CHAPTER 46
GASEOUS FUELS

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46.1 INTRODUCTION **1505**

46.2 NATURAL GAS **1505**
46.2.1 Uses and Distribution 1505
46.2.2 Environmental Impact 1505
46.2.3 Sources, Supply, and Storage 1507
46.2.4 Types and Composition 1507
46.2.5 Properties 1507
46.2.6 Calorific Value or Heating Value 1507
46.2.7 Net Heating Value 1507
46.2.8 Flame Stability 1509
46.2.9 Gas Gravity 1509
46.2.10 Wobbe Index 1512
46.2.11 Flame Temperature 1512
46.2.12 Minimum Ignition Temperature 1512
46.2.13 Flammability Limits 1512

46.3 LIQUEFIED PETROLEUM GASES **1514**

46.1 INTRODUCTION

Gaseous fuels are generally easier to handle and burn than are liquid or solid fuels. Gaseous fossil fuels include natural gas (primarily methane and ethane) and liquefied petroleum gases (LPG; primarily propane and butane). Gaseous man-made or artificial fuels are mostly derived from liquid or solid fossil fuels. Liquid fossil fuels have evolved from animal remains through eons of deep underground reaction under temperature and pressure, while solid fuel evolved from vegetable remains. Figure 46.1, adapted from Ref. 1, shows the ranges of hydrogen/carbon ratios for most fuels.

46.2 NATURAL GAS

46.2.1 Uses and Distribution

Although primarily used for heating, natural gas is also frequently used for power generation (via steam turbines, gas turbines, diesel engines, and Otto cycle engines) and as feedstock for making chemicals, fertilizers, carbon-black, and plastics. It is distributed through intra- and intercontinental pipe lines in a high-pressure gaseous state and via special cryogenic cargo ships in a low-temperature, high-pressure liquid phase (LNG).

Final street-main distribution for domestic space heating, cooking, water heating, and steam generation is at regulated pressures on the order of a few inches of water column to a few pounds per square inch, gage, depending on local facilities and codes. Delivery to commercial establishments and institutions for the same purposes, plus industrial process heating, power generation, and feedstock, may be at pressures as high as 100 or 200 psig (800 or 1500 kPa absolute). A mercaptan odorant is usually added so that people will be aware of leaks.

Before the construction of cross-country natural gas pipe lines, artificial gases were distributed through city pipe networks, but gas generators are now usually located adjacent to the point of use.

46.2.2 Environmental Impact

The environmental impact of natural gas combustion is generally less than that of liquid or solid fuels. Pollutants from natural gas may be (a) particulates, if burners are poorly adjusted or controlled (too rich, poor mixing, quenching), or (b) nitrogen oxides, in some cases with intense combustion, preheated air, or oxygen enrichment.

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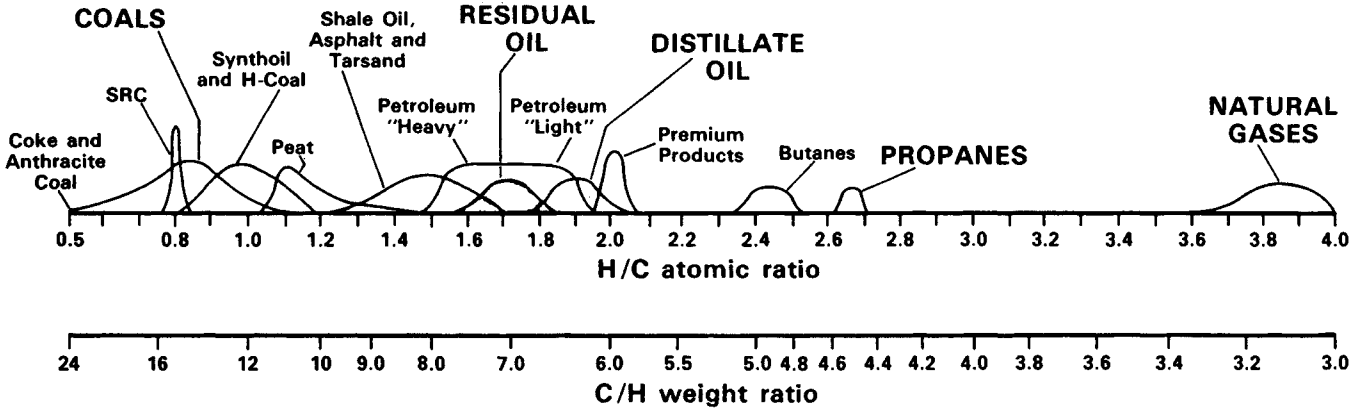

