COAL COMBUSTION AND COMBUSTION PRODUCTS

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Summary

This article aims to present the basic principles and technologies of coal combustion and discusses the impact of coal combustion products on the environment. Man has used coal, as one of the main energy sources, for more than three thousand years. It has greatly improved human living standards, and promoted the economic prosperity of the world. Especially in the last few hundred years, coal combustion technology has been further developed to accommodate various applications and to compete with natural gas and oil. So far, some of the coal combustion technologies have even attained combustion efficiencies of over 99 percent. In the meantime, the pollution problems

resulting from coal combustion are also being solved to a certain extent, with the rapid development of clean coal technology (e.g. circulating fluidized bed combustion, pressurized fluidized bed combustion and various flue gas desulfurization technology), some of which can control the pollutant emission effectively. However, development of more advanced clean coal technology is still a realistic goal.

1. Introduction

Coal is a fossil fuel, formed largely by the partial decomposition and 'coalification' of ancient plants under high pressure of overburden at elevated temperature during the course of hundreds of millions of years. Coal is inhomogeneous and mainly composed of combustible organic matter, mineral matter, and moisture. Since the coal-forming time could be quite different for different coals, a variety of coal types exist, corresponding to various stages of coalification. For the purpose of combustion, coal is classified as lignite, sub-bituminous, bituminous, and anthracite.
Lignite, the youngest coal, is brown to black in color, with a high volatile matter content and a high moisture content. It also has a high ash-content and a low heating-value in comparison with other types of coal. Sub-bituminous coal is black, similar to bituminous in color. It has a lower moisture content than lignite, but is still of relatively low heating value. Bituminous coal has a volatile matter-content from high to medium and low moisture-content. It is easy to ignite and burn-out, and its heating value is high. Anthracite, with the longest coalification age, is the oldest of all coals. It is jet black in color, hard and brittle. Its moisture content is low and carbon content is high. Anthracite has a high heating value but is difficult to ignite and burn out.

Coal is an important energy source for humankind. Coal combustion has been identified in some of the earliest recorded history. According to Elliott and Yoke (1981), the Chinese used coal as early as 1000 BC, while the Greeks and Romans made use of coal before 200 BC. By 1215 AD, trade in coal had started in England. The pioneering uses of coal (e.g., coke, coal tars, gasification), have advanced steadily since the late sixteenth century. Coal combustion technology has been further developed since the late nineteenth century. The coal fixed-bed stoker system was invented in 1822; the firing of pulverized coal occurred in the brick-kiln in 1831, and fluidized-beds were invented in 1931.

Nowadays, direct coal combustion is extensively utilized for industrial and domestic purposes because of the large-scale reserves and low cost of coal. Most of the world's coal is burned in boilers of power plants, industrial boilers, and heat kilns (to produce cement, bricks, etc.). Space heating and domestic consumption also consume a large amount of coal every year.

Since the early 1940s coal combustion has encountered great challenges, one of which has come from natural gas and fuel oil. As natural gas and fuel oil can be burned more conveniently and efficiently, it is necessary to develop advanced coal-burning technology for improving the automatic features and flexibility, and providing higher heat release and higher thermal efficiencies. Another demand is that of environmental protection. Coal is known to be a "dirty," fuel. Coal combustion may emit various pollutants, such as dust, sulfur dioxide, nitrogen oxide, carbon dioxide, heavy metals, etc. These pollutants may seriously worsen the living environment of human beings and directly affect people’s health. Therefore, clean coal combustion technology has to be developed to meet the requirements of the regulations for environmental protection, by reducing emission of pollutants and improving people’s living quality.

2. Basic Processes of Coal Combustion

Coal is an organic fuel. When heated, the organic matter of coal is pyrolyzed, and then evolves as volatile. The remaining solid is a mixture of carbon and mineral matter, which is referred to as “char.” The combustion of coal is primarily the combustion of carbon as well as the volatile matter. It is known that the principal combustion process of coal involves three basic stages: (1) The release of the volatile matter resulting from the heating of coal, (2) The burning of the released volatile matter and (3) The burning of the remaining char. Depending upon specific combustion conditions, the burning process of volatile matter and coal char may take place simultaneously, sequentially, or with some overlapping.

