Table 7 . . . . General Data of Combustible Elements and Compounds

Substance	Molecular Symbol	Chemical Reaction of Combustion	Ignition Temperature[a] F Deg	Calorific Value: Btu per Lb, Gross	Calorific Value: Btu per Lb, Net	Calorific Value: Btu per Cu Ft[b], Gross	Theoretical Oxygen and Air Requirements: Lb per Lb, O_2	Lb per Lb, Air	Cu Ft per Cu Ft, O_2	Cu Ft per Cu Ft, Air
Carbon (to CO)	—	$2C + O_2 = 2CO$	—	3950	—	—	1.33	5.76	—	—
Carbon (to CO_2)	—	$2C + 2O_2 = 2CO_2$	—	14093	—	—	2.66	11.53	—	—
Sulfur (to SO_2)	—	$S + O_2 = SO_2$	—	3983	—	—	1.00	4.29	—	—
Sulfur (to SO_3)	—	$2S + 3O_2 = 2SO_3$	—	5940	—	—	1.50	6.43	—	—
Carbon Monoxide	CO	$2CO + O_2 = 2CO_2$	1166–1319	4347	—	321.8	0.57	2.47	0.5	2.39
Methane	CH_4	$CH_4 + 2O_2 = CO_2 + 2H_2O$	1260–1380	23879	21520	1013.2	3.99	17.27	2.0	9.53
Acetylene	C_2H_2	$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$	763–824	21500	20776	1499	3.07	13.30	2.5	11.91
Ethylene	C_2H_4	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$	986–1123	21644	20295	1613.8	3.42	14.81	3.0	14.29
Ethane	C_2H_6	$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$	990–1120	22320	20432	1792	3.73	16.12	3.5	16.68
Hydrogen	H_2	$2H_2 + O_2 = 2H_2O$	1063–1166	60958[c]	51571[c]	325	7.94	34.34	0.5	2.39
Hydrogen Sulfide	H_2S	$2H_2S + 3O_2 = 2H_2O + 2SO_2$	599–608	7100	6545	647	1.41	6.10	1.5	7.15
Propane	C_3H_8	$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$	950–1080	21661	19944	2590	3.63	15.70	5.0	23.82
n-Butane	C_4H_{10}	$2C_4H_{10} + 13O_2 = 8CO_2 + 10H_2O$	890–1020	21308	19680	3370	3.58	15.49	6.5	30.97
Commercial Propane	—	—	920–1020	21560	19865	2520	3.60	15.58	4.9	23.4
Commercial Butane	—	—	900–1000	21180	19591	3260	3.54	15.3	6.3	30.0

[a] Values in table taken chiefly from page 51 of *Fuel Flue Gases* published by American Gas Association.
[b] Gas measured at 60 F and 30 in. Hg. [c] Value from National Bureau of Standards.

of heating equipment must be sufficiently flexible in performance to provide complete combustion with not only variations in the quality of a fuel but also changes in the rate at which it is supplied. This situation makes it advisable, from a practical standpoint, to insure *complete combustion* but not *perfect combustion* in the sense expressed above. To attempt to do so would undoubtedly result eventually in unsatisfactory performance especially from a safety standpoint. Consequently, common types of heating equipment are usually designed, installed, and adjusted to operate with some excess air. The exact percentage of such air depends on the type of fuel being utilized, as well as anticipated variations in its quantity and quality. Despite these practical limitations, however, it should not be inferred that common types of fuels cannot be utilized economically. Reference to flue loss charts such as Figs. 4 and 5 for gas burning equipment and to the air requirements discussion in Chapter 34 shows that reasonable quantities of excess air do not reduce operating efficiencies appreciably.

Oxygen combines with the combustible elements and compounds of any fuel in accordance with fixed laws. The reactions and resultant products of perfect combustion of common fuel constituents are shown in Table 7. All of the oxygen required for combustion is normally obtained from the surrounding air, which is a mechanical mixture of nitrogen and oxygen with small amounts of carbon dioxide, water vapor and inert gases. For practical combustion calculations, air is considered to consist of 20.9 percent oxygen and 79.1 percent nitrogen by volume, or 23.15 percent oxygen and 76.85 percent nitrogen by weight. The nitrogen, being inert, passes through the reaction without change. Table 7 gives the air quantities corresponding to the oxygen required for perfect combustion.