Fig. 46.1 Hydrogen/carbon ratios of fossil and synthetic fuels. (Adapted from Ref. 1.)

46.2.3 Sources, Supply, and Storage

Natural gas is found with oil deposits (animal fossils) and coal deposits (plant fossils). As-yet untapped supplies are known to exist (1) near the coast of the Gulf of Mexico in very deep geopressured/geothermal aquifers and (2) in difficult-to-separate Appalachian shale formations.

Except for these hard-to-extract supplies, U.S. natural gas supplies have been variously predicted to last 10–20 years, but such predictions are questionable because of the effects of economic and regulatory variations on consumption, production, and exploration. Except for transoceanic LNG vessels, distribution is by pipe line, using a small fraction of the fuel in compressors to provide pumping power.

Storage facilities are maintained by many local gas utilities as a cushion for changing demand. These may be low-pressure gas holders with floating bell-covers, old wells or mines (medium pressure), or cryogenic vessels for high-pressure liquefied gas.

46.2.4 Types and Composition

Natural gases are classified as "sweet" or "sour," depending on their content of sulfur compounds. Most such compounds are removed before distribution. Odorants added (so that leaks can be detected) are usually sulfur compounds, but the amount is so minute that it has no effect on performance or pollution.

Various geographic sources yield natural gases that may be described as "high methane," "high Btu," or "high inert."

46.2.5 Properties

Properties that concern most users of natural gases relate to the heat available from their combustion, flow characteristics, and burnability in a variety of burner types. Strangely, few people pay attention to the properties of their gas until they are forced to substitute another fuel for it. Some properties are listed in Table 46.1.[2]

46.2.6 Calorific Value or Heating Value

The gross or higher heating value (HHV) is usually measured in a steady-state calorimeter, which is a small fire-tube heat exchanger with a water-cooled surface area so large that it cools the products of combustion to the temperature at which they entered as fuel and air (usually 60°F). HHV can be calculated from a volumetric analysis and the calorific values of the pure compounds in the gas (Table 46.2). For example, for a natural gas having the analysis shown in column 2 below, the tabulation shows how a weighted average method can be used to determine the calorific value of the mixture:

Col. 1, Constituent	Col. 2, % Volume	Col. 3, HHV from Table 46.2 (Btu/ft^3)	Col. 4 = (Col. 3 × Col. 2)/100
Methane, CH_4	90	1013	912
Ethane, C_2H_6	6	1763	106
Nitrogen, N_2	4	0	0
Total	100%		1018 Btu/ft^3

It is a convenient coincidence that most solid fossil fuels release about 96–99 gross Btu/ft^3 of standard *air;* liquid fossil fuels release about 101–104 Btu/ft^3; gaseous fossil fuels about 104–108 Btu/ft^3.

This would say that the natural gas in the example above should require about 1017 Btu/ft^3 gas divided by 106 Btu/ft^3 air = 9.6 ft^3 air/ft^3 gas. Precise stoichiometric calculations would say 0.909(9.53) + 0.06(16.7) = 9.58 ft^3 air/ft^3 gas.