2.1 Coal Devolatilization and Volatile Combustion

The release of the volatile matter resulting from the heating of coal belongs to the devolatilization stage. During this stage, moisture present in the coal will evolve as the temperature of coal rises. As the temperature further increases, gases and heavy tarry substances are emitted. The content of these matters can vary from a few percent up to 70–80 percent of the total coal weight, with coal types and heating conditions, etc. Depending on the size, type, and temperature condition of coal, devolatilization takes a few milliseconds or several minutes to complete. A variety of products including tar, hydrocarbon gases, etc. are produced during coal devolatilization. These products are combustible. They react with oxygen in the vicinity of coal particles and form bright diffusion flames. The reactions taking place in the devolatilization and volatile combustion process are so complex that detailed discussion is beyond the scope of this article.

2.2 Coal-Char Combustion

The residual char particles, enriched in carbon, containing most of the mineral matter of the original coal and some surplus nitrogen as well as sulfur, are often spherical (especially for small particles). They are usually very porous and have many cracks, which result from the escape of gaseous products and heat stress. The characteristics of the char depend on the type and size of the original coal as well as on the heating conditions.

The residual char particle can be burned out under an oxidizing condition at sufficiently high temperature. The reaction between the char and oxygen is a gas-solid heterogeneous reaction. The gaseous oxygen diffuses to, and into, the char particle, being absorbed, and reacting on the pore surface of the particle. This heterogeneous process is often much slower than the devolatilization process, requiring seconds to several minutes or more. The rate of this process varies with coal types, temperature, pressure, char characteristics, (the size, surface area, etc.), and oxidizer concentration.

Other reactants, including steam, CO_2 and H_2, can also react with char, but the rates with these reactants are considerably slower than with oxygen.

The primary reactions of char combustion and the heat of the reactions are listed in Table 1.

Reactions	Heat of Reaction (kJ)
$C + O_2 = CO_2$	-392.9
$C + 1/2\ O_2 = CO$	-111.2
$CO + 1/2\ O_2 = CO_2$	-281.7
$C + CO_2 = 2CO$	+170.5

Table 1. Primary Reactions Taking Place During Coal Combustion

The lowest temperature at which coal can be ignited is referred to as the ignition temperature. The ignition temperature for a certain coal is variable under different conditions because of the complexity of the ignition process. For the convenience of comparison, the ignition temperature is specified in terms of specific conditions. Table 2 shows the ignition temperatures of different types of coal. It is obvious that the ignition temperature of coal refers to the temperature that triggers off the release of the volatile. In general, coals containing a higher volatile content have a lower initial volatile—releasing—temperature and are easier to be ignited.

Coal Type	Ignition Temperature/°	Volatile Initial Release Temperature/°
lignite	250–450	130–170
bituminous	400–500	200–300
anthracite	700–800	380–400

Table 2 Coal Ignition Temperature

3. Coal Combustion Technology and Facilities

The basic coal combustion technology can be classified on the basis of the particle size of burning coal and coal-feeding methods, which mainly include the coal fixed-bed combustion, coal suspending combustion, and coal fluidized-bed combustion.

3.1 Coal Fixed-bed Combustion

In early times, the coal fixed-bed combustion was the only known way of burning coal. The coal bed is supported on a grate, which may be fixed or movable, and the air needed for combustion, generally passes upward through the coal bed either by the chimney draught or by a fan. However, as an exception, in some hand-fired domestic appliances the combustion air is drawn downward through the coal bed for eliminating smoke. In general, coal may be fed to the bed in the three modes: overfeed, underfeed, and cross-feed.

3.1.1 Fixed Grate

An overfeed fixed bed on a fixed grate is the most simple way of coal combustion. Fresh coal is spread onto the surface of the burning coal bed manually or by a spreader. From the grate to the bed surface the bed is divided into several zones based on combustion reactions that take place. The combustion zones are shown in Figure 1. The fresh coal on the bed surface is heated rapidly by the hot combustion gas and the radiation from the high-temperature flames and furnace walls. It is advantageous to the ignition of the coal. The burning coal then descends in turn through the reducing region and the oxidization region, becoming ash on the grate, and is finally removed.

