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OPTIMIZATION OF FLUIDIZED BED COMBUSTION OF SEMIRARA COAL

Jessie C. Elauria
Assistant Professor
College of Engineering and Agro-industrial Technology
University of the Philippines at Los Baños
College, Laguna

Ibarra E. Cruz, Ph.D.
Professor
Department of Mechanical Engineering
College of Engineering
University of the Philippines
Diliman, Quezon City, Philippines

ABSTRACT

A study was conducted to determine the suitability of local coal as fuel in fluidized bed combustor (FBC) and to establish the optimum operating conditions of the FBC unit. A 6-inch diameter reactor with Pampanga river sand (mean particle size of 1.139 micrometer) as inert bed material was used in the conduct of the experiment. Combustion tests were run at air flow rates of 180 and 260 L/min, A/F ratios of 7.6 and 11.0 kg of dry air per kg of fuel, bed depths of 6 and 9 inches and bed temperatures of 820 and 910°C. Coal sizes of -1/16 + 1/32, -1/8 + 1/16, and -1/4 + 1/16 inch were evaluated based on their fluidization characteristics prior to experimentation.

Coal size of -1/16 + 1/32 inch registered a minimum fluidizing velocity close to that of the bed material but coal size of -1/16 + 40 mesh is recommended due to higher recovery during size reduction. Combustion efficiency ranged from 52 to 98 percent, while heat output rates ranged from 1,438 to 3,295 Kcal/kg of fuel equivalent to 27.6 and 63.3 percent thermal efficiencies. Combustion and thermal efficiencies are directly affected by air flow, A/F ratio and bed depth. Temperature is also positively related to thermal efficiency. The optimum performance of the FBC unit was found to be at bed temperature range from 902 to 910°C, A/F ratio of 11.0 and 11.6, air flow of 260 to 285 L/min and bed depth of 9.0 to 11.1 inches. The study as a whole showed that low quality coal (low heating value and high ash content) such as Semirara is a viable fuel in fluidized bed combustor.

INTRODUCTION

Coal is an organic rock composed of an assembly of minerals, organic and inorganic materials held molecularly as time progresses. It is not a chemical mixture in the same sense as petroleum, but is a mixture of rock types and minerals which when oxidized (burned) in air, produces heat, combustion products and pollutants.

The bulk of Philippine coal is subbituminous in rank. This is brownish black in color, homogeneous with smooth surface and with no indication of layers. They are intermediate in rank between lignite and bituminous coal. Their calorific values range from 8,300 to 11,500 Btu/lb and therefore classified as low grade fuel (fuels having calorific values less than 10,800 Btu/lb).

Current coal utilization includes direct combustion or burning of coal to generate power and heat, which is what is being practiced in the Philippines today. However in burning local coal, the problems are the following: a) high ash content which decreases its heating value; b) ash fouling at high temperature; and c) emissions of sulfur dioxide and NO_x. These fuel characteristics dictate that the combustor selected for energy conversion process must be capable of handling low grade fuel without ash fouling and reducing the emissions of pollutants. The fluidized bed combustors (FBC) are currently emerging as an alternative to traditional grate system (stoker firing) and pulverized coal firing, since they offer a number of important advantages. The adsorption of sulfur oxides within the bed minimizes the problem of removing these from the flue gas. Furthermore, a low combustion temperature reduces the formation of nitrogen oxides substantially. It is also possible to use lower quality coals which yield very high quantities of ash.

This technology has brought successful results in other countries. However, there has been very limited studies conducted in the Philippines. Thus, this research work aims to assess the suitability of fluidized bed combustion to local coal.

The general objective of the study was to determine the suitability of the fluidized bed combustion technology to local coal and establish the optimum operating conditions of the unit. The study was specifically aimed 1) to characterize the unit with regard to fluidization behavior, 2) to study the effect of operating parameters on the combustion efficiency and thermal efficiency, 3) to develop empirical equations or regression models for the combustion and thermal efficiencies using the response surface method and compare these with experimental results from the combustion tests, and 4) to determine the optimum areas of operation which give rise to optimum combustion and thermal efficiencies.

The operating parameters that were included are a) bed depth; b) air fuel (A/F) ratio; c) air flow; d) coal size distribution, and e) bed temperature,

REVIEW OF LITERATURE

There are several factors influencing the combustion of solid fuel in an atmospheric fluidized bed system. These are a) bed depth, b) fluidizing velocity, c) excess air, d) bed temperature, e) particle size, f) fuel and ash properties g) fuel feeding method, h) geometry of the combustor and i) air feeding method (Botterill, 1983).