46.2.7 Net Heating Value

Because a calorimeter cools the exit gases below their dew point, it retrieves the latent heat of condensation of any water vapor therein. But that latent heat is not recapturable in most practical heating equipment because of concern about corrosion; therefore, it is more realistic to subtract the latent heat from HHV, yielding a net or lower heating value, LHV. This is approximately

$$\frac{\text{LHV}}{\text{unit of fuel}} = \frac{\text{HHV}}{\text{unit of fuel}} - \left(\frac{970 \text{ Btu}}{\text{lb } H_2O} \times \frac{\text{lb } H_2O}{\text{unit of fuel}}\right)$$

Values for the latter term are listed in Table 46.2. (Note that available heat was discussed in Chapter 44.)

Table 46.1a Analyses of Typical Gaseous Fuels[2]

Type of Gas	Analysis in % by Volume								
	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO	H_2	CO_2	O_2	N_2
Acetylene, commercial			(97.1% C_2H_2, 2.5% C_3H_6O)					0.084	0.28
Blast furnace	—	—	—	—	27.5	1.0	11.5	—	60.0
Blue (water), bituminous	4.6	—	—	0.7	28.2	32.5	5.5	0.9	27.6
Butane, commercial, natural gas	—	—	6.0	70.7 *n*-, 23.3 iso-	—	—	—	—	—
Butane, commercial, refinery gas	—	—	5.0	50.1 *n*-, 16.5 iso-			(28.3% C_4H_6)		
Carbureted blue, low gravity	10.9	2.5	—	6.1	21.9	49.6	3.6	0.4	5.0
Carbureted blue, heavy oil	13.5	—	—	8.2	26.8	32.2	6.0	0.9	12.4
Coke oven, by-product	32.3	—	—	3.2	5.5	51.9	2.0	0.3	4.8
Mapp	—	—	15.0	10.0		(66.0% C_3H_4, 9.0% C_3H_6)			
Natural, Alaska	99.6	—	—	—	—	—	—	—	0.4
Natural, Algerian LNG, Canvey	87.20	8.61	2.74	1.07	—	—	—	—	0.36
Natural, Gaz de Lacq	97.38	2.17	0.10	0.05	—	—	—	—	0.30
Natural, Groningen, Netherlands	81.20	2.90	0.36	0.14	—	—	0.87	—	14.40
Natural, Libyan LNG	70.0	15.0	10.0	3.5	—	—	—	—	0.90
Natural, North Sea, Bacton	93.63	3.25	0.69	0.27	—	—	0.13	—	1.78
Natural, Birmingham, AL	90.0	5.0	—	—	—	—	—	—	5.0
Natural, Cleveland, OH	82.9	11.9		0.3	—	—	0.2	0.3	4.4
Natural, Kansas City, MO	84.1	6.7	—	—	—	—	0.8	—	8.4
Natural, Pittsburgh, PA	83.4	15.8	—	—	—	—	—	—	0.8
Producer, Koppers–Totzek[a]	0.09	—	—	—	55.1	33.7	9.8	—	1.3
Producer, Lurgi[b]	5.0	—	—	—	16.0	25.0	14.0	—	40.0
Producer, W-G, bituminous[b]	2.7	—	—	—	28.6	15.0	3.4	0	50.3
Producer, Winkler[b]	1	—	—	—	10	12	22	—	55
Propane, commercial, natural gas	—	2.2	97.3	0.5	—	—	—	—	—
Propane, commercial, refinery gas	—	2.0	72.9	0.8			(24.3% C_3H_6)		
Sasol, South Africa	28.0	—	—	—	22.0	48.9		1.0	
Sewage, Decatur	68.0	—	—	—	—	2.0	22.0	—	6.0
SNG, no methanation	79.9	—	—	—	1.2	19.0	0.5	—	—

[a] O_2-blown.

[b] Air-blown.

