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SPOUTED BED COMBUSTION AND COMBUSTION EFFICIENCY OF THAI LIGNITE CHAR

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ABSTRACT

The combustion of Thai lignite char has been experimentally studied in a 92 mm spouted bed combustor under a variety of major operating conditions. Performance expressed as combustion efficiency and losses are assessed and discussed. Results obtained shows that as high as 89 to 98.5% of combustion efficiency can be achieved under particle feed size ranging from 2.00-4.00 mm, with excess air varying from 107-185 %. The most influential variable affecting combustion performance appeard to be operating bed temperature.

1. INTRODUCTION

Direct combustion of coal to obtain useful heat is normally carried out in different ways: as lumps on a grate, as crushed coal in a fluid bed, and as pulverized coal in an entrained bed [1]. Among these, the fluid bed seems to be attractive from the standpoint of economic and environmental considerations. The advantages of fluid bed combustion claimed most often are essentially its applicability to multi-fuel, its ability to conveniently capture SO_x using sorbent, its emission of No_x at low levels owing to its low operating temperature, and its capability to release energy at high average volumetric rates. Fluid bed combustion systems have several configurations, of which fluidized bed and circulating fluidized bed are most common in application. The application of yet another configuration, the spouted bed, for combustions devices that would be less expensive but would still keep plant emissions within an acceptable level.

Currently, fluidized bed combustion, commercially developed in the 1960s and 1970s, has reached a stage of technological maturity, the capacity of the largest unit in operation being 160 MW. Circulating fluidized bed combustion, developed in the 1980s as a result of attempts to increase combustion performance, is a modified fluidized bed process involving smaller particles at higher velocity coupled with the recovery of entrained solids to the bottom of bed by means of cyclones. The first commercial circulating fluidized bed boiler was Ahlstrom's 20 ton/hr boiler which went on steam in 1979 in Finland [2]. However, at present, spouted bed combustion technology has not yet been fully developed and only a few publications are available in the literature.

Spouted beds were first initially coming into use in Canada in the 1950s for the purpose of wheat drying. The spouted bed technique, as described by Mathur and Epstein [3], is a variant of fluidization which permits agitation of solid materials that are too coarse and uniform in size for good fluidization. Its distinguishing feature from the fluidized bed is the air inlet to the bed. In a spouted bed, gas enters at the bottom of the bed through a small central orifice, instead of a distributor used in a fluidized bed. In a conventional fluidized bed, fluidizing air is evenly distributed across the bottom of the bed so that the momentum distribution is uniform. On the other hand, in a spouted bed the fluid enters as a central jet and induces a systematic cyclical movement of the solid particles. The solid particles are entrained upward the bed through a dilute central core called the *spout* before splashing in the region called *fountain* above the bed surface, as shown in Figure 1. The solids then fall back and move downward as a dense bed region outside the spout, the *annulus*. More informative details of spouted beds can be found in the monograph by Mathur and Epstein [3], and the more recent reviews by Epstein and Grace [4] and Bridgwater [5].

The hydrodynamic features of a spouted bed are significantly different from those of a fluidized bed. A fluidized bed can be considered as consisting of two phases - the bubble and the emulsion. A spouted bed, on the other hand, has three well defined regions - the annulus, the spout, and the fountain. The gas entering at the bottom of the bed through the central orifice flares out in the annulus as it travels upwards. Its flow through the annulus therefore increases with height above the inlet.

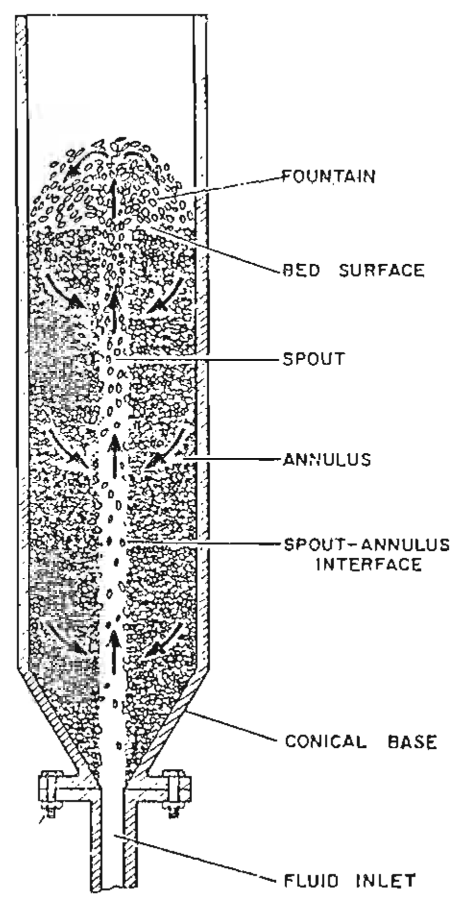

Figure 1 Schematic diagram of a spouted bed [3].