Fluidizing Velocity

Few studies have been done to determine the effect of fluidizing velocity on combustion efficiency. Coal Research Establishment (C.R.E.). National Coal Board found in their experiments on the 6-inch combustor that increasing the fluidizing velocity increased the carbon monoxide in the off gas at both 700 and 800°C. In a similar study conducted by Annamalai et al (1987), they reported that as the velocity was increased from 1.5 to 2.5 times than the minimum fluidizing velocity, Umf, combustion efficiency was reduced due to elutriation of some unburned manure.

Bed Depth

The effects of bed height on the combustion efficiency were studied by Ketley, Rogers and Wright of BCURA and CRE.

In the first study, increasing the bed depth from 12 to 18 inches raised the bed temperature (from 860 to 926°C) and at a height of 37 to 31 inches above the bed surface, the CO_2 content of the flue gas increased (from 12.6 to 15.2 percent), the oxygen content decreased from 5.4 to 2.9 percent and the gas temperature also fell (from 970 to 925°C). This shows that with increasing bed height, the combustion process improved causing an increase in CO_2, while the proportion of heat release above the bed fell, causing the flue gas temperature to fall.

The two set of studies performed by CRE found no significant variation in combustion efficiency as bed height was reduced.

Excess Air Percentage

Szpindler, et al (1974) examined the effect of excess air on bed temperature using a constant superficial velocity of 0.4 m/s. They found out that as the fuel feed rate was increased from 25 kg/hr to 45 kg/hr, the bed temperature rose from 820 to 1100°C. They likewise showed the cooling effect of excess air when burning pure coal.

Combustion Engineering Inc. concluded from their catalytic fluidized combustion process that complete oxidation of the fuel can be obtained with excess air of the order of only 2 to 5 percent.

Coal Size Distribution

Coal size distribution is considered to be a factor in the performance of a FBC. As pointed out by CRE (1968), increasing the size of the coal feed above 10 mesh B.S. would reduce the amount of grinding required but would increase the fluidizing velocity necessary to ensure good fluidization. He likewise said that coal should nevertheless not be crushed too small (below 120 mesh B.S.) to reduce the elutriation of particles of high carbon content from the bed, and keep down the loss of combustion efficiency. In the study conducted by Hainley, et al. (1987) using a two-stage fluidized bed combustion, using coal containing a high concentration of fines (27% < 1mm), the fines escape to the cyclone without burning due to their low minimum fluidization velocity.

Bed Temperature

Szpindler (1974) based on his own experiences reported that the bed has to be heated to more than 550°C for self supporting combustion to take place. However, BCURA in their own experiments reported that combustion of the coal became self supporting only when the temperature at the center of the bed rose to about 400°C.

Raising the bed temperature increases the combustion efficiency although some findings produced opposite results i.e. those performed by Annamalai et. al. (1987) and others. The ash fusion temperature, however, will limit the extent to which raising the bed temperature can be exploited. Szpindler (1974), reported that if the bed temperature is allowed to rise too high (e.g. 1300°C), the bed is subject to sinter and fluidization to fail. He likewise said that the optimum bed temperature range is 825 to 925°C. Howard prefer to control the bed temperature of about 850°C.

(Butuk, 1987) sets the bed temperature at 820°C as the upper limit for operation since the corncob ash tends to soften and then fuse the sand at higher temperatures.

METHODOLOGY

Experimental Set-up

A schematic diagram of the fluidized bed combustion unit is shown in Fig. 1. River sand used as bed material with mean particle diameter of 1.139 micrometer. The reactor, 0.15 m in diameter and 0.9 m in height is insulated inside with castable cement and outside with Kaowool insulation. Above it is a 0.9 m high freeboard carryover space with a 2 inches tube leading to a 0.55 m diameter cyclone made of 1/16 inch thick mild steel plate below of which is a weighed char container. At the bottom of the bed is a plenum chamber separated by an air distributor. The distributor plate is made of 3/16 inch thick stainless steel with 1068 holes of 1.5 mm diameter drilled in it. The combustion air was supplied by a blower driven by a 2 hp a-c motor. The fuel feed system consisted of a feed hopper. A screw feeder runs through the bottom of the hopper leading to the reactor and was driven by an a-c motor attached to a 1:50 reducer unit. Fluidizing air was heated by propane burner until the bed reached the fuel's ignition temperature.

Procedure

Prior to conducting a detailed set of coal combustion experiments in FBC the following additional experiments/preparations were conducted:

1. Determination of physical and chemical/thermal properties of coal samples

Physical Analysis. A three-ton coal sample was sun dried, crushed, and screened to assure uniformity of size and to reduce soil particles.