Table 46.1b Properties of Typical Gaseous Fuels[2]

Type of Gas	Gas Gravity	Calorific Value Btu/ft³ Gross	Calorific Value Btu/ft³ Net	Calorific Value kcal/m³ Gross	Calorific Value kcal/m³ Net	Gross Btu/ft³ of Standard Air	Gross kcal/m³ of Standard Air
Acetylene, commercial	0.94	1410	1360	12548	12105	115.4	1027
Blast furnace	1.02	92	91	819	819	135.3	1204
Blue (water), bituminous	0.70	260	239	2314	2127	126.2	1121
Butane, commercial, natural gas	2.04	3210	2961	28566	26350	104.9	932.6
Butane, commercial, refinery gas	2.00	3184	2935	28334	26119	106.1	944.2
Carbureted blue, low gravity	0.54	536	461	4770	4102	106.1	944.2
Carbureted blue, heavy oil	0.66	530	451	4716	4013	101.7	905.0
Coke oven, by-product	0.40	569	509	5064	4530	105.0	934
Mapp	1.48	2406	2282	21411	20308	113.7	1011.86
Natural, Alaska	0.55	998	906	8879	8063	104.8	932.6
Natural, Algerian LNG, Canvey	0.64	1122	1014	9985	9024	104.3	928.2
Natural, Gaz de Lacq	0.57	1011	911	8997	8107	104.1	927.3
Natural, Groningen, Netherlands	0.64	875	789	7787	7021	104.4	927.3
Natural, Libyan LNG	0.79	1345	1223	11969	10883	106.1	928.2
Natural, North Sea, Bacton	0.59	1023	922	9104	8205	105.0	934.4
Natural, Birmingham, AL	0.60	1002	904	8917	8045	106.1	945.1
Natural, Cleveland, OH	0.635	1059	959	9424	8534	106.2	942.4
Natural, Kansas City, MO	0.63	974	879	8668	7822	106.3	946.0
Natural, Pittsburgh, PA	0.61	1129	1021	10047	9086	106.3	945.1
Producer, Koppers–Totzek[a]	0.78	288	271	2563	2412	135.2	1203
Producer, Lurgi[b]	0.80	183	167	1629	1486	125.3	1115
Producer, W-G, bituminous[b]	0.84	168	158	1495	1406	129.2	1150
Producer, Winkler[b]	0.98	117	111	1041	988	188.7	1679
Propane, commercial, natural gas	1.55	2558	2358	22764	20984	107.5	956.6
Propane, commercial, refinery gas	1.77	2504	2316	22283	20610	108.0	961.1
Sasol, South Africa	0.55	500	448	4450	3986	114.9	1022
Sewage, Decatur	0.79	690	621	6140	5526	105.3	936.2
SNG, no methanation	0.47	853	765	7591	6808	105.8	943.3

[a] O_2-blown.

[b] Air-blown.

46.2.8 Flame Stability

Flame stability is influenced by burner and combustion chamber configuration (aerodynamic and heat transfer characteristics) and by the fuel properties tabulated in Table 46.3.

46.2.9 Gas Gravity

Gas gravity, G (Table 46.1), is the ratio of the actual gas density relative to the density of dry air at standard temperature and pressure (0.0765 lb/ft³). This should not be confused with "specific gravity," which is the ratio of actual density relative to that of water. Gas gravity for natural gases typically ranges from 0.58 to 0.64, and is used in determination of flow rates and pressure drops through pipe lines, orifices, burners, and regulators:

$$\text{flow} = \text{flow coefficient} \times \text{area (ft}^2\text{)} \times \sqrt{2g(\text{psf pressure drop})/\rho}$$

where g = 32.2 ft/sec² and ρ = gas gravity × 0.0765. Unless otherwise emphasized, gas gravity is measured and specified at standard temperature and pressure (60°F and 29.92 in Hg).

