AIR REQUIRED FOR 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 stoichiometric 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

$$= 2.39\ (CO + H_2) + 9.53\ CH_4 + 16.68\ C_2H_6 + 23.82\ C_2H_4 + 30.97\ C_3H_{10} + 11.91\ C_3H_6 + 14.29\ C_2H_4 + 7.15\ H_2S - 4.78\ O_2 + 30.47\ \text{Illuminants} \quad (3)$$

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

$$= 2.47\ CO + 34.34\ H_2 + 17.27\ CH_4 + 16.12\ C_2H_6 + 15.70\ C_2H_4 + 15.49\ C_4H_{10} + 13.30\ C_3H_6 + 14.81\ C_2H_2 + 6.10\ H_2S - 4.32\ O_2 \quad (4)$$

Where approximate results only are desired, values appearing in Table 6 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 10.3; 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.

Table 6 .... Approximate Air Requirements for Stoichiometric Combustion of Fuels[a]

Type of Fuel	Air Required for Stoichiometric Combustion		Approximate Precision, %	Exceptions
	Lb per Lb Fuel	Cu Ft per Unit[b] Fuel		
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 × 0.00057	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.

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 as follows:

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 are not always known, another convenient method of expressing the relation of Equation 5 is as follows:

$$\text{Percent excess air} = \frac{100(O_2 - CO/2)}{N_2 \times 0.264 - (O_2 - CO/2)} \quad (7)$$

As measurement standards for gaseous fuels are almost universally expressed in cubic feet, Equation 8 may be used for computing excess air on a percentage basis for gases.

$$\text{Percent excess air} = \frac{(U - CO_2)}{CO_2} \times 100\,\frac{P}{A} \quad (8)$$

Table 7 .... Approximate Maximum Theoretical (Stoichiometric) CO_2 Values, and CO_2 Values for Various Fuels with Different Percentages of Excess Air

Type of Fuel	Stoichiometric Percent CO_2	Percent CO_2 at Given Excess Air Values		
		20%	40%	60%
Coke	21.0	17.5	15.0	13.0
Anthracite	20.2	16.8	14.4	12.6
Bituminous Coal	18.2	15.1	12.9	11.3
No. 1 and 2 Fuel Oil	15.0	12.3	10.5	9.1
No. 6 Fuel Oil	16.5	13.6	11.6	10.1
Natural Gas	12.1	9.9	8.4	7.3
Carburetted Water Gas	17.2	14.2	12.1	10.6
Coke Oven Gas	11.2	9.2	7.8	6.8
Mixed Gas (Natural and Carburetted Water Gas)	15.3	12.5	10.5	9.1
Propane Gas (Commercial)	13.9	11.4	9.6	8.4
Butane Gas (Commercial)	14.1	11.6	9.8	8.5

where

U = ultimate carbon dioxide, percent of flue gases resulting from stoichiometric combustion.

CO_2 = carbon dioxide content of flue gases, percent.

P = dry products from stoichiometric combustion, cubic feet per cubic foot of gas burned.

A = air theoretically required for complete combustion, cubic feet per cubic foot of gas burned.

As the ratio of P/A is approximately 0.9 for most city gases, a value of 90 may be substituted for $100(P/A)$ in Equation 8 for rough calculation.

Carbon-hydrogen ratios of different fuels vary considerably, hence the maximum or ultimate CO_2 attainable also varies. Theoretical maximum CO_2 values may be calculated from a flue-gas analysis by use of Equation 9.

Maximum theoretical % CO_2

$$= \frac{\%\ CO_2 \text{ in flue gas sample} \times 100}{100 - \left(\dfrac{O_2 \text{ in same sample}}{0.21}\right)} \quad (9)$$

Approximate maximum CO_2 values for stoichiometric combustion of several common types of fuel are shown in Table 7 together with values of CO_2 that will be attained with different amounts of excess air. Desirable values to be attained in practice depend upon the fuel, the method of firing, and other considerations. In general, fuels burned in suspension, such as gas, oil, and pulverized coal, can be burned with a lower amount of excess air than fuels burned on grates.

To produce heat efficiently by burning any common fuel, a number of basic requirements must be met: (1) adequate heat absorbing surface is necessary in the appliance, (2) heat transfer surfaces must be clean on both fire and water or air sides, (3) a minimum amount of excess air must be present, (4) air employed for combustion and combustible gases must be properly mixed, and (5) flue-gas losses must be reduced to a safe minimum.

If insufficient heating surface is employed, or if heat transfer surfaces are covered with soot, ash, or scale, flue losses will generally be excessive due to the large amount of sensible heat escaping to the chimney. Too much excess air dilutes flue gases excessively and increases sensible flue gas loss. On the other hand, a deficiency of excess air will in all probability cause incomplete combustion, and consequent escape of some unburned combustible gases from the appliance. Highest combustion efficiency is obtained when sufficient excess air is supplied and properly mixed with the combustible gases. Even with appliances connected to an effective flue every reasonable precaution should be taken to insure as complete combustion as possible at all times. This is of vital importance in unvented equipment such as a gas space heater, for example. It is considered good practice to supply from 20 to 50 percent excess air, the exact amount depending on the kind of fuel burned and especially on the type of equipment in which it is utilized.

Flue Gas Analysis

As radiation, convection, and conduction losses from common types of central heating appliances are largely employed in heating occupied spaces, flue-gas losses logically become the item of principal concern. Another reason for their importance is the fact that they are usually larger than all other heat losses combined. These important considerations and others indicate not only the desirability but absolute necessity of a reasonably accurate method for determining flue losses even if only approximate operating efficiencies are to be computed.

Customary procedure in arriving at flue-gas losses is to make an analysis of a representative sample of flue gases and to measure their temperature. This information will enable the observer to compute the amount of flue gases produced, the excess air, the actual quantity of air supplied for combustion, and the flue losses. While the analysis of flue gases has been well described in several governmental and other scientific publications, the subject is of such importance that it warrants brief repetition here. Carbon dioxide and oxygen content are of principal interest in determining flue losses. Either or both of these values may be employed in such calculations. While the former constituent is probably most commonly employed, special considerations may make the latter of greater interest. Fortunately, both can be determined readily by use of an Orsat gas analysis apparatus, a device of reasonably simple construction and design. For field testing and burner adjustment, simple portable devices are available for determining carbon dioxide only. See Chapter 16 regarding operation of the Orsat apparatus.

The weight of dry flue gas per pound of fuel burned is widely used in combustion loss calculations. For solid fuels this item may be determined by application of Equation 10.

Pounds dry flue gas per pound fuel

$$= \frac{11CO_2 + 8O_2 + 7(CO + N_2)}{3(CO_2 + CO)} \times C \quad (10)$$

Values for CO_2, O_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.

Total dry gas volumes of flue gases resulting from the combustion of one cubic foot of gaseous fuels for various percentages of CO_2 may be determined by application of Equation 11:

Cubic feet dry flue gases per cubic foot fuel gas

$$= \frac{\text{Cubic feet } CO_2 \text{ produced per cubic foot of gas burned} \times 100}{\text{Percent } CO_2 \text{ by analysis}} \quad (11)$$

After obtaining the quantity of flue gases from Equations