Chemical/Thermal analysis. Coal samples was sent to the laboratory for the following chemical/thermal analysis: a) proximate analysis (by Furnace Method), b) ultimate analysis (using Elemental Analyzer), and c) moisture content determination (by oven method).

2. Determination of minimum fluidization velocities

Minimum fluidizing velocity (under cold condition) was determined experimentally and then compared with the value obtained using the Ergun equation. Minimum fluidizing velocities under hot (combustion) condition were computed at two bed temperature levels.

3. Particle size characterization

The bed material was poured on a standard set of sieve screens of different aperture sizes. The mass of the bed material retained by a particular aperture size was measured and the mass fraction of bed material (mi/mt) for each aperture size was calculated, then the mean particle size was determined using equation 1.

$$dm = (\text{summation of } x_i/d_i)^{-1} \qquad \text{(Eq.1)}$$

where x_i is the mass fraction of particle and
d_i is screen size in um

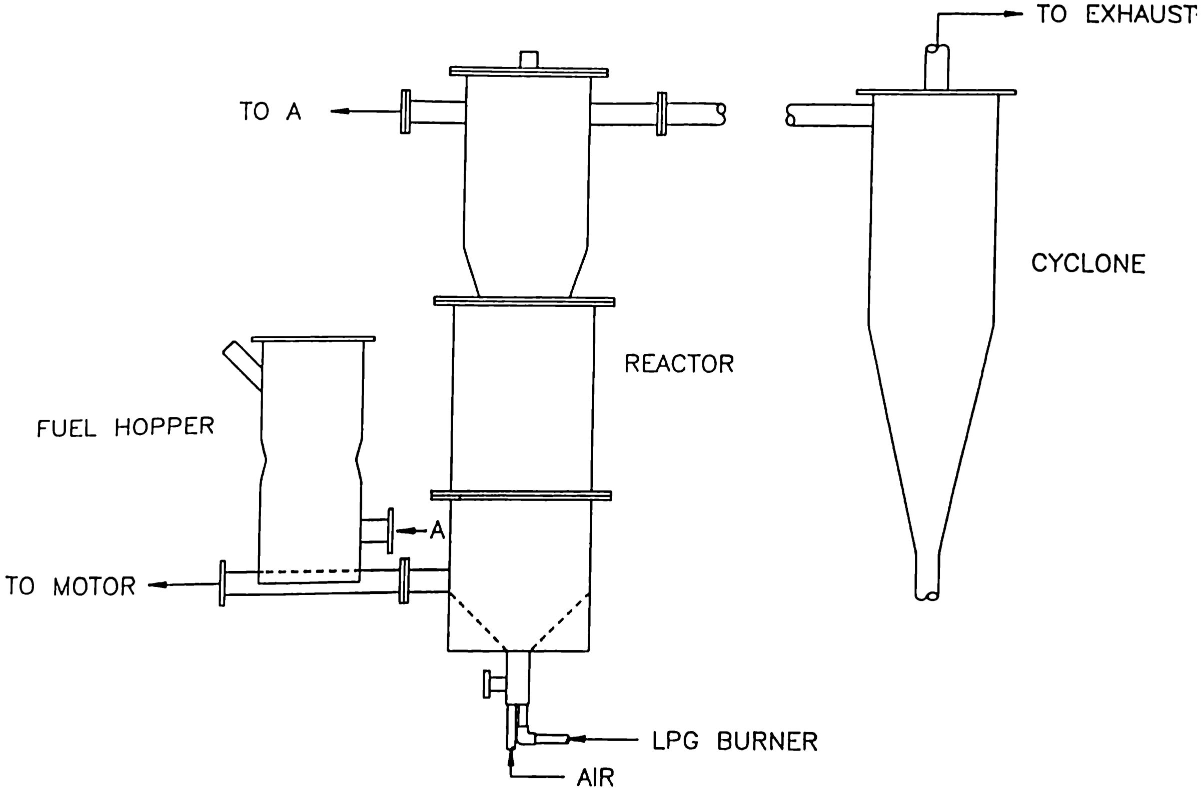


Figure 1. Schematic diagram of FED-ITDI FBC unit

In determining the A/F ratio the stoichiometric air was calculated using the elemental composition of Semirara coal selected. The fuel feed rates were then calculated for each rate of air flow (180 L/min and 260 L/min) to obtain A/F ratios of 7.6 and 11.0. Motor calibration equation was used to convert each fuel feed rate to motor speed in rpm. The rest of the experimental procedures are as follows:

(a) The reactor was pre-heated to 100°C using LPG before the bed material was fed at 100 rpm motor speed until the bed temperature reached 400°C.

