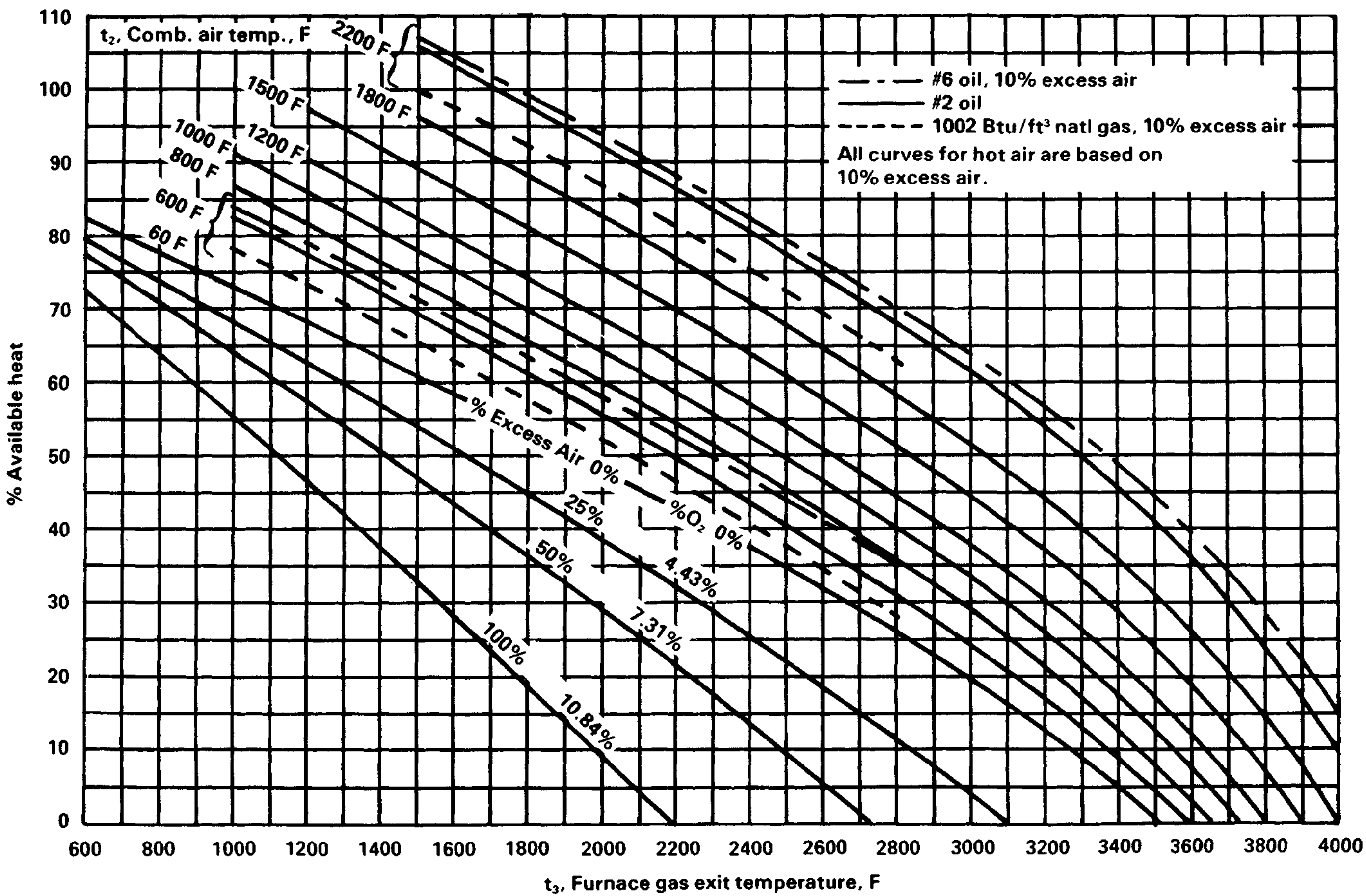

Fig. 53.2 Available heat with preheated combustion air at 10% excess air. Applicable only if there is no unburned fuel in the products of combustion. Corrected for dissociation. (Reproduced with permission from *Combustion Handbook*.[3]) See also Figs. 44.3 and 44.4.

