Experimental Research on Lignite Fluidized Bed Combustion

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Burning Characteristics of Lignite Fuel

Lignite fuel is highly volatile and has a low ignition temperature, and is consequently easy to burn. In practice, however, when burning low grade lignite fuel in stokers or pulverized coal furnaces, some difficulties may occur due to high moisture content and low ash fusing point. In general, the moisture content of lignite fuel is above 30% and the sum of the moisture content and ash content is higher than 50%. Its heating value is about 2,000-2,500 kcal/kg and the ash-deformation temperature is higher than 1,100 C.

Burning lignite fuel in fluidized beds has many obvious advantages:

(1) High heat accumulation of the fuel bed. This provides a sufficient heat source to dry and preheat the lignite and helps high moisture lignite to ignite in time, resulting in a stable combustion condition.

As an example, a factory installed a fluidized-bed boiler with steam capacity of 10 t/hr. During the first winter of boiler operation, the air required for combustion was delivered into the furnace by drawing in outside air, which was approximately -30^{o}C. In order to prevent the frozen coal from partially melting into a large lump in the coal bunker, the bunkers were installed outdoors. During the winter, frozen coal, together with ice particles, was delivered directly into the furnace via belts. The walls became covered with ice frost like the outside of a refrigerator. Despite such difficult conditions, the combustion process in the furnace was normal and the combustion was stable as long as the temperature of the fuel bed was above 600^{o}C.

Another factory trial successfully fired three lignites with high moisture content. The measured characteristics of the fuels are given in Table 1.

Table 1. Typical Analysis of Lignites Fired in Trials

Type	I	II	III
Moisture content as fired (%)	27.21	46.01	56.82
Ash content as fired (%)	26.2	23.37	16.13
Volatile matter as fired (%)	24.1	19.83	14.91
Fixed carbon (%)	22.4	10.43	12.14
Lower heating value (kcal/kg)	2551	1470	1230

(2) The normal temperature range for fluidized beds is 850-950^{o}C. This is much lower than the lignite ash-deformation point, and the temperature field is even, with no possibility of slagging.

(3) Ash erosion is not usually high. This is because the fly-ash particles flying out of the fluidized bed are not subjected to temperatures above their fusion point. Thus the erosion potential of the fly-ash is probably lower than that leaving conventional furnaces.

(4) Since the operating temperature for a lignite fluidized bed boiler may be relatively low, the load range can be much wider. As the temperature of the fluidized bed varies from 600°C to 900°C, the load range for a single fluidized bed can be easily varied from 50% to 100%. Using a separated fluidized bed operation, the minimum load can be further reduced, resulting in a much lower value than the low load stable operating range of a pulverized-coal furnace.

(5) The erosion of the submerged tubes in lignite fluidized-bed boilers is not serious due to the relatively loose character of lignite ash. In most fluidized bed boilers operated for many years, the erosion of the submerged tubes has not been a problem, although there may be some exceptions.

(6) The specific gravity of lignite ash is relatively low. For this reason the air pressure of the plenum may have a lower value than when using high low-grade coals. The plenum air is usually supplied at a pressure of 500 mm water.

(7) It's easier to ignite a lignite fluidized-bed boiler. We have ignited run of the mine (ROM) lignite fuel successfully many times when the temperature of the fuel bed was about 400°C.

(8) When lignite fuel is thrown into the high-temperature fuel beds, the fuel is suddenly heated and crumbles easily by itself, allowing coal particles as-fired to be very coarse. Operating experiments in Heilang Jiang and Yunnan provinces also proved that the maximum diameter of particles may be raised to 20-25 mm, slightly reducing power consumption for crushing and making it easier to sieve.

Fluidized Bed Boilers with a Rear-Installed Cyclone Furnace

At present, one of the main problems for existing fluidized-bed boilers is low combustion efficiency. The main reason for lower combustion efficiency and higher unburned combustible solids losses is the high carbon content in the fly-ash. The small particles may be blown off the high-temperature fluidized bed, resulting in an unburned carbon loss in the fly-ash.

Another important characteristic of lignite fuel is its high volatile content. The heat released from the volatile matter is about one-half of the coal heating value. In addition, lignite particles may break up during the burning process, forming many small coal particles. Therefore, one of the important characteristics for firing lignite in fluidized-bed boilers is possibly that more volatile matter and small coal particles are burning in the suspension chamber (freeboard).