Air supplied to the combustion reaction is in most instances introduced in two ways. *Primary air* is introduced through or with the fuel, and *secondary air* is supplied to the flames issuing from the fuel.

Incomplete combustion is obtained when any of the combustible elements are not completely oxidized in the combustion reaction. This condition not only represents inefficient use of the fuel but also presents a hazard because carbon monoxide is usually one of the products of incomplete combustion. For example, a hydrocarbon may not oxidize completely to carbon dioxide and water, as indicated in Table 7, but may also form alcohols, ketones, aldehydes, or carbon monoxide depending on where and how the reaction is interrupted. Too low a temperature (such as may be caused by flame impingement on a cold surface), a poor oxygen supply to the flames (due to insufficient or poorly located air supply, or smothering by products of combustion not properly vented), or insufficient mixing of the air and fuel, are the primary causes of incomplete combustion.

Heat of Combustion

As previously stated, the process of combustion results in the evolution of heat. The heat generated by the complete combustion of a unit of fuel is constant for a given combination of combustible elements and compounds, and is known as the *heat of combustion*, *calorific value*, or *heating value* of the fuel. The heat of combustion of the several substances found in common fuels is given in Table 7.

The calorific value of a fuel may be determined either by direct measurement of the heat evolved during combustion in a calorimeter, or it may be computed from the ultimate analysis and the heat of combustion of the several chemical elements in the fuel. When the heating value of a fuel is determined in a calorimeter, the water vapor is condensed and the latent heat of vaporization is included in the heating value of the fuel. The heating value so determined is termed the *gross* or *higher* heating value, and this is what is ordinarily meant when the heating value of a fuel is specified.

When combustion is complete, the carbon in the fuel unites with oxygen to form carbon dioxide, CO_2, the hydrogen unites with oxygen to form water vapor, H_2O, and the nitrogen, being inert, passes through the reaction without change. When combustion is incomplete, some of the carbon may unite with oxygen to form carbon monoxide, CO, and some of the hydrogen and hydrocarbon gases may not be

burned at all. When carbon monoxide or other combustible gases are present in the flue gases, there is a loss of heat produced per unit of fuel consumed, and consequently, a lower combustion efficiency is obtained. Incomplete combustion may result from any or all of the following three conditions: (1) inadequate air supply, (2) insufficient mixing of air and gases, and (3) a temperature too low to produce ignition or maintain combustion.

AIR REQUIRED FOR PERFECT COMBUSTION

Air requirements for combustion of solid and liquid fuels are ordinarily expressed in pounds. On the other hand similar requirements for gaseous fuels are usually stated on a cubic foot basis. For solid and gaseous fuels this method of treatment corresponds to the standards of measurement commonly employed by these two industries.

The weight of air required for perfect combustion per pound of solid or liquid fuel may be calculated after substitution of the proper percentages by weight of the various elements obtained from an ultimate analysis of the fuel in Equation 2. For gaseous fuels see Equation 3 for volume of air required.

Solid or Liquid Fuels:

Pounds air required per pound fuel

$$= \frac{34.56}{100}\left[\frac{C}{3} + \left(H - \frac{O}{8}\right) + \frac{S}{8}\right] \quad (2)$$

For Gaseous Fuels:

Cubic feet air required per cubic foot gas

$$= 2.39\,(CO + H_2) + 9.53\,CH_4 + 16.68\,C_2H_6$$
$$+ 23.82\,C_3H_8 + 30.97\,C_4H_{10} + 11.91\,C_2H_2 + 14.29\,C_2H_4$$
$$+ 7.15\,H_2S - 4.78\,O_2 + 30.47\ \textit{Illuminants} \quad (3)$$

