POWER PLANT COMBUSTION THEORY

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Contents

Summary

When a simple fuel such as carbon is burned in air, it combines with the oxygen to produce carbon dioxide. If a hydrocarbon fuel is burned then, in addition, water is produced from the hydrogen. Similarly various combustible impurities, such as sulfur, produce their respective oxides, in this case sulfur dioxide.

Simple chemical balances of the reactants and products enable the quantities required or produced to be determined. Ideally there should be no reactants left over in the products to obtain chemically correct or stoichiometric combustion. The nitrogen in the air has to be taken into account. Although it passes through the combustion process essentially unreacted, it does dilute both the reactants and the products. The chemical equation describing the combustion process therefore must include an amount of nitrogen on each side. With this taken into account the required air-fuel mass ratios can be determined for any particular fuel.

Similarly it is possible to work backwards from a chemical analysis of the exhaust gas, using the combustion equations, to determine the fuel constituents or air-fuel ratio. This is a convenient method of monitoring the combustion efficiency of the boiler. In practice, for complete combustion of the fuel, it is necessary to provide some excess air beyond that necessary for stoichiometric conditions so some oxygen usually appears in the exhaust gas.

It is also possible to determine the boiler thermal efficiency from an exhaust gas analysis. The flue gas carries away a considerable amount of heat which is not transferred to the water-steam circuit. Knowledge of the heating value of the fuel, the gas-fuel ratio, the specific heat of the gases and their exhaust temperature is sufficient to determine the boiler efficiency which is usually around 90 percent for large units.

1. Combustion Fundamentals

1.1. Definitions of combustion

Combustion is the rapid chemical combination of oxygen with certain elements. Although similar to oxidation, it occurs very much faster and requires a certain minimum temperature to initiate the reaction. This rapid chemical reaction can be controlled so that, in normal circumstances, it is not explosive. For effective combustion the reacting elements must be mixed with the oxygen, maintained at a suitable temperature and given sufficient time to react. Hence the three T's of combustion, turbulence, temperature and time, which determine the success or otherwise of a combustion process. Combustion processes release heat so generally, once ignition has been accomplished, the temperature is maintained at a suitable value. As combustion proceeds the concentration of the oxygen and the reacting elements decreases and continued turbulence is required to bring unreacted elements into contact with the oxygen. Adequate time is thus required from initial ignition to affect complete combustion.

1.2. Principles of Combustion

The most suitable combustible fuels are those made up primarily of carbon or hydrocarbons where the main constituents are carbon and hydrogen. All fossil fuels derived originally from carboniferous matter fall into this category. Other elements such as sulfur are also combustible and, if present in the fuel, contribute to the generation of heat but produce undesirable products such as sulfur dioxide. Pure hydrocarbon fuels have the advantage of producing carbon dioxide and water vapor, both relatively innocuous products. Oxygen is readily available from the atmosphere but is not pure. The major constituent of the air is nitrogen and, although the relatively inert gas passes through the combustion process largely unreacted, it does produce some undesirable nitrogen oxide at high temperatures. Generally combustion for large scale heat production should proceed continuously under stable conditions. This implies that the fuel and oxygen must be supplied to the combustion zone continuously and the products of combustion likewise removed. Within the combustion zone the air containing oxygen must be brought into intimate contact with the fuel, irrespective of whether it is in gaseous, liquid or solid form. This requires that fuel be well dispersed and the air turbulent in the combustion zone. Liquid and solid fuels require suitable division into small particles to ensure intimate mixing with the air.

Solid fuels usually produce significant amounts of ash which must be removed from the combustion zone but only after sufficient time has been allowed for the combustible elements within the fuel particles to have fully reacted with the oxygen of the air.

The purpose of combustion is to produce heat which is radiated from the combustion zone or carried away by the gaseous products of combustion. This heat is to be transferred effectively to the working fluid of the thermodynamic cycle but a certain portion is inevitably lost to the environment when the exhaust gases are discharged to the atmosphere.

1.3. Combustion Equations

When various elements are burned in oxygen the products of the combustion process can be determined from basic chemical equations.

When a solid fuel such as carbon is used, the product is carbon dioxide:

$$C + O_2 = CO_2 \tag{1}$$

When a simple gaseous fuel such as methane is burned, water vapor as well as carbon dioxide is produced:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{2}$$

For more complex liquid hydrocarbon fuels, such as oil, which contain mixtures of different hydrocarbons, the equations have to be written in a slightly different form and the amount of each element in the fuel has to be considered.

