PRODUCTION OF STEAM

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Contents

Summary

In order to extract heat from fuel it must first be processed and then burned. Most solid fuels such as coal require specific processing to ensure proper mixing with the combustion air while liquid and gaseous fuels are more readily combustible. Most processing requires crushing and grinding to produce small quickly combustible particles but for certain applications gasification is an alternative method of preparation.

Fuel may be burned in various ways which ensure intimate mixing of the fuel and air but the most common method is to burn it in suspension where the fuel and air are mixed in a turbulent flame. This promotes rapid combustion and a high rate of heat release. Suspension firing is suitable for solid, liquid and gaseous fuels.

Following combustion, the exhaust gas usually requires some treatment to minimize the release of ash in particulate form and of certain combustion products. Most plants burning solid fuels and heavy liquids have electrostatic precipitators or baghouses to trap the flyash while plants burning fuels having high sulfur contents have more recently been fitted with desulfurization units.

Heat may be obtained directly, without combustion of a fuel, from below the earth or from the sun. The main problem with such resources is lack of concentration of the energy. An extensive collection system is required and this adds enormously to the cost of handling what is often perceived as free energy.

Nuclear energy on the other hand is extremely concentrated. Only a tiny amount of fuel

is required to produce a large amount of power. This makes it very desirable for the production of heat on a large scale in central generating plants. A distinct advantage of nuclear energy is that there are no combustion gases released to the atmosphere and hence no atmospheric pollution. On the other hand the radioactive spent fuel products have to be stored indefinitely in secure areas. The amount to be stored however is relatively small and safe methods of disposal have been devised.

The overall safety of nuclear plants is of concern following the accidents at Three Mile Island and Chernobyl. These concerns have been addressed in some advanced nuclear reactor designs where passive safety is a feature. This concept ensures that a nuclear reactor remains in a safe condition without operator intervention following various postulated accidents.

1. Introduction

1.1. Importance of Steam

All thermal power plants, by definition, produce work, in the form of electricity, from heat. The heat is generated mostly by combustion of a chemical fuel or fission of a nuclear fuel. In rare cases heat may be supplied from a natural source such as the earth (geothermal) or the sun (solar) but the scale of this is practically negligible at the present time. The process of producing work from heat requires a thermodynamic cycle with a working fluid to convey the heat from the heat source, at an elevated temperature, to the heat sink, at a lower temperature. For large scale applications this fluid must be relatively cheap and abundant and have desirable heat transport properties. Water fits these requirements very well particularly as the change in phase from liquid to vapor and back to liquid is accompanied respectively by a large absorption and rejection of heat. This enables this fluid to transport much larger quantities of heat per unit mass than other working fluids such as, for example, air. As a result water-steam is the working fluid of choice and is used in the majority of thermal power cycles for the production of electricity. Steam is generated from water in fossil fueled boilers and in nuclear fueled reactors and then utilized in steam turbines to produce electrical power. The production of steam is thus a key element in the production of electrical power.

Gas turbines utilize air as the working fluid in their thermodynamic cycles. Air is convenient to use, as the combustion process and the thermodynamic cycle can be combined thus simplifying enormously the structure of the plant. This is a big advantage but constraints in fuel cost and availability as well as in overall cycle efficiency and plant capacity make gas cycles less attractive than the steam cycle for large scale applications. The advent of combined cycles with their high thermal efficiency has however made them very attractive for certain applications. A combined cycle however reverts back to steam as the working fluid for part of the combined cycle. Thus even such installations make use of water to generate steam.

1.2. Scope of Topic

Having identified steam as the dominant working fluid in thermal power plants, this topic is concerned primarily with the generation of steam.

The chapter on *Power Plant Technology* covered the more theoretical aspects of thermal power plants and dealt with thermodynamic cycles, heat transport and material considerations. These are all aspects where there is the potential for generic improvements to increase plant efficiency and reliability. This topic covers various aspects of steam generation particularly those where there is likely to be future development, for example, reduced gaseous emissions from fossil fired plants and enhanced safety for nuclear fueled plants. The chapter on *Production of Power* covers the use of hot high energy working fluids such as steam or gas to produce electrical power. All large installations make use of turbines through which the steam or gas expands as this type of machine has an extremely high power to weight ratio.