Principally, the combustion processes in a spouted bed, as in a fluidized bed, involve burning of fuel particles in a hot bed of inert solids. The inert bed material may be ash or sand or a SO_2 absorbant, e.g. limestone. Combustion take place in all the three regions of gas-solid contact, i.e. the annulus, the spout, and the fountain, of a spouted bed. In a fluidized bed, on the other hand, solid combustion in the dilute phase, i.e. the bubble, is normally negligible. Since larger particles are normally used in spouted beds compared to fluidized beds, relatively high superficial gas velocity would be employed in operation, resulting in a higher volumetric heat release rate. Once the coal is fed through the feeder at a level above the fountain, or pneumatically through the spout, it is rapidly dispersed in the bed. Under normal operating conditions, the carbon content in bed solids is relatively low, for instance, less than 1.6% by weight [6]. Consequently, its fluid mechanics is essentially governed by the size of inert bed material, not of the burning coal. The bed temperature is usually, as in typical fluidized beds, between 650 ^{o}C to 950 ^{o}C, where the lower temperature is a limit of combustion stability and the higher temperature is the ceiling for clinker free operation [6], [7]. In order to increase the carbon efficiency, some of the combustible particulates elutriated from the bed may be collected and reinjected into the bed by means of cyclones.

Considerable research efforts have been recently expended in studying the feasibility of using spouted bed as combustor. Advantages such as design simplicity and ability to burn low quality solid fuels have been reported [8]. Because of its special hydrodynamic features, e.g. spouting gas entering through a small inlet orifice, a spouted bed is expected to be able to utilize larger fuel particles (>6 mm) compared with fluidized bed; this would lead to a reduction of energy requirement for crushing coal. Also, the key advantages of fluidized bed combustors are expected to be retained in a spouted bed combustor. Thus it is expected to minimize NOx formation due to low operating temperature. A high level of SO_x retention in the bed using limestone is also expected because of its suitable operating temperature (< 900 ^{o}C), and improved limestone utilization is expected due to high attrition rate. Another recorded advantage of spouted bed is that its pressure drop requirement is low: only about two thirds of that fluidized beds [9].

Coal combustion performance in spouted bed, as in fluidized bed, is essentially dependent on several variables related to the characteristics of coal, the combustor design, and the operative combustion conditions. The influence of the major variables such as superficial gas velocity, excess air, operating bed temperature, and char feed size on combustion efficiency and losses purposely investigated in this paper.

In the literature, combustion efficiency is often defined in two different ways: either based on carbon losses or based on energy losses [10]. The losses based on carbon is simply calculated by combining the carbon losses associated with bed drain and elutriated fines with the carbon loss due to CO formation. The combustion efficiency is thus obtained by subtracting the total carbon losses from the carbon contained in the feed coal [11], [12], [13]. Combustion efficiency defined on the basis of energy losses is obtained by subtracting the energy losses owing to the unburned carbon in elutriated fines, unburned carbon in outflow (if any), and CO in flue gas from the energy content in feed coal [14]. The latter definition has been adopted in this study.

2. MATERIALS

The properties of lignite char and the inert bed material used are presented in Table 1. Lignite char instead of lignite was deliberately used to avoid fragmentation, which is likely to be occurred in case of lignite due to excessive devolatilization. The char was obtained by heating lignite from Ban-Pu mine, Thailand, in a muffle furnace under nitrogen atmosphere. Here Char of narrow size range was used with sand as the inert bed material.

Table 1 Properties of Sand and Lignite Char Tested.