Gaseous fuels may contain a wide variety of components classified as *illuminants*, which are not separated by the usual methods of gas analysis. The principal illuminants in addition to ethylene (C_2H_4) and acetylene (C_2H_2) which are included in Equation 3, with the air required per cubic foot of gas are: propylene, 21.44; butylene, 28.58; pentene, 35.73; benzene, 35.73; toluene, 42.88; and xylene, 50.02. Since toluene and xylene are normally scrubbed from the gas before distribution, they may be disregarded in computing air required for a fuel gas. An approximate value of 30.47 (as shown in Equation 3) may, therefore, be employed. If ethylene and acetylene are included as *illuminants*, it is suggested that the value 19.65 be used.

If it is desired to make the gas calculations on a weight basis the equation is expressed as follows:

Pounds air required per pound fuel

$$= 2.47\,CO + 34.34\,H_2 + 17.27\,CH_4 + 16.12\,C_2H_6$$
$$+ 15.70\,C_3H_8 + 15.49\,C_4H_{10} + 13.30\,C_2H_2$$
$$+ 14.81\,C_2H_4 + 6.10\,H_2S - 4.32\,O_2 \quad (4)$$

Where approximate results only are desired, values appearing in Table 8 may be substituted for Equations 2, 3, and 4; or the air required for perfect combustion may be estimated by assuming that 0.9 cu ft air is required per 100 Btu of fuel.

Where extreme precision is involved it is suggested that the reader refer to scientific literature published on the subject of combustion and related topics by the various industries concerned. If approximate values for theoretical air requirements suffice, or if complete information on the fuel is not available, the following values should also be found helpful:

1. *Solid Fuels* (Pounds air per pound fuel): Anthracite, 9.6; Semi-Bituminous, 11.2; Bituminous 10.5; Lignite 6.2; and Coke 11.2.
2. *Fuel Oil* (Pounds air per gallon): Commercial Standard No. 1, 102.6; No. 2, 105.5; No. 5, 112; No. 6, 114.2.
3. *Gaseous Fuels* (Cubic feet of air per cubic foot): Natural, 10.0; Mixed Natural and Manufactured, 8.0; Manufactured, 4.7, Propane, 23.8, Butane, 31.0.

COMBUSTION EFFICIENCY FROM THE FLUE-GAS ANALYSIS

Excess Air

A commonly employed index of efficiency of combustion is the relation existing between the amount of air theoretically required for perfect combustion and the amount of air actually supplied. Since the difference between air supplied for combustion and theoretical air required is characterized as excess air, its percentage may be calculated by use of the following equation,

Percent excess air

$$= \left(\frac{\text{Air supplied} - \text{Theoretical air}}{\text{Theoretical air}}\right) \times 100 \quad (5)$$

The amount of dry air supplied per pound of fuel burned may be obtained from Equation 6 which has reasonable precision for most solid and liquid fuels. Values for CO_2, CO and N_2 are percentages by volume from the flue-gas analysis, and C is the weight of carbon burned per pound of fuel, corrected for carbon in the ash.

Pounds dry air supplied per pound of fuel

$$= \frac{3.04N_2}{(CO_2 + CO)} \times C \quad (6)$$

Because excess air calculations are almost invariably made from Orsat analysis results, and theoretical air requirements

Table 8 . . . . Approximate Air Requirements for Theoretically Perfect Combustion of Fuels[a]

Type of Fuel	Air Required for Perfect Combustion: Lb per Lb Fuel	Air Required for Perfect Combustion: Cu Ft per Unit[b] Fuel	Approximate Precision, %	Exceptions
Solid	Btu per lb × 0.00073	Btu per lb × 0.0097	3	Fuels containing more than 30% water
Liquid	Btu per lb × 0.00071	Btu per lb × 0.0094	3	Results low for gasoline and kerosine
Gas	Btu per lb × 0.00067	Btu per cu ft × 0.0089	5	Gases of 300 Btu per cu ft or less

[a] Values in table taken from page 278 of *Gaseous Fuels*, 1948, published by American Gas Association.
[b] Units for solid and liquid fuels in pounds, for gas in cubic feet.