(b) At this temperature saw dust was fed to the reactor as an auxiliary fuel for pre-heating to avoid early agglomeration of sand and coal sample until the bed temperature reached 500-550°C.

(c) Coal was fed at 75 rpm until the bed temperature reached 700-750°C and LPG was then turned off. Pre-heating time was normally 3 hours.

(d) When the bed temperature reached the desired operating temperature (820, 865 or 910°C) FBC was allowed to operate to stabilize the condition before any adjustment was made. The bed temperature was however controlled by an automatic on/off action switch connected to the screw feeder.

(e) Once the steady state was reached, experimental data were recorded for temperatures at three various locations, bed pressure drop and air and fuel rates.

(f) Motor speed was adjusted for the next A/F ratio and the gate valve was likewise adjusted for the next air flow rate.

(g) Gas sample was taken at the exit using gas sampling bag and coal refuse from the cyclone was collected at the end of each run.

(h) The next day the FBC unit was cleaned of sand inside the reactor and coal in the hopper.

Test Conditions

Three levels of variables were used in the experimental design. The coded and measured levels for the four (4) variables are shown in Table 1.

The high and low levels followed the 2^4 factorial design with each run duplicated for experimental error and the middle level or center point run three times.

Instrumentation

The fuel feed rate was determined by measuring the motor speed using its calibration curve. Air flow rate was measured using rotameter. Pressure drops along the reactor column were measured using water tube manometers as a check on the quality of fluidization. Temperatures were measured by three chromel-alumel thermocouples and read from the data recorder attached to the unit.

Table 1. The experimental factor levels, corresponding to levels of the coded values.

FACTOR	-1	0	1
A/F ratio Kgd.a./Kgfuel	7.6	9.3	11.0
air flow, L/min	180	220	260
bed depth, inches	1d*	1.25d*	1.5d*
bed temperature, Celsius	820	865	910

*d = 6 in.

Method of Analysis

Two parameters were used as dependent variables to assess the over-all performance of the FBC unit. These were as follows:

(a) Combustion efficiency,n_c (%). This is defined as the measure of completeness of burning of the fuel. In equation form

$$n_c = \frac{(THR - HLC)}{THR} \times 100\% \qquad \text{(Eq. 2)}$$

where THR is theoretical heat release or energy input and HLC is the heat loss through exhaust in the form of unburnt combustibles elutriated and entrained out of the bed through gaseous combustibles such as CO, CH_4, and H_2.

(b) Thermal efficiency, n_t (%). This is defined as the heat output rate measured during the test period divided by the input energy as calculated from the weight of fuel consumed times its higher heating value. In equation from,

$$n_t = \frac{\text{Heat output rate}}{\text{energy input}} \times 100\% \qquad \text{(Eq. 3)}$$

$$= \frac{\text{summation of sensible heat of flue gas}}{m_f HV_f} \times 100\ \%$$

where m_f is mass of fuel
and HV_f is heating value of fuel.

The output were measured at seventeen different combinations (a total of 35 runs) following the Box-Behnken method of experimentation.

Analysis of variance was conducted to determine the main and interaction effects of the four independent variable(s) or factor(s) in the combustion study. Multiple regression analysis was then performed to determine the relationship between the significant independent variables and the dependent variables, combustion and thermal efficiencies. To determine the optimum operating conditions, the method of steepest ascent was used to calculate the stationary points (optimum operating conditions) as well as the predicted responses at these points were computed. The canonical analysis was performed to determine the type of response (maximum. minimum or saddle points).