Sand	
Bulk density, $g.cm^{-3}$	1.45
True density, $g.cm^{-3}$	2.63
Lignite Char (prepared from lignite supplied from Ban-Pu mine, Lampoon, Thailand)	
Proximate analysis, % on Wet Basis:	
Fixed Carbon	57.50
Volatile Matter	31.78
Ash	7.46
Moisture	3.16
total	100.00
Ultimate Analysis, % on Wet Basis	
Carbon	64.91
Hydrogen	5.23
Oxygen	17.44
Sulfur	1.26
Nitrogen	0.54
Ash	7.46
Moisture	3.16
total	100.00

3. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental combustor used is schematically shown in Figure 2. It consisted of a 9.2 cm I.D. by 1.9 m high cylindrical stainless steel column. A 10 cm long air chamber located below the column was separated from it by an orifice plate having a central hole of 10 mm diameter. The hole was covered with a stainless steel screen to prevent particles dropping into the air chamber. The lower part of the combustor column, extending up to approximately

20 cm above the orifice plate, could be removed through flanging in order to change and collect the bed inventory. It was externally wound with 3 sets of stainless steel cooling tubes, 6 mm I.D, each having three turns around the lower column. Both this lower part and the air chamber were insulated with ceramic fiber insulator, 2.5 cm thick. To maintain bed temperature at the desired level, besides controlling water flow rate, water could be passed through any or all of the water coiled tubes. Along the combustor column were K type thermocouples inserted at seven fixed positions. To permit direct observations during combustion, a quartz glass was provided at the top above the combustor column and another at the top of an inclined port connected to the column, 25 cm above the orifice plate. The top of the combustor was connected with two cyclones in series to capture the entrained bed material. The cyclone collectors were connected to a 2.5 cm diameter vertical pipe. The lower part of this pipe was provided with a threaded cap and a gate valve about 20 cm apart in order to allow collection of elutriated fines at desired time intervals.

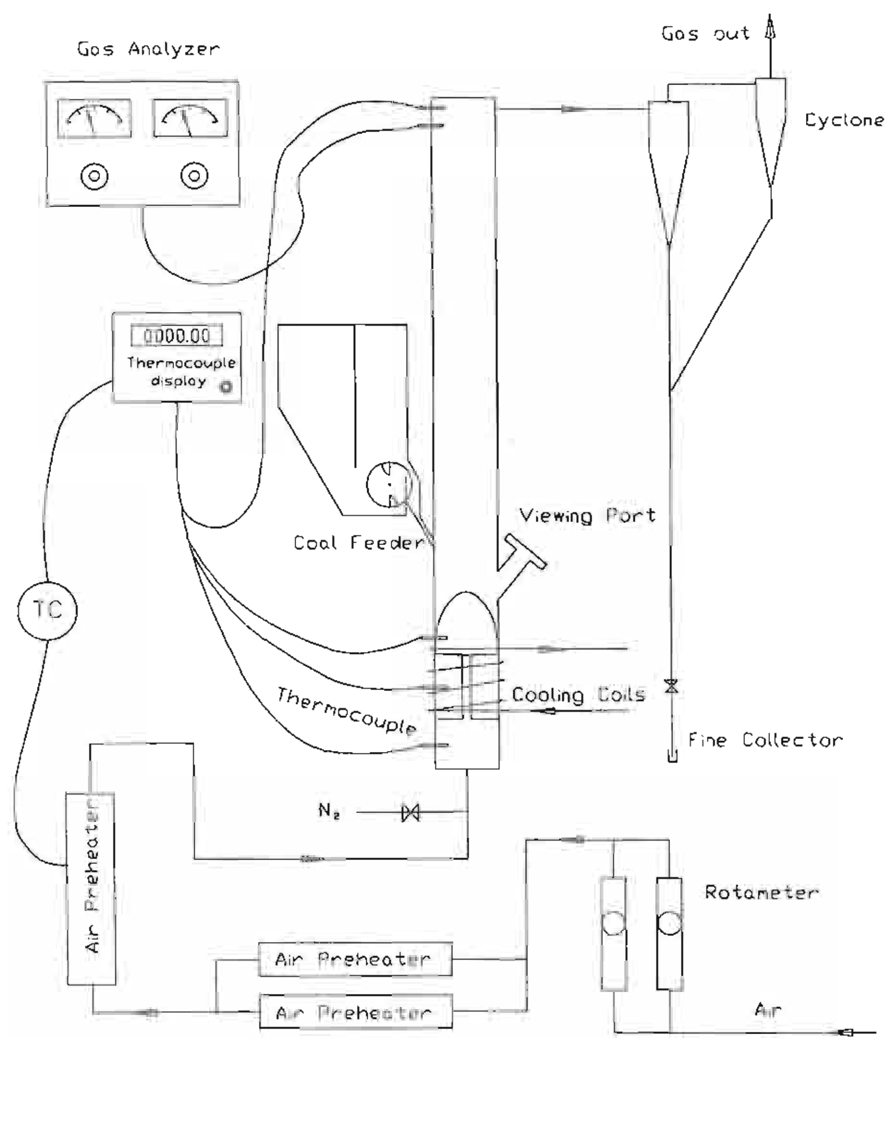

Figure 2 A schematic of a continuous spouted bed combustor used in experiment.