Table 46.1c Combustion Characteristics of Typical Gaseous Fuels[2]

Type of Gas	Wobbe Index	Vol. Air. Req'd per Vol. Fuel	Stoichiometric Products of Combustion				Flame Temperature (°F)[b]
			% CO_2 Dry[a]	% H_2O Wet	% N_2 Wet	Total Vol. / Vol. Fuel	
Acetylene, commercial	1559	12.14	17.4	8.3	75.8	12.66	3966
Blast furnace	91.0	0.68	25.5	0.7	74.0	1.54	2559
Blue (water), bituminous	310.8	2.06	17.7	16.3	68.9	2.77	3399
Butane, commercial, natural gas	2287	30.6	14.0	14.9	73.2	33.10	3543
Butane, commercial, refinery gas	2261	30.0	14.3	14.4	73.4	32.34	3565
Carbureted blue, low gravity	729.4	5.05	14.0	18.9	69.8	5.79	3258
Carbureted blue, heavy oil	430.6	5.21	15.7	16.6	70.3	6.03	3116
Coke oven, by-product	961.2	5.44	10.8	21.4	70.1	6.20	3525
Mapp	1947	21.25	15.6	11.9	74.4	22.59	3722
Natural, Alaska	1352	9.52	11.7	18.9	71.6	10.52	3472
Natural, Algeria LNG, Canvey	1423	10.76	12.1	18.3	71.9	11.85	3483
Natural, Gaz de Lacq	1365	9.71	11.7	18.8	71.6	10.72	3474
Natural, Groningen, Netherlands	1107	8.38	11.7	18.4	72.0	9.40	3446
Natural, Kuwait, Burgan	1364	10.33	12.2	18.3	71.7	10.40	3476
Natural, Libya LNG	1520	12.68	12.5	17.4	72.2	13.90	3497
Natural, North Sea, Bacton	1345	9.74	11.8	18.7	71.7	10.77	3473

Natural, Birmingham, AL	1291	9.44	11.7	18.6	71.8	10.47	3468
Natural, East Ohio	1336	9.70	11.9	18.7	71.7	10.72	3472
Natural, Kansas City, MO	1222	9.16	11.8	18.5	71.9	10.19	3461
Natural, Pittsburgh, PA	1446	10.62	12.0	18.3	71.9	11.70	3474
Producer, BCR, W. Kentucky	444	3.23	23.3	14.7	66.0	3.88	3514
Producer, IGT, Lignite	562	4.43	18.7	17.5	67.0	5.24	3406
Producer, Koppers–Totzek	326.1	2.13	27.7	12.6	63.2	2.69	3615
Producer, Lurgi	204.6	1.46	18.4	15.5	68.9	2.25	3074
Producer, Lurgi, subbituminous	465	2.49	23.4	19.6	61.5	3.20	3347
Producer, W-G, bituminous	183.6	1.30	18.5	9.8	73.5	2.08	3167
Producer, Winkler	118.2	0.62	24.1	9.3	68.9	1.51	3016
Propane, commercial, natural gas	2029	23.8	13.7	15.5	73.0	25.77	3532
Propane, commercial, refinery gas	2008	23.2	14.0	14.9	73.2	25.10	3560
Sasol, South Africa	794.4	4.30	12.8	21.0	68.8	4.94	3584
Sewage, Decatur	791.5	6.55	14.7	18.4	69.7	7.52	3368
SNG, no methanation	1264	8.06	11.3	19.8	71.1	8.96	3485

[a]Ultimate.

[b]Theoretical (calculated) flame temperatures, dissociation considered, with stoichiometrically correct air/fuel ratio. Although these temperatures are lower than those reported in the literature, they are all computed on the same basis; so they offer a comparison of the relative flame temperatures of various fuels.

Table 46.2 Calorific Properties of Some Compounds Found in Gaesous Fuels

Compound	Wobbe Index	Gross Heating Value[d] (Btu/ft³)	Net Heating Value (Btu/ft³)	Pounds, Dry poc[a] per std ft³ of Fuel	Pounds H_2O per std ft³ of Fuel	Air Volume per Fuel Volume
Methane, CH_4	1360	1013	921	0.672	0.0950	9.56
Ethane, C_2H_6	1729	1763	1625	1.204	0.1425	16.7
Propane, C_3H_8	2034	2512	2328	1.437	0.1900	23.9
Butane, C_4H_{10}	2302	3264	3034	2.267	0.2375	31.1
Carbon Monoxide, CO	328	323	323	0.255	0	2.39
Hydrogen, H_2	1228	325	279	0	0.0474	2.39
Hydrogen Sulfide, H_2S	588	640	594	0.5855	0.0474	7.17
N_2, O_2, H_2O, CO_2, SO_2	0	0	0	[b]	[c]	0

[a]poc = products of combustion.

