10 or 11, the excess air quantity may be determined by subtracting the quantity of dry flue gases which would result from stoichiometric combustion. Computations of flue losses are described in the next section on Energy Balance.

Application of the preceding equations and tables are illustrated by *Examples 1* and *2*.

Example 1: The analysis of the flue gases resulting from the burning of a natural gas is 10.0 percent CO_2, 3.1 percent O_2, and 86.9 percent N_2 by volume. The analysis of the fuel is 90 percent CH_4, 5 percent N_2, and 5 percent C_2H_6 by volume. Find U the maximum theoretical percent CO_2 and the percent excess air.

Solution: From Equation 9,

$$U = \frac{(10.0)(100)}{100 - \left(\frac{3.1}{0.21}\right)} = 11.8\%\ CO_2$$

From Equation 8,

$$\text{Percent Excess Air} = \frac{(11.8 - 10.0) \times 90}{10} = 16.2$$

Example 2: For the analysis in *Example 1* find, per cubic foot of fuel gas, the cubic feet of dry air required for combustion, the cubic feet of each constituent in the flue gases, and the total volume of dry and wet flue gases.

Solution: From Equation 3 (or Table 6) the volume of dry air required for combustion is: $(9.53)\ (CH_4) + (16.68)(C_2H_6) = 9.53 \times 0.90 + 16.68 \times 0.05 = 9.41$ cu ft/cu ft gas.

From Table 5, the constitutents per cubic foot of flue gas are: Nitrogen, N_2:

From methane = $(0.9\ CH_4)(9.53 - 2.0)$	= 6.78
From ethane = $(0.05\ C_2H_6)(16.68 - 3.5)$	= 0.66
Nitrogen in fuel =	0.05
Nitrogen in excess air = $0.791 \times 0.162 \times 9.41$	= 1.20
Total Nitrogen	8.69 cu ft

Oxygen, O_2:
Oxygen in excess air = $0.209 \times 0.162 \times 9.41$ = 0.32 cu ft

Carbon dioxide, CO_2:

From methane = $(0.9\ CH_4)(1.0)$	= 0.90
From ethane = $(0.05\ C_2H_6)(4.0/2.0)$	= 0.10
Total Carbon Dioxide	1.00 cu ft

Water vapor, H_2O (does not appear in Orsat analysis):

From methane = $(0.9\ CH_4)(2.0)$	= 1.8
From ethane = $(0.05\ C_2H_6)(6.0/2.0)$	= 0.15
Total water vapor	= 1.95 cu ft

Total volume of dry gas per cubic foot of gas:

$$8.69 + 0.32 + 1.00 = 10.01 \text{ cu ft}$$

Total volume of wet gases per cubic foot of gas (neglecting water vapor in combustion air):

$$10.01 + 1.95 = 11.96 \text{ cu ft}$$

The cubic feet of dry flue gas per cubic foot of fuel gas may also be computed from Equation 11 as follows:

$$\frac{(1.00)(100)}{10.0} = 10.0 \text{ cu ft}$$

ENERGY BALANCE

The usual practice in analyzing the performance of heating appliances is to make an accounting, insofar as possible, of the disposition of all heat units available in the quantity of fuel burned. This accounting is called an *energy balance*. Various components of this balance are generally expressed in terms of Btu per pound of fuel burned, or as a percentage of its heating value. Components of special interest are listed as items 1 to 7 inclusive.

1. Heat transferred to heating medium computed as the product of the mass rate of flow and the enthalpy change.
2. Heat loss in the dry chimney gases.