In order to minimize grinding effect on the feed fuel, a special feeding device similar to those of Campbell [15] and Ross [16] was designed as shown schematically in Figure 3. The feeder was essentially a 10 cm I.D. rotating drum with pockets drilled into its circular surface. Each pocket was about 1.5 cm wide by 1.5 cm deep. The drum, working like a bucket elevator, scooped up particles from a reservoir and then dropped them into a feed line running directly into the combustor freeboard, 30 cm above the orifice plate. Char feed rate could be controlled directly by varying the speed of motor driving the drum.

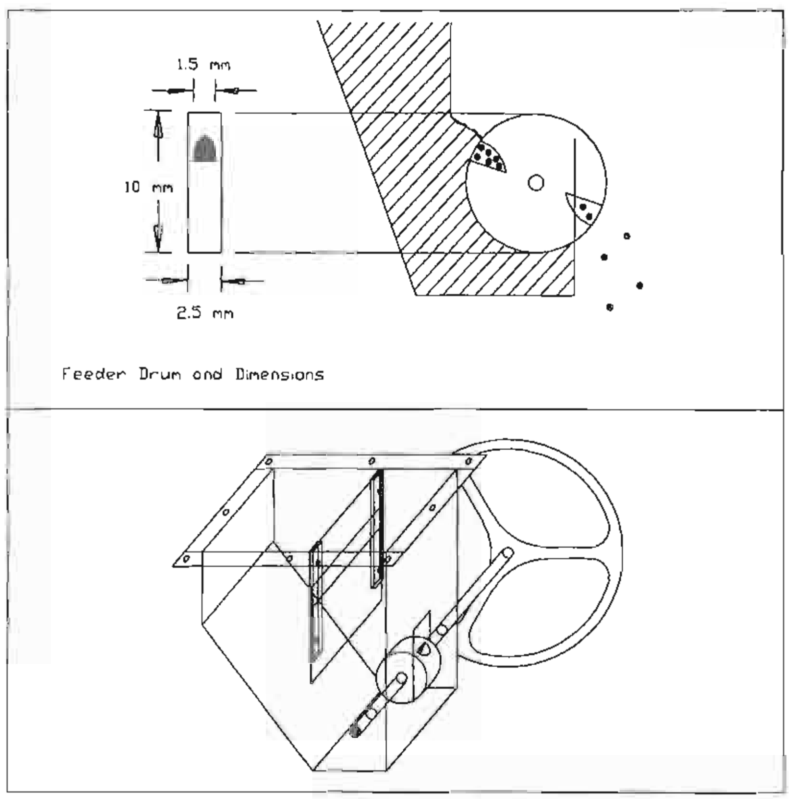

Figure 3 Details of coal feeder.

Air, the flow rate of which was directly measured with two parallel rotameters, was electrically preheated before entering the combustor. Two sets of preheaters arranged in series were used for preheating the air. In addition to the spouting air a nitrogen gas cylinder was also connected to spouting gas inlet in order to allow abrupt cessation of combustion at any time by changing spouting gas from air to nitrogen. Two gas analyzers were used for measuring CO, CO_2 and O_2. Measurement of CO and CO_2 was made by means of an infrared analyzer (model ZFJ2, FUJI). Oxygen concentration was registered continuously by a Paramagnetic Oxygen Analyzer (type ZAJ, FUJI), connected in series with the CO/CO_2 analyzer. The off-gas was sampled continuously from the top of the combustor by an auxiliary air pump, passing through a cooling coil immersed in water, then a silica gel drier, and finally a dust cleaning filter at a flow rate of approximately 1 l/min before entering the analyzers. To start a run, the bed was first charged with inert sand to provide a static bed depth of 8 cm. About 2 kg of lignite char was poured into the closed hopper, and air was turned on with a flow rate sufficient to maintain spouting, as indicated by the pressure monitoring on a U-tube manometer connected to the bed just above the orifice plate. When the bed was preheated to a temperature of approximately 400 °C, the char feeder was started; combustion was then sustained by itself and the bed temperature increased rapidly. During the period of temperature rise, air flow rate had to be decreased gradually since the superficial spouting gas velocity increased with temperature. Bed temperature, measured at the center of the annulus 4 cm above the orifice plate, was maintained at a desired level by adjusting char feed rate, the amount of electrical current supplied to the preheaters, and the flow of water passing through the cooling coils. Most of the freeboard was left uninsulated in order to favour gas cooling and minimize postcombustion of elutriated carbon fines. Typical profiles of temperature along the bed and freeboard are illustrated in Figure 4.