The optimization of the combustion process in the suspension chamber to obtain better performance is an important factor in determining the combustion efficiency of lignite fluidized-bed boilers. One effective measure for reducing the fly-ash carbon content is using a fly-ash recycle for refiring in the fluidized beds or applying fly-ash refiring beds. However, this will complicate the system and its construction for small-capacity, fluidized-bed boilers. Practically, providing high temperature within the suspension chamber (freeboard) may exert an afterburning action for various fuels. For this reason, we suggest limiting the heat exchange surface as much as possible or not placing them in the freeboard. This will raise the gas temperature in the upper part of the furnace as high as possible. The ignition temperature for lignite fuel is relatively low. Thus, the increased temperature will exert sufficient afterburning action on the suspension chamber (freeboard). Providing a sufficiently high temperature in the suspension chamber is an important condition in achieving better combustion.

Another important condition is how to organize the aerodynamic field of the suspension chamber. In 1972, we designed a fluidized-bed boiler with a rear-installed cyclone furnace, shown in Fig. 1. Good results were obtained. Afterwards, we designed several dozen fluidized-bed boilers for lignite, the majority using rear-installed cyclone furnaces. The design of this cyclone furnace is based on the characteristics of a horizontal cyclone furnace. The aerodynamic field for a cyclone furnace is very complex. Its complexity assists in sufficient mixing of combustibles and oxygen in the gas flow. This is due to the increase in the relative velocity between the gas flow and the fly-ash and thus an increase in the diffusion velocity of oxygen to the fly-ash. These effects result in an increased burning velocity for coal particles. Furthermore, the residence time for fly-ash in the cyclone furnace is obviously prolonged. This is especially true for ash particles having a medium diameter. The carbon content for this part of the fly-ash, in general, gives the highest value. In addition, a cyclone furnace collects dust within the furnace. It may reduce erosion on the convection heating surfaces and reduce the load on the dust-collecting plants.

Note that although the dimension of the convex collar for cyclone furnace outlets is not large, its effect on the aerodynamic field is quite important. The scheme for an aerodynamic field in a cyclone furnace with and without a collar is shown in Fig. 2. It was also shown by cold modeling that the separation efficiency for cyclone furnaces with collars is much higher than for those without collars.

Aerodynamic Fields for Horizontal Cyclone Furnaces

In order to recognize the mechanism for the separating and afterburning action in the cyclone furnace and to investigate for a more reasonable construction, we have performed cold modeling for the horizontal cyclone furnace and tested the aerodynamic field in this type of furnace.

The maximum particle size leaving the cyclone furnace is expressed by the following relationship:

$$d_{max}^{1.6} = 13.88 \frac{W_r^{1.4} R''^2 r_g v^{0.6}}{W_t'^2 R_o r}$$

where

w_t' = velocity in inlet of cyclone furnace (m/sec)

w_r = radial velocity (m/sec)

R" = radius of the exit (m)

r_g = specific gravity of gas (kg/m^3)

v = coefficient of kinematic viscosity of gas, (m^2/sec)

R_o = radius of the lower boundary of inlet (m)

r = specific gravity of particle (Kg/m^3)

From the above, we can approximate the diameter of a particle in cyclonic motion at the exit boundary of a cyclone furnace. Some large particles of diameter above d_{max} near the wall will be moved towards the wall and then pass down the wall. The other large particles will continue their circumferential movements in various values of the radius until the wall is reached or their diameter is reduced to less than d_{max}. The particles of diameter less than d_{max} may be moving with the air flow out of the cylone furnace, but the small particles near the wall may also be separated from the gas flow. Therefore, d_{max} may be considered as the limit of the maximum particle diameter leaving the cyclone furnace. Because particles are not spherical d_{max} obtained from the above equation should be divided by a coefficient ϕ, called the particle shape coefficient, as a correction. Only after this may the value be considered as the actual size.

For the cold modeling experiment, the above expression for d_{max} gives a value of about 94 μm. Experimental measurements show a maximum particle diameter of 142 μm. If this value is corrected for particle sphericity (ϕ = .66) a value of 93.72 μm is found which is very close to d_{max} from the above expression.

For conditions typical of an operating cyclone furnace, the maximum particle diameter leaving the furnace from the above equation is about 320 μm. For some factory furnaces the experimental value is about 500 μm. This is equivalent to a spherical diameter of 330 μm (ϕ = 0.66) which is close to 320 μm.