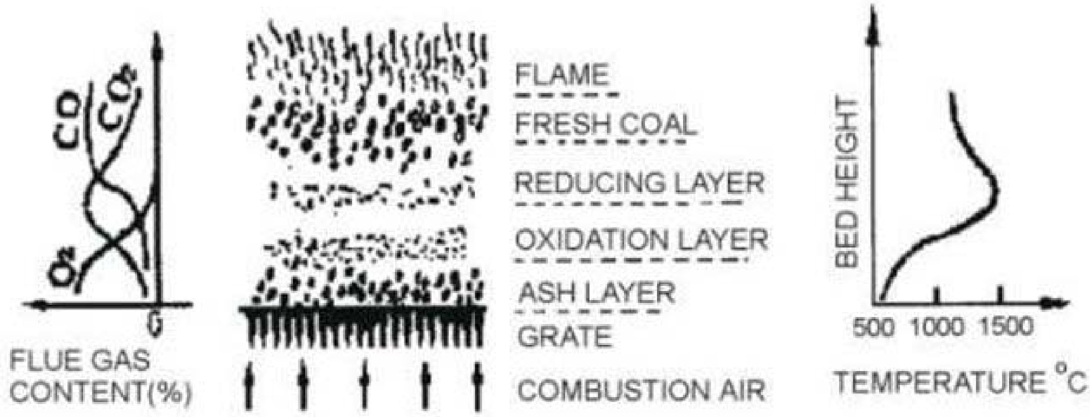

Figure 1. Coal Fixed Bed Combustion

The combustion air is generally supplied from the grate, flowing upwards through the fuel-bed. The air is first heated by the coal ash, and then reacts with the high temperature coal char. The combustion reaction produces CO_2 and releases a large amount of heat, resulting in the rapid rise in the bed temperature. The oxygen will be finally used up with the progressing of the oxidizing reaction. The bed layer where the oxidizing reaction takes place is referred to as the oxidizing layer, which is the highest temperature zone in the bed. If the thickness of the coal-bed is greater than that of the oxidizing layer, a reducing layer will appear on top of the oxidizing layer, where CO_2 can react with carbon at high temperature, producing CO. Therefore; different combustion reactions may take place with different combustion products, depending on the bed thickness. For this reason, two different combustion methods were designed accordingly, i.e., the shallow-bed combustion and the thick-bed combustion.

In the shallow-bed combustion, the coal bed is about 100–150mm thick for bituminous, so there is no occurrence of reducing reaction. All air needed in combustion is supplied from the bottom of the bed. In the thick-bed method, the bed thickness is about 200–400 mm for bituminous, its combustion air is provided separately. The primary air is provided from the bottom of the bed, and the secondary air is provided over the bed to burn out the combustible gas produced by the bed. The ratio of the primary air to the secondary air depends on the coal volatile content and the amount of combustible gases.

Coal can be fed not only onto the bed, but also under the bed. This is the underfeed mode. In this mode, burning coal moves in co-current flow with the combustion air. The released volatile matter, moisture, and combustion air pass up through the bed so that less smoke is emitted in part-load operations. The underfeed-stoker designed to burn bituminous and anthracite for firing boilers and warm-air furnaces is automatic and often used for residential purposes. In the stoker, coal is fed from a bin or hopper by a feed screw into the bottom of a conical retort, through the inner and outer walls from which air from a motor-driven fan is supplied for combustion. According to A. Ralph, the underfeed-stoker is not used for the firing of huge boilers, because of the impossibility of building them large enough to burn coal at the required rate. In the intermediate sizes, the stoker tends to lose its favorable position due to its sensitivity to the caking and ash fusion characteristics of coal. Thus, the successful operation of this type of stoker lies in the careful selection of the coal used on it and a conservative rating to avoid a high rate of burning as well as an excellent mechanical design.

3.1.2 Moving Grate

The chain-grate stoker is a typical automatic moving stoker. Its moving grate carries the coal bed on it passing through the high temperature areas of furnaces. The coal overfeed mode combines with the moving grate, forming a spreader stoker (Figure 2), in which coal is spread onto a moving bed by a spreader. The moving grate moves from the rear wall to the front wall or vice versa depending on the type of the spreader. As in the case of fixed grate, most fresh coal falls onto the burning coal bed, getting better ignition condition. Spreader stokers are of adaptability to a wide range of types and sizes of coals, ability to respond quickly to the change of load, and relative freedom from slag and deposit problems in the furnace or on the heating surface. The disadvantages of this type of stoker are the tendency to excessive smoke emission at part loads, high carry-over of fly ash and cinder at high loads, which can be minimized by an over-jet, for increasing the turbulence in the furnace to reduce smoke and by the use of dust collectors to reduce the emission of fly ash from the stack.