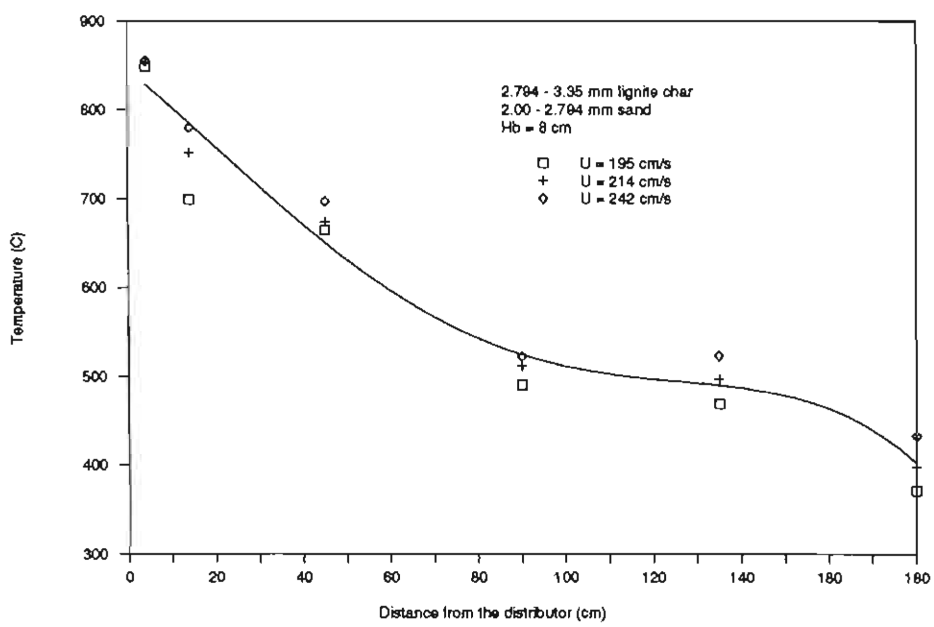

Figure 4 Axial temperature profiles of the combustor.

After steady-state was achieved, as indicated by constant bed temperature and off-gas concentrations, elutriation rate of fines was measured by collecting fines from cyclones for a specific time interval. Conditions and ranges of combustion tests are summarized in Table 2.

The experimental tests of combustion efficieneies were arranged into five series. The firrt series involved using 3.35-4.00 mm char feed size with operating bed temperature being fixed at 850 °C, while volumetric air flow rate (at room temperature) was varied from 210 l/min to 260 l/min. The second and third series were similar to the first except that the char feed size was 2.794-3.35 mm and 2.00-2.794 mm, respectively. The fourth series set char feed size at 2.794-3.35 mm and fixed bed temperature at about 707 °C, with volumetric air flow rate varying from 210 l/min to 260 l/min. In the last series, the char feed size was in the range 2.794-3.35 mm and volumetric air flow rate was 230 l/min while the bed temperature was varied from 636 to 850 °C. The variables to be measured and recorded for each experimental run were as follows:

(a) Char feed rate, determined from the speed of motor driving the feeder and its calibration curves.

(b) Mean O_2, CO, and CO_2 concentrations in the off-gas.

(c) Rate of elutriated fines collected at the cyclones and its mean earbon content.

(d) Mean operating bed temperature.

(e) Volumetric air feed rate and its corresponding superficial gas velocity at the operating bed temperature.

Table 2 Operating conditions of combustion tests in spouted bed.

Bed temperature (°C)	636, 707, 850
Spouting air velocity at bed temperature, ($cm.s^{-1}$)	170, 173, 187, 211, 195, 214, 242
Volumetric air flow rate, (l/min)	210, 230, 260
Excess air factor	1.070-2.024
Unexpanded bed depth (cm)	8.0
Char feed size, (mm)	2.00-2.7994, 2.794-3.35, 3.35-4.00
Sand diameter, (mm)	2.00-2.0794

4. RESULTS AND DISCUSSION

Efficiency of lignite char combustion observed in this study ranged from 89 to 98.5 % under excess air varying from 107 to 185 %. The superficial gas velocity was varied from 170 to 242 cm/s. For low ash char used here, the ash produced on burning was elutriated from the bed because the particularly high gas velocity created in the spout region functioned as an entrainment duct for removing tiny particles. Very little accumulated ash was found after quenching the bed with nitrogen gas when operation last as long as 3-4 hours.