Summarizing, the principal causes of afterburning action in cyclone furnaces are:

(1) Large particles of fly-ash are thrown by the high centrifugal force toward the wall. These particles then pass rapidly down the inner walls of the cyclone furnace. Although these particles are separated rapidly, due to the high relative velocity they can be burned up within a short time. Since large particles have partially burned within the fluidized bed, the carbon content of these particles would not be as high.

(2) Based on the above principle, medium particles will move around the circumference with different radii until they have burned to a size less than d_{max} and then leave the cyclone furnace. So the residence time of the medium particles within the cyclone furnace is greatly increased resulting in greater char combustion.

In addition, the action of the collar mounted at the throat forces the air flow at and around the throat to change its direction repeatedly (rotating 180^{o}). This forms an intense turbulence and recirculating movement of the particles (see Fig. 1). The latter recirculates in the cyclone axially and at the same time rotates around the cyclone axis, also increasing the residence time of the particles within the cyclone furnace. Cold modeling has confirmed that some medium-size particles are rotating continually within the cyclone furnace until the fan is shut down.

Based upon theoretical analysis and some experimental data from the domestic research unit, it has been found that particles of medium size have the highest carbon content, and that this type of particles is in the majority. For example, experimental data obtained in the fluidized bed boiler burning local coal at Che-Jiang University has shown that the heat loss for particles ranging from 0.13 to 0.375 mm is over 70% of the total heat loss of fly-ash. The majority of these particles may be just the rotating particles within the cyclone furnace. Therefore, the cyclonic action of the cyclone furnace may be very effective in reducing the carbon-content of fly-ash.

Experimental Research on the Cyclone Furnace Under Thermal State

The carbon content of the ash samples taken from various parts of the boiler flue gas were determined and are summarized in the following table.

Table 2. Ash Size Distribution and Carbon Content in Various Parts of Flue Gas

Granularity mm	Ash separated in cyclone furnace		Ash in precipitating chamber		Ash in dust collector	
	proportion by weight %	carbon content %	proportion by weight %	carbon content %	proportion by weight %	carbon content %
	1.87	1.18				
1-2	5.83	1.76				
0.5-1	36.4	1.08	4.64			
0.28-0.5	25.8	1.3	15.4	18.48	1.25	35.86
0.09-0.28	24.8	0.93	59.3	9.91	33	18.89
0.09	5.2	1.05	20.66	4.12	65.18	8.53

In a typical boiler, a two-stage dust collector is used. About 60% of the total fly-ash is collected in the precipitating chamber. The remaining ash is then removed by the dust collector. Based on the above data, we can draw the following conclusions:

(1) The ash particle size in precipitating chambers and dust collectors is scarcely larger than 0.5 mm. It is reasonable to assume that particles greater than 0.5mm will not leave the cyclone furnace. This is in accordance with the results from the cold modeling experiment.

(2) Ash particles with diameters of 0.25 - 0.5mm in the fly-ash have the highest carbon content. However, most of this fly-ash size fraction has been separated from the gas flow in the cyclone furnace and its proportion by weight in the fly-ash is not high. When a boiler operates at normal capacity, the average carbon content for fly-ash is 11.85%. This value may be considered relatively low.

(3) The ash particles separating from the gas flow in the cyclone furnace have a significantly lower carbon content than that observed in the ash overflow. In general, the medium particles of fly-ash have higher carbon content, while the carbon content of ash particles ranging from 0.28 to 0.5 mm separated in the cyclone furnace is only 1.3%. This shows that the degree of burn-up for ash separated within cyclone furnaces is rather high.

(4) Since the separation efficiency for cyclone furnaces is rather high (about 50%), the ash particles burn more completely with the result that the boiler combustion efficiency increases. During operation periods at rated capacity, the unburned combustible solid losses are 3.8% and the unburned gas losses are 0.67% while the combustion efficiency can be as high as 95.47%.

When the temperature of fluidized bed section is 900^{o}C at rated capacity, the gas temperature measured at the cyclone furnace exit is 920^{o}C, that is the temperature difference between the latter and the former is 20^{o}C. This shows that there are some combustibles still burning in the suspension chamber and in the cyclone furnace. According to calculations, the total fraction burned in the suspension chamber and cyclone furnace is 0.3.

In experimental tests with another lignite fluidized bed boiler of the same type, the fraction burned in the cyclone furnace itself was found to be 0.172.

