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 employed for computing excess air on a percentage basis for gases.[7]

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

where

U = ultimate carbon dioxide, percent of flue gases resulting from perfect combustion.
CO_2 = carbon dioxide content of flue gases, percent.
P = dry products from perfect 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. Where they are unknown, 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 perfect combustion of several common types of fuel are shown in Table 9 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.

Table 9 .... Approximate Maximum Theoretical CO_2 Values, and CO_2 Values for Various Fuels with Different Percentages of Excess Air

Type of Fuel	Maximum Theoretical or Ultimate 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

To produce heat efficiently by burning any common fuel, a number of basic requirements must be met: (1) adequate heat absorbing surface of proper shape and construction is necessary in the appliance, (2) heat transfer surfaces must be clean, (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 44 for details regarding the 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 10 or 11, the excess air quantity may be determined by subtracting the quantity of dry flue gases which would result from perfect combustion. Computations of flue losses are described in the next section on Heat 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:

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

From Equation 8,

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

Example 2: For the analyses 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 7) 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 7, *the constituents per cubic foot of 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 $= (0.9CH_4)(1.0)$	$= 0.90$
From ethane $= (0.05C_2H_6)(4.0/2.0)$	$= 0.10$
Total Carbon Dioxide	1.00 cu ft

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

$(0.9\ CH_4)(2.0)$	$= 1.8$
$(0.05\ C_2H_6)\ (6.0/2.0)$	$= 0.15$
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:

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

HEAT 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 a *heat balance*. Various components of this balance are generally expressed in terms of Btu per pound of fuel burned, or as a percentage of its calorific value. Components of special interest are listed as items 1 to 7 inclusive.

1. Useful heat transferred to heating medium, *usually computed* by determining the rate of flow of the heating fluid through the heating device, and the change in enthalpy of the fluid (heat added) between the inlet and outlet.

2. Heat loss in the dry chimney gases.

$$h_1 = w_g c_p\ (t_g - t_a) \quad (12)$$

3. Heat loss in water vapor formed by the combustion of hydrogen.

$$h_2 = \frac{9H_2}{100}\ (1089 - t_a + 0.455t_g) \quad (13)$$

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

$$h_3 = 0.455\ M\ w_a\ (t_g - t_a) \quad (14)$$

5. Heat loss from incomplete combustion.

$$h_4 = 10143C\left(\frac{CO}{CO_2 + CO}\right) \quad (15)$$

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

$$h_5 = 14600^a\left(\frac{C_a}{100} - C\right) \quad (16)$$

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