[b]Weight of N_2, O_2, CO_2, and SO_2 in fuel.

[c]Weight of H_2O in fuel.

[d]Higher heating value (HHV).

46.2.10 Wobbe Index

Wobbe index or Wobbe number (Table 46.2) is a convenient indicator of heat input considering the flow resistance of a gas-handling system. Wobbe index is equal to gross heating value divided by the square root of gas gravity; $W = \text{HHV}/\sqrt{G}$.

If air can be mixed with a substitute gas to give it the same Wobbe index as the previous gas, the existing burner system will pass the same gross Btu/hr input. This is often invoked when propane–air mixtures are used as standby fuels during natural gas curtailments. To be precise, the amount of air mixed with the propane should then be subtracted from the air supplied through the burner.

The Wobbe index is also used to maintain a steady input despite changing calorific value and gas gravity. Because most process-heating systems have automatic input control (temperature control), maintaining steady input may not be as much of a problem as maintaining a constant furnace atmosphere (oxygen or combustibles).

46.2.11 Flame Temperature

Flame temperature depends on burner mixing aerodynamics, fuel-air ratio, and heat loss to surroundings. It is very difficult to measure with repeatability. Calculated adiabatic flame temperatures, corrected for dissociation of CO_2 and H_2O, are listed in Tables 46.1 and 46.3 for 60°F air; in Chapter 53 it is listed for elevated air temperatures. Obviously, higher flame temperatures produce better heat-transfer rates from flame to load.

46.2.12 Minimum Ignition Temperature

Minimum ignition temperature, Table 46.3, relates to safety in handling, ease of light-up, and ease of continuous self-sustained ignition (without pilot or igniter, which is preferred). In mixtures of gaseous compounds, such as natural gas, the minimum ignition temperature of the mixture is that of the compound with the lowest ignition temperature.

46.2.13 Flammability Limits

Flammability limits (Table 46.3, formerly termed "limits of inflammability") spell out the range of air-to-fuel proportions that will burn with continuous self-sustained ignition. "Lower" and "upper" flammability limits [also termed lower explosive limit (LEL) and upper explosive limit (UEL)] are designated in % gas in a gas–air mixture. For example, the flammability limits of a natural gas are 4.3% and 15%. The 4.3% gas in a gas–air mixture means 95.7% must be air; therefore, the "lean limit" or "lower limit" air/fuel ratio is 95.7/4.3 = 22.3:1, which means that more than 22.3:1 (volume ratio) will be too lean to burn. Similarly, less than (100 − 15)/15 = 5.67:1 is too rich to burn.

Table 46.3 Fuel Properties That Influence Flame Stability[2,a]