As clarification, the individual chapters within this topic cover the most important individual aspects of steam generation. Only current technology for large scale steam generation is considered. The main reason for this approach is that thermal power plants are very capital intensive and have long operating lives. This makes the industry conservative with regard to unproven innovations and technological evolution is slow. It is possible that some plants will still be running half a century after commissioning. Reference to current technology will therefore be appropriate for many years to come. Nevertheless there are many new developments and possibilities for adopting other technologies. These are outlined in this introductory topic. Naturally it is impossible to predict which way technology will develop but indications are that the thrust will be towards the reduction of effluents that have an adverse effect on the environment. The implementation of such developments is likely to be driven by legislation rather than by economy or efficiency.

1.3. Current Trends

There are two distinct aspects driving changes in power plant technology. One is environmental considerations as mentioned above. The other is financing of new installations.

With regard to the environment there has, in recent years, been an effort to reduce the emission of sulfur oxides and nitrogen oxides. This can be done by appropriate selection of the fuel or proper choice of cleanup technology for the exhaust gases. Since the demand for electricity is ever increasing it follows that new plants must have reduced emission criteria just to maintain total emissions at the current level.

The aspect of financing is related to reduced economic growth and reduced government spending on large scale projects in recent years. Generally private enterprise is less willing to invest in projects with a low return and a long pay-back period. There is thus an incentive to build plants with a lower capital cost and a shorter construction period and to refurbish older plants.. There are various ways of achieving this but a combined cycle plant is a ready solution.

2. Coal Gasification

2.1. Fuel Characteristics

Fossil fuels consist of mixtures of various combustible elements and compounds such as carbon and hydrocarbons. Some of these, notably sulfur, produce undesirable combustion products. To reduce emissions of sulfur dioxide, the sulfur should either be removed before or after combustion. Gaseous fuels are generally relatively pure and, if any undesirable sulfur compounds such as hydrogen sulfide are present, they can be readily removed prior to combustion. This makes gaseous fuels relatively clean burning. Liquid fuels are also relatively uncontaminated mixtures of hydrocarbons but some heavy fuel oils do contain sufficient sulfur and ash to necessitate appropriate flue gas treatment after combustion. Removal of sulfur prior to combustion is not economically feasible with current technology so, to reduce undesirable emissions, the choices are to switch to a cleaner burning fuel or to install flue gas treatment facilities. Solid fuels generally contain large amounts of incombustible material which forms ash and often undesirable amounts of sulfur. Although current flue gas cleanup technology is able to remove over 99 percent of particulate matter and up to 90 percent of the sulfur dioxide, this may not be sufficient to meet emission requirements when burning particularly contaminated fuels. Coal is the most abundant solid fuel and in fact the most widely used fuel in fossil fired plants. This is likely to continue well into the future because of the vast reserves of coal still available. The best coal however tends to be used first so in future years there is likely to be deterioration in the quality of coal available for power generation. This combined with more stringent emission control regulations may make it impossible to burn readily available coal with current flue gas treatment technology. A solution to this potential difficulty is the conversion of poor quality coal into a cleaner gaseous fuel prior to combustion. Thus coal gasification becomes an attractive alternative technology.

2.2. Gasification Process

Coal gasification processes were commercialized in the middle of the past century to support various industries including the synthesis of liquid fuels and various plastics. Because of the diversity of coal available and products required several different processes evolved. The underlying principles though are common.

When coal, which consists mainly of carbon, is burned in an adequate supply of air, the oxygen combines with the carbon to form carbon dioxide and all the available chemical energy is released. If the amount of air supplied is restricted, there is less oxygen available and carbon monoxide is formed instead. Less heat is produced by the reaction but the resulting carbon monoxide itself still contains potential chemical energy. The heat released in producing carbon monoxide promotes other chemical conversions so that hydrogen and methane are produced as well. Both of these are pure gaseous fuels. In essence, part of the chemical energy in the original coal is used to convert the bulk of its constituents into a combustible gaseous fuel with the remaining chemical energy still available for release during subsequent combustion. Incombustible constituents which would form ash are left behind. Sulfur in the fuel is converted primarily to hydrogen sulfide and can be separated from the resulting gas. Subsequent combustion of the resultant clean gaseous fuel then produces a flue gas that is free from particulates and sulfur dioxide.