RESULTS AND DISCUSSION

Fluidization characteristics

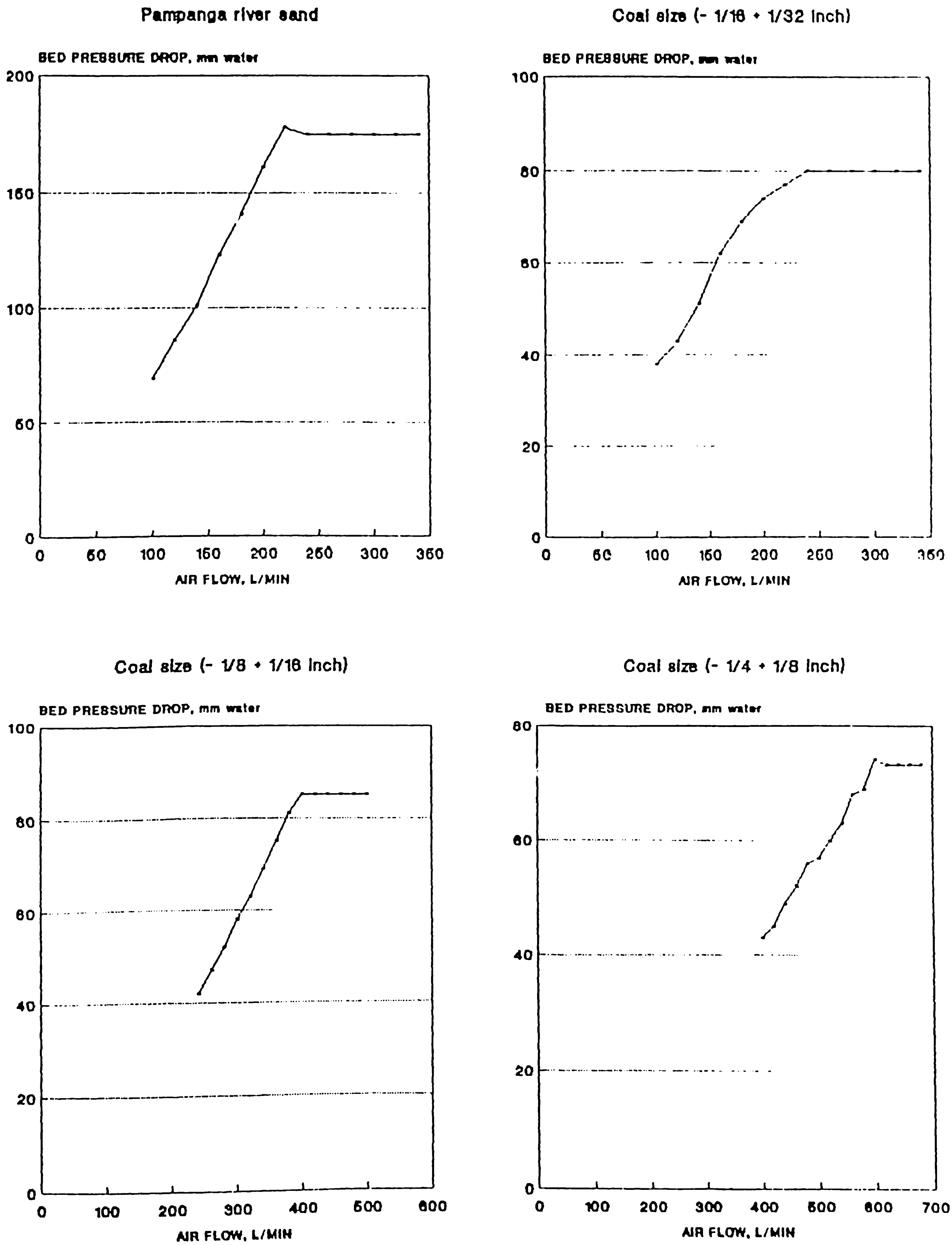
Cold flow fluidization studies performed with air at room temperature using ordinary (black) river sand and Pampanga (white) river sand using three different static bed heights (6, 9, and 12 inches) showed that both fluidized at the same air flow rate equivalent to minimum fluidizing velocity, (Umf) of 0.45 m/s. Higher pressure drops were however recorded using Pampanga river sand.

Of the three different coal sizes (- 1/4 + 1/8, - 1/8 + 1 /8 + 1/16, and - 1/16 + 1/32 inch) tested for cold flow fluidization, coal sample size of - 1/16 + 1/32 inch approximates the minimum fluidizing velocity of the bed material at 0.5 m/s (Fig. 2) This study showed that the only suitable coal size as fuel for this type of FBC was -1/6 + 1/32 inch. The theoretical minimum fluidization velocity was computed at 0.428 m/s which is within 5 percent difference of the experimental value.

The minimum air flow required to fluidize the bed was 494.5 L/min under cold condition and 85.5 L/min under hot condition.

Physical and chemical/thermal properties

Bulk density of Pampanga river was determined at 1,330 Kg/m^3 while coal of -1/16 + 40 mesh size has a density of 810 Kg/m^3.



Pampanga river sand

Coal size (- 1/16 + 1/32 inch)

Coal size (- 1/8 + 1/16 inch)

Coal size (- 1/4 + 1/8 inch)

Figure 2. Air flow vs. bed pressure drop

The ultimate analysis of semirara coal selected (sun dried) with size - 1/16 + 40 mesh mined from Unong Pit showed that it has a calorific value of 5,204 Kcal/Kg and moisture content of 12 percent. Coal contains small percentage of sulfur (1.04 %) and a significant amount of ash (11.4 %).