$$q_1 = w_s c_{ps}(t_s - t_a) \qquad (12)$$

3. Heat loss in water vapor in products formed by combustion.

$$q_2 = \frac{9H_2}{100}\left[(h)_{st} - (h_f)_{ta}\right] \qquad (13)$$

4. Heat loss in water vapor in the air supplied.

$$q_3 = M\, w_s[(h)_{st} - (h_f)_{ta}] \qquad (14)$$

5. Heat loss from incomplete combustion.

$$q_4 = 10143C\left(\frac{CO}{CO_2 + CO}\right) \qquad (15)$$

6. Heat loss from unburned carbon in the ash or refuse.

$$q_5 = 14600\left(\frac{C_a}{100} - C\right) \qquad (16)$$

7. Radiation and all other unaccounted for losses.

Radiation and convection losses from a heating appliance are not usually determined by direct measurement. For this reason they, together with any other losses not measured, are determined by subtracting the total of items 1 to 6 from the heat of combustion of the fuel. If the heating appliance is located within the heated space, however, radiation and convection losses may be considered as useful heat rather than lost heat. They may, therefore, be omitted from calculations of heat losses, or added to item 1. If there is CO in the flue gases, small amounts of unburned hydrogen and hydrocarbons will probably also be present. The small losses due to incomplete combustion of these latter gases would also be included in item 7.

Symbols used in Equations 12 to 16 inclusive are:

q_1 = heat loss in the dry chimney gases, Btu per pound of fuel.
q_2 = heat loss in water vapor from combustion of hydrogen, Btu per pound of fuel.
q_3 = heat loss in water vapor in combustion air, Btu per pound of fuel.
q_4 = heat loss from incomplete combustion of carbon, Btu per pound of fuel.
q_5 = heat loss from unburned carbon in the ash, Btu per pound of fuel.
$(h_f)_{ta}$ = enthalpy of saturated steam at combustion air temperature, Btu per pound.
$(h)_{st}$ = enthalpy of superheated steam at gas temperature and 1 psia, Btu per pound.
$(h_f)_{ta}$ = enthalpy of saturated water at air temperature, Btu per pound.
w_s = weight of dry flue gas per pound of fuel (from Equation 10), pounds.
c_{ps} = mean specific heat of flue gases at constant pressure (c_p ranges from 0.242 to 0.254 for flue gas temperatures from 300 F to 1000 F),[3] Btu per pound.
t_s = temperature of flue gases at exit of heating device, Fahrenheit.
t_a = temperature of combustion air, Fahrenheit.
H_2 = percentage of hydrogen in fuel by weight from ultimate analysis of fuel burned.
M = humidity ratio of combustion air, pounds of water vapor per pound of dry air.

w_a = weight of combustion air per pound of fuel used, pounds, from Equations 2, 4, 5, 6, 7 and 8.
CO, CO_2 = percentages of CO, CO_2 in flue gases by volume.
C = weight of carbon burned per pound of fuel corrected for carbon in ash, pounds.

$$C = \frac{WC_a - W_aC_a}{100W} \qquad (17)$$

where

C_a = percentage of carbon in the fuel by weight from the ultimate analysis.
W_a = weight of ash and refuse, pounds.
C_a = percent of combustible in ash by weight (combustible in ash is usually considered to be carbon).
W = weight of fuel used, pounds.

Flue-gas losses for solid and liquid fuels, listed as items 2, 3 and 4 of the heat balance, may be determined with sufficient precision for most purposes from curves shown in Fig. 1, if CO_2 content and temperature of flue gases are known. Values of the losses plotted for fuel oil were computed from the ultimate analysis of a typical fuel oil used in domestic burners, while those presented for the several ranks of coal were computed from typical ultimate analyses shown in Table 1. Curves for medium-volatile bituminous coal may be used for high-volatile bituminous coal with negligible error.

Utilization of gaseous fuels, for numerous reasons, is generally a more simple process than is the case with either solid or liquid fuels. Accordingly, the determination of a practical heat balance is also a more simple procedure in that items 5 and 6 do not generally apply to gas installations. A series of typical alignment charts is combined in Fig. 2 for use in determining flue losses of items 2, 3 and 4 from common types of gas burning appliances. To determine flue losses place a straight edge extending from the corrected temperature reading to the percent CO_2 recorded. Percent flue loss is indicated where the straight edge intersects the flue loss column. The operating efficiency of a gas appliance can then be computed with sufficient precision by application of Equation 18.