During the gasification process there are two important phases, namely coal devolatilization and char gasification. When subject to elevated temperatures, the coal releases its volatile matter leaving a carbon char which is then converted into a gas. The type of process has a bearing on the constituents of the final product that is different processes produce different mixtures of gases. This is due to the different chemical reactions which may occur preferentially at different temperatures and pressures. The ultimate objective is to produce a product with as high a calorific or heating value as possible. Some of the principle gasification processes are given below.

2.3. Gasification Methods

Although there are many different gasification processes, they can be divided into three basic methods. All three methods employ a system of bringing cool lumps or particles into contact with a stream containing oxygen and steam to provide the appropriate reactants and sufficient heat to promote gasification processes.

The basic chemical reactions that take place during the gasification process are given below. The first step is the combustion of some carbon in the coal with a sub-stoichiometric amount of oxygen

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

The carbon dioxide then reacts with additional carbon to form carbon monoxide.

$$CO_2 + C = 2\,CO \tag{2}$$

The steam reacts with the remaining carbon to form carbon monoxide and hydrogen.

$$H_2O + C = CO + H_2 \tag{3}$$

If the oxygen is supplied in a natural air stream then a certain fraction of nitrogen is carried through and dilutes the product producing a gas of low heating value. To obtain a gas of higher heating value the air stream must be enriched in oxygen or replaced with an oxygen stream.

2.3.1. Moving Bed

In the moving bed gasifier, shown in Figure 1, coarsely crushed coal with lumps less than 50 mm is added to the top of the bed while the ash remaining after gasification is removed from the bottom. Steam and oxygen or air is supplied from the bottom of the bed and the raw gas removed from the top, so the reactants pass through the bed in a countercurrent fashion.

The highest temperatures are in the combustion zone near the bottom of the bed. Above this is the devolatilization zone where the main gasification reactions between the coal and the steam and carbon dioxide occur. At the top of the bed the fresh coal is heated by the gas which leaves at relatively low temperatures ranging from 430°C to 650°C.

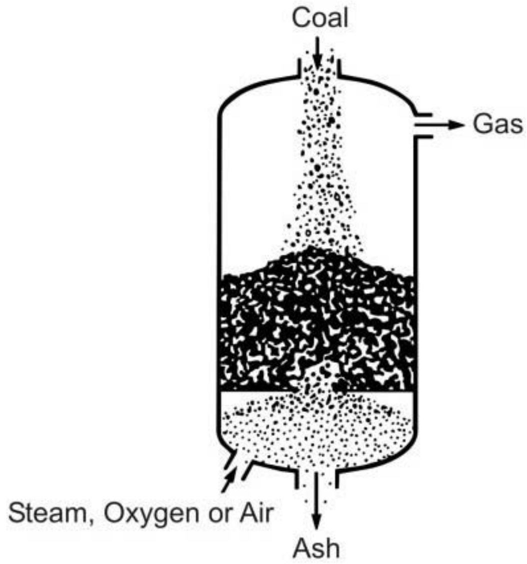

Figure 1: Moving bed gasifier (courtesy of Babcock & Wilcox)

2.3.2. Fluidized Bed

The fluidized bed gasifier, shown in Figure 2, has a bed of finely crushed coal with the particle size less than 6 mm. The bed is maintained in a fluidized state by an upward current containing steam and oxygen. Thus, unlike the moving bed gasifier, the reaction zone is not segregated into discrete layers. The fresh feed particles are thoroughly mixed with the reacted char particles. The temperature throughout the bed is uniform and the gasification reactions occur at all levels. Since the coal feed mixes with the bed rather than contacts the exiting gas, the final gas temperature is much higher than in the moving bed gasifier, being in the range of 930°C to 1040°C.

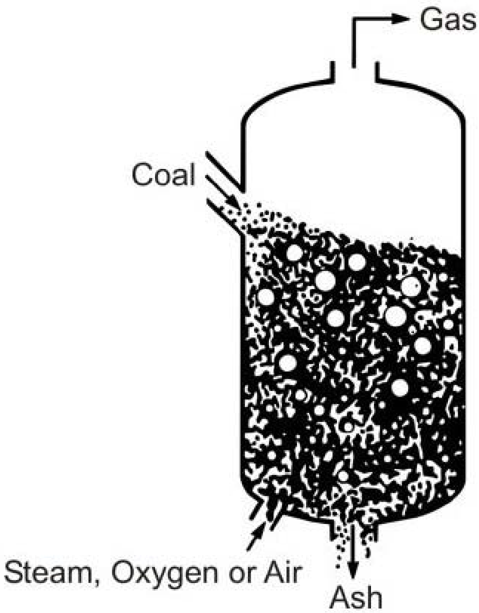

Figure 2: Fluidized bed gasifier (courtesy of Babcock & Wilcox)