Thermal analysis of coal indicated that volatile release occurred at temperature as low as 400°C. The minimum bed temperature required to ignite it was found to be about 460°C. The proximate analysis showed that Semirara coal samples used contain almost the same percentages of fixed carbon, and volatile matter having 29.2 percent and 30.6 percent respectively. Coal samples contain a total moisture of 27 percent.

Results of tests on melting temperature of coal ash conducted, in Calaca, Batangas showed an initial deformation temperature of 1,250°C and fluid temperature of 1,550°C.

Coal particle size selection

Three coal sizes were initially considered, -1/4 + 1/8, -1/8 + 1/16, and -1/16 + 1/32 inch. The first two were rejected based on their large minimum fluidizing velocities as well as due to problems encountered when used as fuel. Being coarse, the fuel inside the hopper offered lesser resistance than the bed material inside the reactor.

Coal samples around to size of -1/16 + 1/32 inch resulted in a percentage recovery of only about 20 percent. .Extending the minimum size to + 40 mesh increased the recovery to 80%.

Bed agglomeration

The only serious operating problem which arose during the conduct of the experiment was sintering or agglomeration. This phenomena was observed on two occasions namely;

a) during the preheating process

Poor mixing of air and LPG triggered agglomeration of sand due to incompletely burned hydrocarbons reaching the bed forming small agglomerates.

b) when operating at too high bed temperature

Sintering problems had sometimes been experienced at temperature exceeding 950°C. However, below 910°C no significant agglomeration problem had ever been encountered. Agglomeration at very high bed temperature was the results of ash reaching the so-called initial deformation temperature. Although the 950°C bed temperature is way below the initial deformation of coal ash the coal temperature is actually several hundred degree higher than the bed temperature.

Performance of FBC

Combustion/thermal efficiency

The combustion efficiency, rates of heat output and thermal efficiency are shown in Table 2. Combustion efficiency ranged from 52 to 98 percent. Of the total heat loss, 97 percent is contributed by combustible gases in the flue gas on the average. Of this 97 percent, 87 percent was due to CO. This corresponds to 95 percent by volume of the total combustible gases.

Rates of heat output ranged from 1,438 to 3,295 Kcal/kg of fuel corresponding to 27.6 percent and 63.3 percent thermal efficiencies respectively. In general higher thermal and combustion efficiencies occurred at the same air flow. A/F ratio and bed depth levels. High thermal efficiency were observed at higher bed temperature level. Volumetric gas analysis showed that CH_4 and CO were mostly the combustible gases.

TABLE 2. Thermal Performances of FED-ITDI FBC unit using Semirara Coal selected as Fuel

PARAMETERS				THERMAL PERFORMANCES		
BED TEMP CELSIUS	A/F RATIO	AIR FLOW L/M	BED DEPTH IN	COMB. EFF. %	HEAT OUTPUT RATE	THERMAL EFF %
820	11.0	180	6	83.89	2366.20	45.47
910	11.0	180	6	82.82	2531.23	48.64
820	7.6	180	6	52.36	1437.61	27.63
910	7.6	180	6	51.56	1595.39	30.66
820	11.0	260	6	91.18	2941.94	56.53
910	11.0	260	6	90.18	3168.05	60.88
820	7.6	260	6	71.21	2040.48	39.21
910	7.6	260	6	70.08	2255.01	43.33
820	11.0	180	9	84.18	2519.48	48.41
910	11.0	180	9	83.41	2805.86	53.84
820	7.6	180	9	55.92	1539.92	29.59
910	7.6	180	9	54.79	1819.79	34.97
820	11.0	260	9	98.28	3172.37	60.96
910	11.0	260	9	97.00	3295.41	63.32
820	7.6	260	9	75.95	2131.86	40.97
910	7.6	260	9	74.06	2439.80	46.88

Factors Affecting Combustion Efficiency

The FBC unit normally operates at relatively lower temperature than traditional combustion equipment, and so no amount of dissociation is expected. The completeness of