Fuel	Minimum Ignition Temperature, °F(°C)	Calculated Flame Temperature, °F(°C)[b]		Flammability Limits, % Fuel Gas by Volume[c]		Laminar Flame Velocity, fps(m/sec)		Percent Theoretical Air for Maximum Flame Velocity
		In Air	In O_2	Lower	Upper	In Air	In O_2	
Acetylene, C_2H_2	581(305)	4770(2632)	5630(3110)	2.5	81.0	8.75(2.67)	—	83
Blast furnace gas	—	2650(1454)	—	35.0	73.5	—	—	—
Butane, commercial	896(480)	3583(1973)	—	1.86	8.41	2.85(0.87)	—	—
Butane, *n*-C_4H_{10}	761(405)	3583(1973)	—	1.86	8.41	1.3(0.40)	—	97
Carbon monoxide, CO	1128(609)	3542(1950)	—	12.5	74.2	1.7(0.52)	—	55
Carbureted water gas	—	3700(2038)	5050(2788)	6.4	37.7	2.15(0.66)	—	90
Coke oven gas	—	3610(1988)	—	4.4	34.0	2.30(0.70)	—	90
Ethane, C_2H_6	882(472)	3540(1949)	—	3.0	12.5	1.56(0.48)	—	98
Gasoline	536(280)	—	—	1.4	7.6	—	—	—
Hydrogen, H_2	1062(572)	4010(2045)	5385(2974)	4.0	74.2	9.3(2.83)	—	57
Hydrogen sulfide, H_2S	558(292)	—	—	4.3	45.5	—	—	—
Mapp gas, C_3H_4	850(455)	—	5301(2927)	3.4	10.8	—	15.4(4.69)	—
Methane, CH_4	1170(632)	3484(1918)	—	5.0	15.0	1.48(0.45)	14.76(4.50)	90
Methanol, CH_3OH	725(385)	3460(1904)	—	6.7	36.0	—	1.6(0.49)	—
Natural gas	—	3525(1941)	4790(2643)	4.3	15.0	1.00(0.30)	15.2(4.63)	100
Producer gas	—	3010(1654)	—	17.0	73.7	0.85(0.26)	—	90
Propane, C_3H_8	871(466)	3573(1967)	5130(2832)	2.1	10.1	1.52(0.46)	12.2(3.72)	94
Propane, commercial	932(500)	3573(1967)	—	2.37	9.50	2.78(0.85)	—	—
Propylene, C_3H_6	—	—	5240(2893)	—	—	—	—	—
Town gas (Br. coal)	700(370)	3710(2045)	—	4.8	31.0	—	—	—

[a]For combustion with air at standard temperature and pressure.

[b]Flame temperatures are theoretical—calculated for stoichiometric ratio, dissociation considered.

[c]In a fuel–air mix. Example for methane: the lower flammability limit or lower explosive limit, LEL = 5% or 95 volumes air/5 volumes gas = 19.1 air/gas ratio. From Table 46.2, stoichiometric ratio is 9.56:1. Therefore excess air is 19 − 9.56 = 9.44 ft^3 air/ft^3 gas or 9.44/9.56 × 100 = 99.4% excess air.

Table 46.4a Physical Properties[a] of LP Gases[b,5]

	Propane	*iso*-Butane	Butane
Molecular weight	44.09	58.12	58.12
Boiling point, °F	−43.7	+10.9	+31.1
Boiling point, °C	−42.1	−11.7	−0.5
Freezing point, °F	−305.8	−255.0	−216.9
Density of liquid			
Specific gravity, 60°F/60°F	0.508	0.563	0.584
Degrees, API	147.2	119.8	110.6
Lb/gal	4.23	4.69	4.87
Density of vapor (ideal gas)			
Specific gravity (air = 1)	1.522	2.006	2.006
Ft^3 gas/lb	8.607	6.53	6.53
Ft^3 gas/gal of liquid	36.45	30.65	31.8
Lb gas/1000 ft^3	116.2	153.1	153.1
Total heating value (after vaporization)			
Btu/ft^3	2,563	3,369	3,390
Btu/lb	21,663	21,258	21,308
Btu/gal of liquid	91,740	99,790	103,830
Critical constants			
Pressure, psia	617.4	537.0	550.1
Temperature, °F	206.2	272.7	306.0
Specific heat, Btu/lb, °F			
c_p, vapor	0.388	0.387	0.397
c_v, vapor	0.343	0.348	0.361
c_p/c_v	1.13	1.11	1.10
c_p, liquid 60°F	0.58	0.56	0.55
Latent heat of vaporization at boiling point, Btu/lb	183.3	157.5	165.6
Vapor pressure, psia			
0°F	37.8	11.5	7.3
70°F	124.3	45.0	31.3
100°F	188.7	71.8	51.6
100°F (ASTM), psig max	210		70
130°F	274.5	109.5	80.8

[a]Properties are for commercial products and vary with composition.