(i) Effect of Superficial Gas Velocity on Combustion Efficiency

Figure 5 shows that at high operating bed temperature (850 °C) combustion efficiency profiles tend to decrease slightly with an increase in gas velocity. The effect of char feed size is relatively small as shown by the upper three lines. Increasing gas velocity increases the quantity of char attrited and elutriated, and thus tends to reduce carbon conversion efficiency. On the other hand, higher velocity also produees an increase in bed oxygen; char burning rate and post combustion of fines are hence expected to increase. Together, these two opposite effects result in a slight decrease in efficiency at 850 °C as superficial gas velocity increases.

Also, as shown in Figure 5, when bed temperature is reduced from 850 °C to 707 °C, combustion efficieney drops considerably from around 98% to about 90%, indicating that operating bed temperature has a strong influence on combustion efficiency. The drop in efficiency is due to slower reaction rate at lower bed temperature resulting in higher carbon loading, which in turn creates higher losses due to attrition. Also post combustion of attrited fines is less as bed temperature is lower.

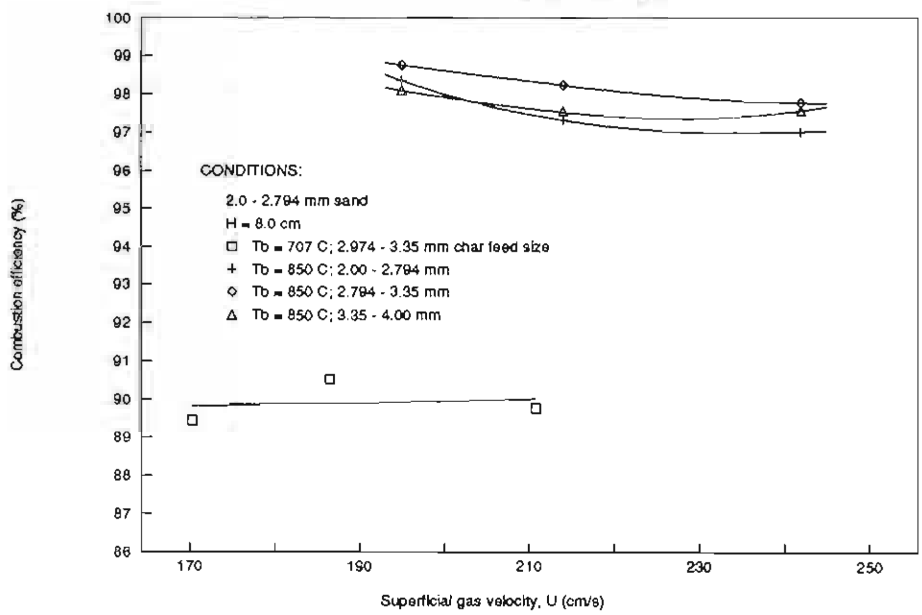

Figure 5 Influence of superficial gas velocity on combustion efficiency.

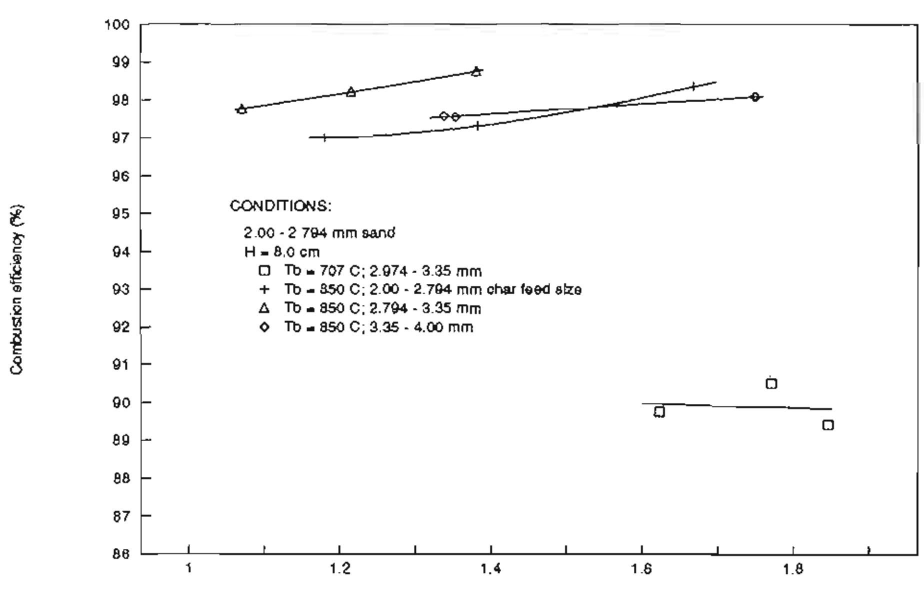

Figure 6 Influence of excess air on combustion efficiency.