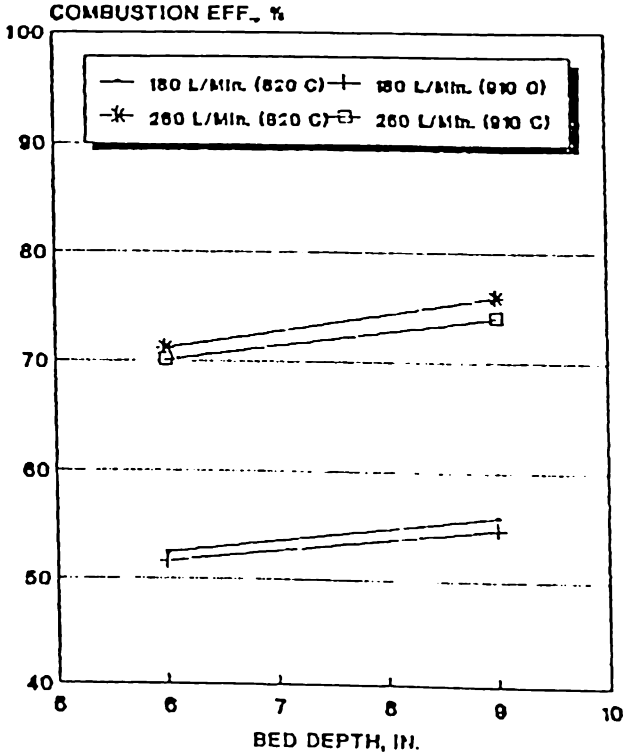


Figure 2a. Effect of air flow on combustion efficiency (A/F = 7.8)

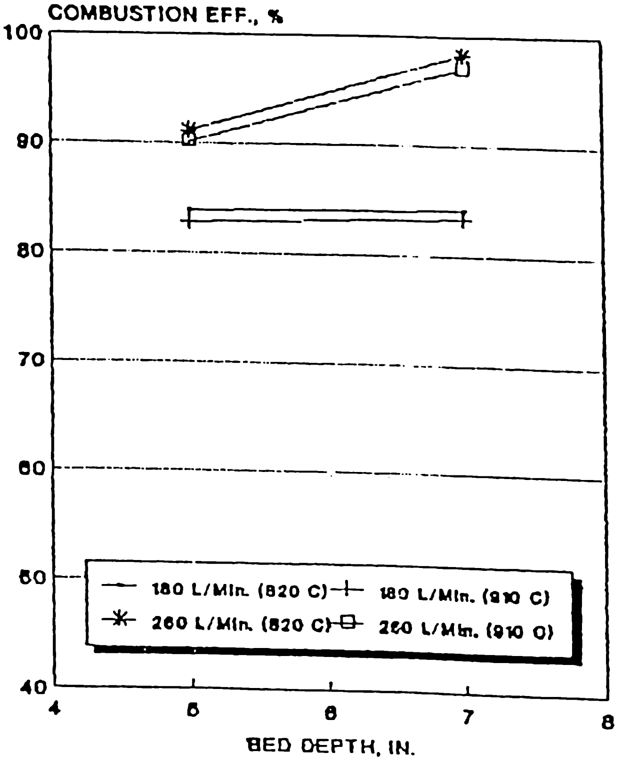


Figure 2b. Effect of air flow on combustion efficency (A/F = 11.0)

combustion as affected by the four variables used in the study merely depends on the dominance of either of the reactions below:

Oxidation Reaction

$$2C + O_2 \text{ ------------> } 2CO_2$$

Reduction Reaction

$$CO_2 + C \text{ -----------> } 2CO$$

The effect of air flow, A/F ratio, bed depth and bed temperature are shown in Fig. 3.

Air flow

In general, combustion efficiency is higher at higher air flow of 260 L/min than at 180 L/min regardless of bed temperature, A/F ratio and bed depth. This could be explained by the lower value of heat losses in the form of unburnt combustible gases produced namely, CH4 and CO. Although the amount of unburnt carbon is higher at 260 L/min in most cases, this represents only less than 3 percent of the total heat loss thus efficiency is still higher at higher air flow. This could be explained by oxygen starvation near the fuel feed point at 180 L/min and better solid mixing due to higher superficial velocity at 260 L/min.

Consider the feed rate of 1.62 Kg/hr at 75 rpm, the use of single fuel feed point using screw feeder caused a high concentration of fuel per kilogram of dry air when providing an air flow of 180 L/min providing an A/F ratio of 7.6. To the wall of the combustor near the fuel feed point there was an abundance of fuel due to serious maldistribution. In this region, oxygen starvation occurred as oxygen far from this region escaped without reacting with the fuel resulting in a lower actual A/F ratio. As air flow was increased to 260 L/min equivalent to an A/F ratio of 11.0, more oxygen was available for reaction with the fuel resulting in a higher actual A/F ratio than before. The effect of A/F ratio is discussed further in the next section.