The results of the data for the above two experiments are basically the same. It can be seen from the above summary that the total fraction of combustion in suspension chambers and cyclone furnaces in fluidized bed boilers is relatively high. Thus the organization of the combustion process is highly significant in obtaining better boiler combustion efficiency.

The separation efficiency for cyclone furnaces, η_f, is the ratio of ash separated in the cyclone furnace, ΔG, to ash leaving the cyclone furnace, G", plus the ash separated, ΔG, that is

$$\eta_f = \frac{\Delta G}{G'' + \Delta G} \times 100\%$$

The unburned carbon content of the ash is included in the above expression. The results of the tests are summarized in Table 3.

Table 3. Separation Efficiency for a Cyclone Furnace as a Function of Ash Particle Size

Granularity mm	>1	0.5-1	0.28-0.5	0.09-0.28	<0.09
Separating efficiency η_f %	100	93.7	75.3	39.3	13.7

The average separating efficiency is about 50%.

Conclusions

(1) Lignite of high moisture content is not an easy to burn fuel. At present, for typical industrial boilers in our country, there has not been a furnace-type which has the ability to burn high moisture content lignite fuels economically with the exception of fluidized bed furnaces. Burning lignite fuel in utility boilers presents many significant difficulties also. Existing experiments show that fluidized bed boilers can successfully burn low-grade lignite fuel having moisture content up to 56.82% or ash content up to 46.8%.

(2) Rear-installed cyclone furnaces have an obvious effect of increasing oombustion efficiency for lignite fluidized bed boilers. The combustion efficiency for boilers of such types may be as high as 95%. Its main function consists of prolonging the residence time of the medium particles which contain higher carbon content within the furnace. This creates better conditions for carbon combustion. The total fraction of combustion in the suspension chamber and cyclone furnace is about 0.3.

(3) The separation efficiency for cyclone furnaces is about 50%. The majority of particles having diameters larger than 0.5mm may be separated from the gas flow in the furnace. The approximate maximum particle diameter leaving the cyclone furnaces may be obtained from the following formula.

$$d_{max}^{1.6} = 13.88 \frac{W_r^{1.4} \; R''^{2} \; 0.6}{W_t'^{2} \; R_o \; r}$$

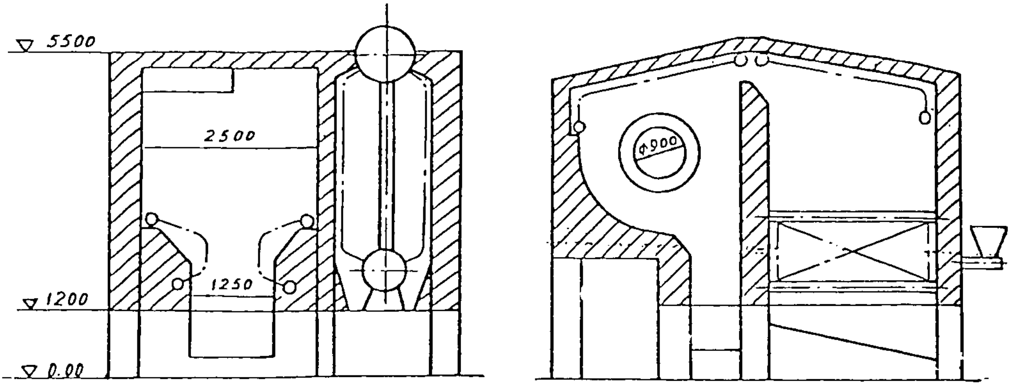

Figure 1. Fluidized-Bed Boiler with Rear-Installed Cyclone Furnace

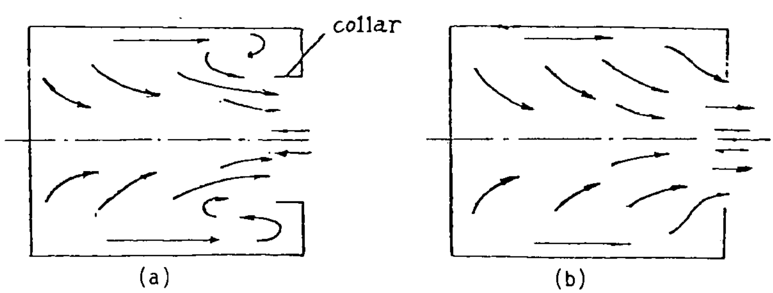

Figure 2. Effect of Collars on the Aerodynamic Field in a Cyclone Furnace: (a) With Collar. (b) Without Collar.