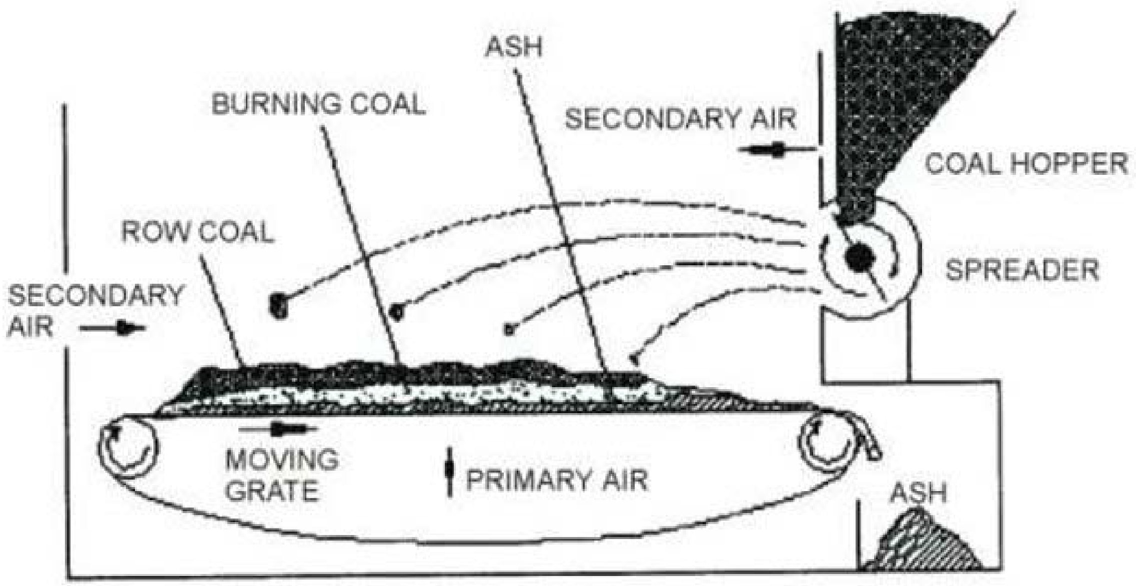

Figure 2. Spreader Stoker

On a considerable number of these moving grates coal is fed not by spreaders, but from a hopper under an adjustable guillotine-type gate. The gate controls the thickness of the coal bed. This is referred to as the cross feed mode. In the moving grate, the coal bed carried by the grate moves from the front wall to the rear wall in furnace, and the coal drying, devolatilization, volatile combustion, char combustion and ash removing take place in the bed with the bed moving. The combustion regions in the moving bed are shown in Fig. 3. The coal on the surface of the bed is ignited by the radiation of the furnace, and the combustion is transmitted downwards. In general, a front arch and a long rear arch are used to insure stable ignition and fine mixing of fuel and oxygen. This type of equipment remains suitable for the plants which can be assured of a longtime supply of a suitable coal, and which do not require rapid changes of load. The problems of smoke at low loads and that of carry-over of fly ash are much less acute than they are with spreader feeding of coal.