2.3.3. Entrained Flow

The entrained flow gasifier, shown in Figure 3, utilizes finely ground coal with a particle size of less than 150 μm. The pulverized coal is carried with the stream containing steam and oxygen and the gasification reactions occur while in suspension. Since there is a parallel flow of reactants the exit temperatures are higher than in the other two methods, being generally above 1260°C. This results in a large amount of sensible heat energy in the raw gas so some form of heat recovery is desirable. Furthermore the temperatures are above the ash fusion temperature so provision must be made to handle liquid ash.

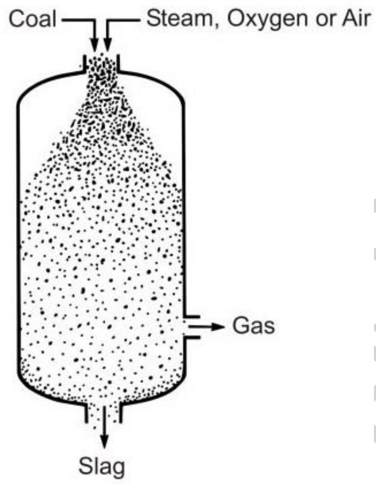

Figure 3: Entrained flow gasifier (courtesy of Babcock & Wilcox)

It follows from the above that the different methods provide for the use of coals having different characteristics and produce different product mixtures due to the different temperatures at which gasification occurs. The use of oxygen or air as a reactant also has a bearing on the product due to the chemical influence or diluting effect of the nitrogen. When air is used, obviously nitrogen is a major constituent of the raw product. With an oxygen blown unit, the product gas consists primarily of carbon monoxide (CO) and hydrogen (H_2) as well as some carbon dioxide (CO_2), methane (CH_4) and water vapor (H_2O). Sulfur and nitrogen in the coal form some hydrogen sulfide (H_2S), carbonyl sulfide (COS), ammonia (NH_3) and hydrogen cyanide (HCN). There are various other impurities arising from the chemical content of the ash.

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Bibliography

Black & Veatch (1996). *Power Plant Engineering*, Chapman and Hall.[Covers all basic aspects of power plant technology with separate topics by specialist authors.]

British Electricity International (1991). *Modern Power Station Practice*, Volume B, Boilers and Ancillary Plant, Pergamon Press.[Very comprehensive text directed towards the design and operation of both fossil fuel boilers and nuclear reactors as well as transmission systems.]

British Electricity International (1992). *Modern Power Station Practice*, Volume E, Chemistry and Metallurgy, Pergamon Press.[Very comprehensive text directed towards the design and operation of both fossil fuel boilers and nuclear reactors as well as transmission systems.]

Elliott T.C. (1989). *Standard Handbook of Power Plant Engineering.* McGraw-Hill.[This gives good information on the basics of power generation with reference to different plant components.]

El-Wakil M.M. (1984). *Powerplant Technology*, McGraw-Hill.[General and well written text on all aspects of power generation including evolving technologies.]

Knief R.A. (1992). *Nuclear Engineering, Theory and Technology and Nuclear Power*, Hemisphere Publishing.[Comprehensive book on nuclear energy. Includes the configuration of different reactor types.]

Rahn F.J., Adamantiades A.G., Kenton J.E. & Braun C. (1991). *A Guide to Nuclear Power Technology*, John Wiley & Sons.[Comprehensive book on nuclear energy. Includes different reactors types as well as fuel requirements and processing.]

Singer J.G. (1991). *Combustion Fossil Power*, Combustion Engineering, Asea Brown Boveri.[Good book on fossil fuel fired boilers including fossil fuel characteristics.]

Stultz S.C. & Kitto J. B. (1992). *Steam, Its Generation and Use*, Babcock & Wilcox.[Specialized book on boiler plant technology. Includes sections on environmental aspects as well as nuclear energy. Leading text on steam generation.]

Woodruff E.B., Lammers H.B. & Lammers T.F. (1998). *Steam Plant Operation*, McGraw-Hill.[]

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.