2. Combustion Calculations

2.1. Concept of the Mole

Each element has a specific atomic mass and each compound a specific molecular mass. These values are based on the number of protons and neutrons in the atom and, as such, are somewhat arbitrary masses. Carbon has an atomic mass of 12, oxygen an atomic mass of 16 while carbon dioxide has a molecular mass of 44.

The mass of a substance in kilograms equal to its molecular mass is called a *kilogram-mole* or often simply a *mole* of the substance. In the case of oxygen combining with carbon, converting to moles yields

$C + O_2 = CO_2$

12 kg-mole C + 32 kg-mole O_2 = 44 kg-mole CO_2

12 kg C + 32 kg O_2 = 44 kg CO_2

This demonstrates a method of carrying out combustion calculations where an amount of a reactant or a product is to be determined.

In the case of a gas the volume occupied by one mole is called the *molar volume*. The volume of one mole of an ideal gas is the same for all gases at any particular temperature and pressure. One mole of oxygen therefore occupies the same volume as one mole of carbon dioxide even though their masses are different.

This concept allows the conversion from volumes to masses. Therefore, if the constituents of a gas are known by volume, their respective masses can be determined. Thus a mixture of 50 percent carbon dioxide and 50 percent oxygen contains one mole of CO_2 for each mole of O_2 but 44 kg of CO_2 for every 32 kg of O_2.

2.2. Composition of Air

Atmospheric air is composed of 78 percent nitrogen, 21 percent oxygen, 1 percent argon and trace amounts of carbon dioxide and other gases. For the purpose of calculations the argon and nitrogen are lumped together as "atmospheric nitrogen" to make up 79 percent. The ratio of nitrogen to oxygen is thus 3.76.

In all practical applications of combustion the oxygen is supplied as a constituent of atmospheric air and the nitrogen passes through essentially unreacted. In effect the nitrogen dilutes both the oxygen and the combustion products and appears on both sides of the combustion equation. For carbon burning in air the combustion equation is thus:

$C + O_2 + 3.76\ N_2 = CO_2 + 3.76\ N_2$

From a chemical point of view this is no different from the previous equation except that nitrogen has been added and a mass balance using the mole concept yields the following:

12 kg C + 32 kg O_2 + 105.3 kg N_2 = 44 kg CO_2 + 105.3 kg N_2

The procedure enables the amount of air required to burn a certain quantity of fuel to be determined. In this case the air-fuel ratio is:

$$m_{\text{air}} / m_{\text{fuel}} = 11.44 \text{ kg air / kg fuel}$$

This assumes that combustion occurs under chemically correct or *stoichiometric* conditions and that all the fuel is completely reacted with all the oxygen.

2.3. Excess Air Requirements

Stoichiometric combustion conditions as described above are an ideal situation difficult to achieve in practice. As the oxygen and fuel are consumed, the remaining reactants become more dilute and more time is required for them to come into contact with one another. Even with good turbulence it is unlikely that the last remaining particles of fuel will react with the highly diluted oxygen remnants. The result is that a certain amount of unreacted fuel and oxygen will leave the combustion space.

To overcome this problem the quantity of air supplied is increased slightly above the theoretical air amount. During the last stages of combustion there will thus be significantly more oxygen in the combustion mixture so that the possibility of reaction with the last remaining particles of fuel is much enhanced. In this way virtually complete combustion can be ensured but some oxygen will pass through unreacted. Most combustion processes operate with a certain amount of *excess air* which can be accounted for in the combustion calculations by multiplying the theoretical air quantity by the appropriate factor. For say 25 percent excess air, this factor is 1.25 and the combustion equation for burning carbon becomes:

$$C + 1.25 (O_2 + 3.76 N_2) = CO_2 + 0.25 O_2 + 4.70 N_2$$

Converting this to kilogram-moles to obtain a mass balance gives the following

$$12 \text{ kg C} + 40 \text{ kg } O_2 + 131.6 \text{ kg } N_2 = 44 \text{ kg } CO_2 + 8 \text{ kg } O_2 + 131.6 \text{ kg } N_2$$

The corresponding air fuel ratio to give 25 percent excess air is then given by:

$$m_{\text{air}} / m_{\text{fuel}} = 14.3 \text{ kg air / kg fuel}$$

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.