$$\text{Percent Combustion Efficiency} = \frac{\left(\text{Gross Btu of fuel gas per cubic foot}\right) - \left(\text{total flue losses per cubic foot fuel gas}\right)}{\text{Gross Btu of fuel gas per cubic foot}} \times 100 \qquad (18)$$

Reference to Table 7 will show that ultimate CO_2 percentage values of fuel gases vary. While personal errors involved in CO_2, temperature, and chart determinations, would doubtless more than offset any inaccuracies due to universal use of the alignment charts shown, precise laboratory work may require a more exact method. For more complete information the reader is referred to *Combustion*, 3rd Edition, and *Gaseous Fuels*, (published by American Gas Association) and particularly to tables covering various properties of different commercial gases included in these publications.

CONDENSATION AND CORROSION

Sulfur dioxide or sulfur trioxide, formed by the combustion of sulfur in fuels, are the principal corroding substances in flue gases. They become active whenever sufficient moisture is present for the formation of sulfurous or sulfuric acid.[9] Traces of vanadium are occasionally found in residual fuels. This element acts as a catalyst in accelerating the change of sulfur dioxide to the trioxide form.[10] Excessive spot temperatures in the combustion chamber or elsewhere, are also destructive in that they may result in rapid oxidation of ordinary heating surfaces. *American Standard Requirements* for gas furnaces, floor furnaces, and recessed heaters, for example, specify that minimum spot heating surface temperatures during normal operation must neither fall below 178 F (50 F above average dew point) nor exceed 830 F to 1230 F on any portion of the heating surface, depending on the type and thickness of the metal. In any event it is usually desirable to maintain flue-gas temperatures within the limits indicated not only throughout the appliance, but in its connecting vent, flue, or chimney as well. Otherwise, excessive condensation and corrosion problems, with resultant customer dissatisfaction, will in all probability be the result. Average dew-point temperatures of flue gases resulting from the combustion of various fuels, when burned with the amount of excess air normally supplied to insure complete combustion are shown in Table 8.

Table 8 .... Average Flue Gas Dew Point for Various Fuels

Type of Fuel	Average Dew Point Temperature, F
Anthracite	68
Semi-Bituminous Coal	84
Bituminous Coal	93
Oil	111
Natural Gas	127
Manufactured Gas	137
Propane Gas (2500 Btu/cu ft)	119
Butane Gas (3200 Btu/cu ft)	124
Butane-Air Gas Mixture (535 Btu/cu ft)	121

SOOT

The deposit of soot on the flue surfaces of a boiler or heater acts as an insulating layer over the surface, and reduces the heat transmission to the water or air. The *Bureau of Mines Report of Investigations*. No. 3272[11] shows that the loss of seasonal efficiency is not so great as has been believed, and usually is not over 6 percent because the greater part of the heat is transmitted through the combustion chamber surfaces. The *Bureau of Standards Report* BMS 54[12] points out that, although the decrease in efficiency of an oil fired boiler, due to soot deposits is relatively small, the attendant increase in stack temperature may be considerable.

Condensation frequently occurs during idle summer periods as a result of moisture in the air condensing on the cooler boiler surfaces. This condition, combined with surfaces coated with sulfur-bearing soot and fly ash can also result in sulfurous acid and accelerated corrosion.

The soot accumulation clogs the flues, reduces the draft, and may prevent proper combustion. Soot can probably be most effectively removed by a jet of compressed air, by means of a brush, or a vacuum cleaner. However, it has been found that copper chloride, lead chloride, tin chloride, zinc chloride, and some other salts are partially effective in removing soot from furnaces and boilers when properly used.[13] These are preferably applied to the surfaces. A discussion of instruments and methods of evaluating smoke will be found in Chapter 16.

AIR SUPPLY TO FUEL-BURNING EQUIPMENT

All rooms or spaces containing boilers, furnaces, water heaters, or any other fuel-burning equipment must be provided with a constant supply of combustion air at adequate static pressure to insure proper combustion of the fuel.