Table 53.2 Fuel Savings (%) Resulting from Use of Preheated Air with Natural Gas and 10% Excess Air[a]

t_3, Furnace Gas Exit Temperature (°F)	t_2, Combustion Air Temperature (°F)													
	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1800	2000	2200
1000	13.4	15.5	17.6	19.6	—	—	—	—	—	—	—	—	—	—
1100	13.8	16.0	18.2	20.2	22.2	—	—	—	—	—	—	—	—	—
1200	14.3	16.6	18.7	20.9	22.9	24.8	—	—	—	—	—	—	—	—
1300	14.8	17.1	19.4	21.5	23.6	25.6	27.5	—	—	—	—	—	—	—
1400	15.3	17.8	20.1	22.3	24.4	26.4	28.4	30.2	—	—	—	—	—	—
1500	16.0	18.5	20.8	23.1	25.3	27.3	29.3	31.2	33.0	—	—	—	—	—
1600	16.6	19.2	21.6	24.0	26.2	28.3	30.3	32.2	34.1	35.8	—	—	—	—
1700	17.4	20.2	22.5	24.9	27.2	29.4	31.4	33.4	35.3	37.0	38.7	—	—	—
1800	18.2	20.9	23.5	26.0	28.3	30.6	32.7	34.6	36.5	38.3	40.1	—	—	—
1900	19.1	21.9	24.6	27.1	29.6	31.8	34.0	36.0	37.9	39.7	41.5	44.7	—	—
2000	20.1	23.0	25.8	28.4	30.9	33.2	35.4	37.5	39.4	41.3	43.0	46.3	—	—
2100	21.2	24.3	27.2	29.9	32.4	34.8	37.0	39.1	41.1	43.0	44.7	48.0	51.0	—
2200	22.5	25.7	28.7	31.5	34.1	36.5	38.8	40.9	42.9	44.8	46.6	49.9	52.8	—
2300	24.0	27.3	30.4	33.3	36.0	38.5	40.8	42.9	45.0	46.9	48.7	52.0	54.9	57.5
2400	25.7	29.2	32.4	35.3	38.1	40.6	43.0	45.2	47.2	49.2	51.0	54.2	57.1	59.7
2500	27.7	31.3	34.7	37.7	40.5	43.1	45.5	47.7	49.8	51.7	53.5	56.8	59.6	62.2
2600	30.1	33.9	37.3	40.5	43.4	46.0	48.4	50.6	52.7	54.6	56.4	59.6	62.4	64.9
2700	33.0	37.0	40.6	43.8	46.7	49.4	51.8	54.0	56.1	58.0	59.7	62.8	65.5	67.9
2800	36.7	40.8	44.5	47.8	50.8	53.4	55.8	58.0	60.0	61.9	63.5	66.5	69.1	71.3
2900	41.4	45.7	49.5	52.8	55.7	58.4	60.7	62.8	64.7	66.4	68.0	70.8	73.2	75.2
3000	47.9	52.3	56.0	59.3	62.1	64.6	66.7	68.7	70.4	72.0	73.5	75.9	78.0	79.8
3100	57.3	61.5	65.0	68.0	70.5	72.7	74.6	76.2	77.7	79.0	80.2	82.2	83.8	85.2
3200	72.2	75.6	78.3	80.4	82.2	83.7	85.0	86.1	87.1	87.9	88.7	89.9	90.9	91.8

[a]These figures are for evaluating a proposed change to preheated air—not for determining system capacity.
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Table 53.3 Effect of Combustion Air Preheat on Flame Temperature

Excess Air (%)	Preheated Combustion Air Temperature (°F)	Adiabatic Flame Temperatured (°F) With 1000 Btu/scf Natural Gas	With 137,010 Btu/gal Distillate Fuel Oil	With 153,120 Btu/gal Residual Fuel Oil
0	60	3468	3532	3627
10	60	3314	3374	3475
10	600	3542	3604	3690
10	700	3581	3643	3727
10	800	3619	3681	3763
10	900	3656	3718	3798
10	1000	3692	3754	3831
10	1100	3727	3789	3864
10	1200	3761	3823	3896
10	1300	3794	3855	3927
10	1400	3826	3887	3957
10	1500	3857	3918	3986
10	1600	3887	3948	4014
10	1700	3917	3978	4042
10	1800	3945	4006	4069
10	1900	3973	4034	4095
10	2000	4000	4060	4121
0	2000	4051	4112	4171

REFERENCES

1. *Heat Requirements for Direct-Fired Air Heating,* North American Mfg. Co., Cleveland, OH, 1981.
2. *Steam—Its Generation and Use,* Babcock and Wilcox, New York, 1978.
3. R. J. Reed, *Combustion Handbook,* 3rd ed., Vol. 1, North American Manufacturing Co., Cleveland, OH, 1986.
4. R. J. Reed, *Combustion Handbook,* 4th ed., Vol. 2, North American Manufacturing. Co., Cleveland, OH, 1997.