(ii) Effect of Excess Air on Combustion Efficiency

Figure 6 brings out the effect of excess air on the combustion efficiency profile. At high bed temperature (850 °C), increasing the level of excess air essentially increases the average oxygen concentration throughout the combustor, thus increasing the char burning rate and hence the combustion efficiency. However, the combustion efficiency at low operating bed temperature (707 °C) is not much affected by excess air.

The influence of char size shown in the Figures 5 and 6 also indicates that at temperature 850 °C, combustion efficiency tends to be slightly higher for intermediate char feed size (2.794-3.35 mm) compared to those of smaller (2.00-3.35 mm) and coarser (3.35-4.00 mm) sizes. Similar variation of the combustion efficiency with particle feed size was also observed in fluidized bed by Bukur and Amundson [17]. The reason for this behavior may be that when too small char is used, the mass of the elutriable fines constitutes a significant fraction of the fuel fed to the bed. If the char feed size is too large, the average size of bed char particles and carbon loading are expected to be high; this again is expected to lead to higher attrition rate.

(iii) Effect of Operating Bed Temperature on Combustion Losses

The total combustion loss for each experimental run carried out here obviously comes from two sources: the heat content of elutriated fines and the heating value of CO in the flue gases.

The influence of operating bed temperature on losses due to unburned CO and elutriated carbon for a given char feed size 2.794-3.35 mm and volumetric air flow rate 230 l/min measured at 30 °C is shown in Figure 7. The elutriation loss is seen to be in significantly dependent on operating bed temperature. The slight decrease in loss due to elutriated fines at high temperature is due to higher in-bed combustion of attrited fines. The unburned CO loss in flue gas, on the other hand, is highly temperature dependent, decreasing very steeply with increasing bed temperature with the value nearly approaching zero as temperature approaches 850 °C. This indicates that at relatively low operating bed temperature there is a potential for unacceptably high emissions of carbon monoxide. Similar rapid increase in emissions was also observed in a small scale fluidized bed combustor by Sarofim and Beer [18] when the bed temperature had been reduced. The CO loss profile can be explained from the two-film theory proposed by Avedesian and Davidson [19] as well as Ross and Davidson [16]. According to this theory, the primary product of oxidation of a carbon particle is CO, which diffuses away from the burning particle, reacting as it goes out with the incoming oxygen to form CO_2. Oxygen is kept away from the particle surface by the outward flow of CO. It appears that the remaining amount of CO diffusing away unreacted is significantly dependent on temperature, as well as oxygen concentration. So at higher operating bed temperature, when amount of oxygen roughly remains the same, it is likely that CO will be fast used up before it can leave the spouted bed, which is obviously consistent with the result given here. Also at low bed temperature the total loss is mainly due to CO formation while at high temperature it is mostly due to elutriation of combustible fines. In actual applications, where crushed coal, rather than monosize char would be used, the loss due to elutriation is expected to be much higher since a sizable fraction of the feed coal would be elutriable fines.