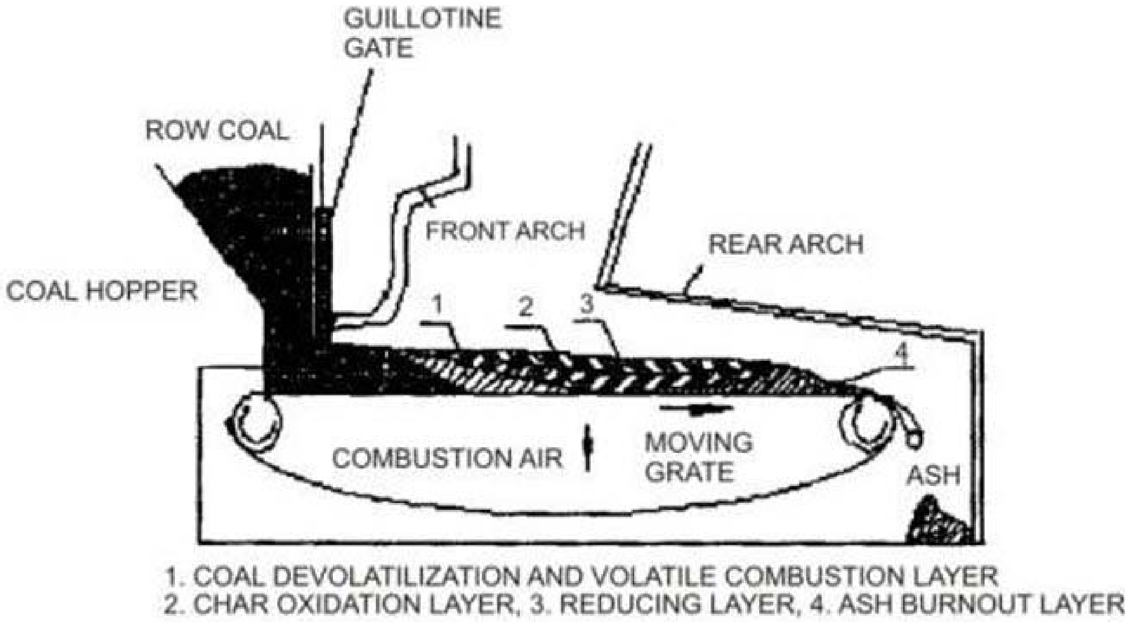

Figure 3. Guillotine Gate Stoker

Besides the chain-grate stoker, there are also some other types of moving grate-stokers, such as, vibrating grate-stoker, reciprocating grate-stoker, etc.

The coal fixed-bed combustion is particularly sensitive to coal properties, which is partly the reason why other methods of burning coal, less sensitive to fuel characteristics, have been developed. The fuel bed, however, is still an important method of burning coal especially in industrial boilers.

3.2 Coal Particle Suspension Combustion

Pulverized coal combustion taking place in a suspension phase was first used as a means of firing cement kilns. In the 1920s, it began to be applied to power generation. From 1930 onwards, nearly all coal-fired power plants and large industrial boilers have been fired by pulverized fuel rather than by stoker system because of the two principal advantages: (1) The pulverized fuel combustion allows a wider range of coals than a stoker. (2) In practice, the stoker is limited to a maximum output of about 30 MW (thermal), whereas that of the pulverized fuel system can be two orders of magnitude higher.

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Bibliography

Elliot M. A. and Yohe G. R. (1981). Coal Industry; Research and Prospects, *Chemistry of Coal Utilization*, (Secondary Supplementary Volume) (ed. Elliot M. A.). New York: John Wiley & Sons (translated into Chinese). [This presents the history of coal utilization.]

Feng Junkai (1992). *The Principle and Calculation of Boiler*, (in Chinese). Beijing, China: Science Press. [This presents the pulverized coal combustion technology.]

Merrick D. (1984) *Coal Combustion and Conversion Technology*. London, UK: Macmillan Publishers LTD. [This presents the developing history of some combustion technologies and the impacts of coal combustion on the environment.]

Ralph A. S., and Bertrand A. L. , (1963). *Combustion Process, Chemistry of Coal Utilization*, (Supplementary Volume) (ed. Lowry H. H.), 773–809. New York: John Wiley & Sons. [This presents various coal combustion technologies.]

Yerushami (1979). *Powder Technology*, 24, 187–205 [This presents the concept of the fast fluidized bed.]

Zhang Mingyao (1998). *Combined Cycle Power Generation in Coal Fired Pressurized Fluidized Bed Combustion*, (in Chinese), Nanjing, China: Southeast University Press. [This presents the technology of coal pressurized fluidized bed combustion.]

Zheng Chuguang (1996). *Clean Coal Technology*, (in Chinese), Wuhan, China: CCUST Press. [This presents the influences of coal combustion on the environment and a variety of clean coal technologies.]

Biographical Sketch

Xianglin Shen was born on 11 December 1946 in Changsha, China. He graduated from the Department of Engineering Mechanics and Mathematics at Tsinghua University in 1970 and from the Department of Engineering Mechanics at Tsinghua University with an MS degree in 1982. From 1985 to 1986 he visited the Department of Fuel and Energy at Leeds University in the UK as visiting scholar; he now is a professor at the Thermoenergy Engineering Research Institute of Southeast University; working in the field of combustion and heat transfer.