[b]All values at 60°F and 14.696 psia unless otherwise stated.

For the flammability limits of fuel mixtures other than those listed in Table 46.3, the Le Chatelier equation[3] and U.S. Bureau of Mines data[4] can be used.

46.3 LIQUEFIED PETROLEUM GASES

LP gases (LPG) are by-products of natural gas production and of refineries. They consist mainly of propane (C_3H_8), with some butane, propylene, and butylene. They are stored and shipped in liquefied form under high pressure; therefore, their flow rates are usually measured in gallons per hour or pounds per hour. When expanded and evaporated, LPG are heavier than air. Workmen have been asphixiated by LPG in pits beneath leaking LPG equipment.

The rate of LPG consumption is much less than that of natural gas or fuel oils. Practical economics usually limit use to (a) small installations inaccessible to pipe lines, (b) transportation, or (c) standby for industrial processes where oil burning is difficult or impossible.

LPG can usually be burned in existing natural gas burners, provided the air/gas ratio is properly readjusted. On large multiple burner installations an automatic propane–air mixing station is usually installed to facilitate quick changeover without changing air–gas ratios. (See the discussion of Wobbe index, Section 46.2.10.) Some fuel must be consumed to produce steam or hot water to operate a vaporizer for most industrial installations.

Table 46.4 lists some properties of commercial LPG, but it is suggested that more specific information be obtained from the local supplier.

Table 46.4b Physical Properties[a] of LP Gases[b,5]

	Propane	*iso*-Butane	Butane
Flash temperature, °F (calculated)	−156	−117	−101
Ignition temperature, °F	932	950	896
Maximum flame temperature in air, °F			
Observed	3497	3452	3443
Calculated	3573	3583	3583
Flammability limits, % gas in air			
Lower	2.37	1.80	1.86
Higher	9.50	8.44	8.41
Maximum rate flame propagation in 1 in. tube			
Inches per second	32	33	33
Percentage gas in air	4.6–4.8	3.6–3.8	3.6–3.8
Required for complete combustion (ideal gas)			
Air, ft^3 per ft^3 gas	23.9	31.1	31.1
lb per lb gas	15.7	15.5	15.5
Oxygen, ft^3 per ft^3 gas	5.0	6.5	6.5
lb per lb gas	3.63	3.58	3.58
Products of combustion (ideal gas)			
Carbon dioxide, ft^3 per ft^3 gas	3.0	4.0	4.0
lb per lb gas	2.99	3.03	3.03
Water vapor, ft^3 per ft^3 gas	4.0	5.0	5.0
lb per lb gas	1.63	1.55	1.55
Nitrogen, ft^3 per ft^3 gas	18.9	24.6	24.6
lb per lb gas	12.0	11.8	11.8

[a]Properties are for commercial products and vary with composition.

[b]All values at 60°F and 14.696 psia unless otherwise stated.

REFERENCES

1. M. G. Fryback, "Synthetic Fuels—Promises and Problems," *Chemical Engineering Progress* (May 1981).
2. R. J. Reed (ed.), *Combustion Handbook,* Vol. I, North American Mfg. Co., Cleveland, OH, 1986, pp. 12, 36–38.
3. F. E. Vandeveer and C. G. Segeler, "Combustion," in *Gas Engineers Handbook,* C. G. Segeler (ed.), Industrial Press, New York, 1965, pp. 2/75–2/76.
4. H. F. Coward and G. W. Jones, *Limits of Flammability of Gases and Vapors* (U.S. Bureau of Mines Bulletin 503), U.S. Government Printing Office, Washington, DC, 1952, pp. 20–81.
5. E. W. Evans and R. W. Miller, "Testing and Properties of LP-Gases," in *Gas Engineers Handbook,* C. G. Segeler (ed.), Industrial Press, New York, 1965, p. 5/11.