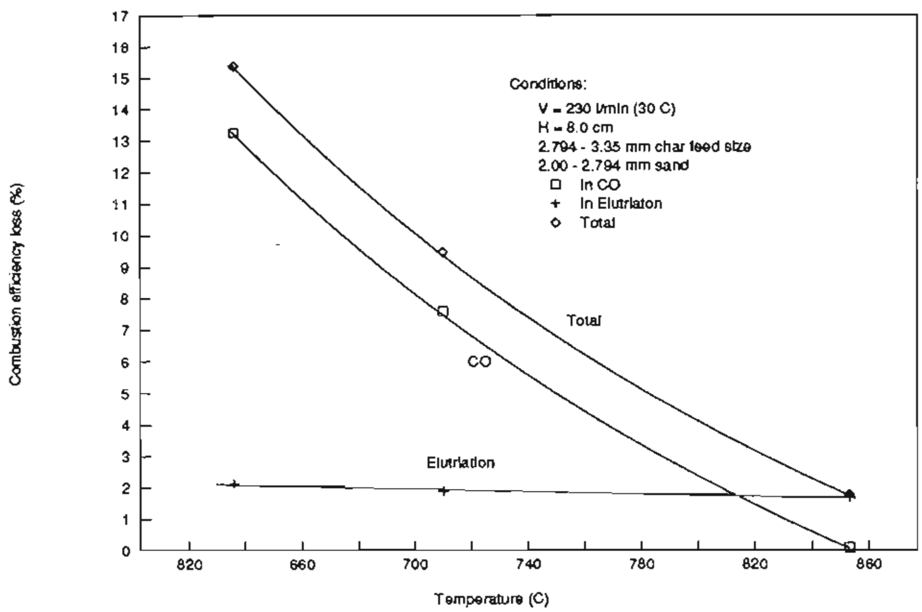

Figure 7 Combustible losses due to unburned CO, unburned C in elutriated fines, and total loss as a function of bed temperature.

(iv) <u>Effect of Superficial Gas Velocity on Combustion losses</u>

Figures 8 shows the variation of the individual efficiency losses - unburned CO, elutriated fines, and total - with superficial gas velocity for various char feed sizes at operating bed temperature of 850 °C. It shows that the total loss increases with a decreasing rate as superficial gas velocity increases. For intermediate 2.794-3.35 mm char feed size, the loss is the lowest compared to other feed size ranges, 2.00-2.794 mm and 3.35-4.00 mm. The energy loss owing to elutriated material slightly increases with increasing spouting gas velocity and is lower for higher feed size. The slight increase in CO loss with superficial velocity is probably due to combustion at a relatively low temperature of more elutriated fines in the freeboard.

5. CONCLUSIONS

The combustion efficiency of lignite char in a spouted bed depends strongly on the operating bed temperature. At a bed temperature of 850 °C the efficiency is about 98.5 %, the loss being practically due to carry over of combustible material from the bed. The efficiency loss due to elutriation of fines is not much affected by variation of bed temperature. The loss due to CO formation, however, increases rapidly as bed temperature drops below 850 °C and is the main cause of efficiency loss at low operating temperature. Only slight variation of combustion efficiency with excess air was observed; the variation was less than 2 percentage points within the range 1.07-1.85 of excess air used in this study. The combustion efficiency for intermediate feed size (2.794 -3.35 mm) was slightly higher than the efficiency for smaller (2.00-2.794 mm) or coarser (3.35-4.00 mm) particles.

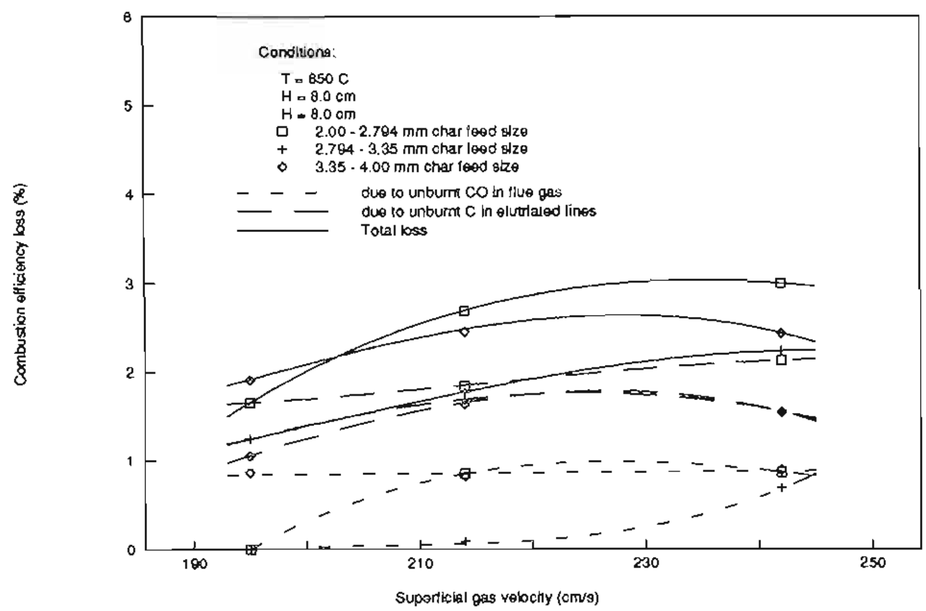

Figure 8 Variation of combustion efficiency losses due to unburned CO, unburned C in elutriated fines, and total loss with superficial spouting gas velocity.

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