At the same feed rate and air flow of 260 L/min, the combustion efficiency is higher by as much as 44 percent than at 180 L/min. This was brought about by lower concentration of fuel at 260 L/min than at 180 L/min resulting in an A/F ratio of 11.0 and 7.6 respectively.

At the same A/F ratios. combustion efficiency at 260 L/min was still higher than at 180 L/min by about 10 percent at A/F ratio of 11.0 and 20 percent at A/F ratio of 7.6. This was explained by having higher fluidizing velocity at 260 L/min which is about 3 Umf than at 180 L/min (about 2Umf) which enabled better mixing of the fuel with the bed materials. At an air flow of 180 L/min, fuel fed to the reactor was concentrated on one region limiting the amount of oxygen to react with the fuel resulting in an actual A/F ratio nearly equal to that of stoichiometric A/F ratio.

A/F ratio

Combustion efficiency is much higher at A/F ratio of 11.0 that at 7.6. At a lower A/F ratio of 7.6 more fuel is available for a limited amount of air. Near the fuel feed point oxygen

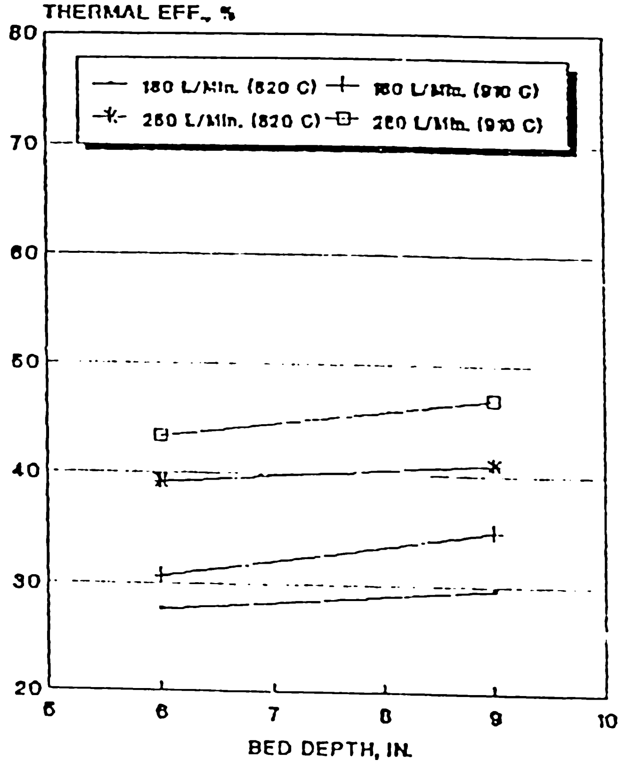


Figure 3a. Effect of air flow on thermal efficiency (A/F = 7.8)

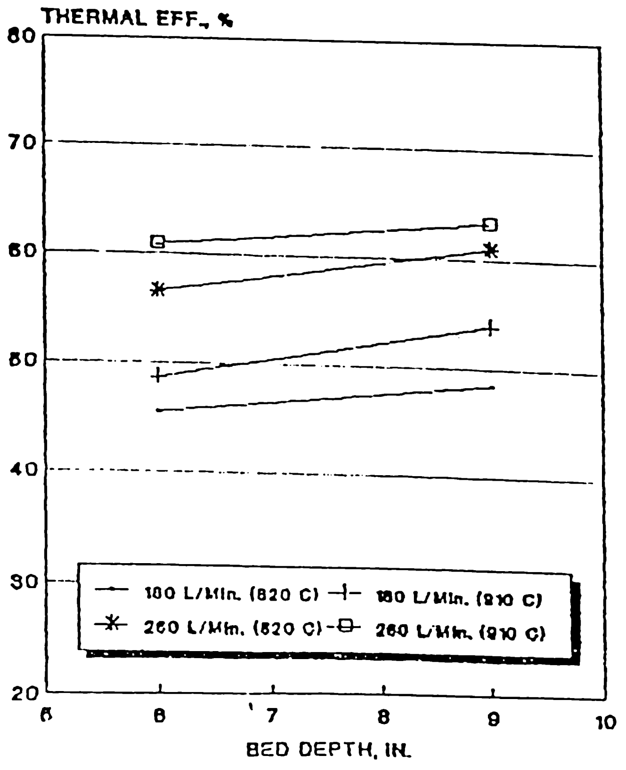


Figure 3b. Effect of air flow on thermal efficiency (A/F = 11.0)

was completely utilized by the oxidation reaction resulting in CO_2. As CO_2 moved upward it reacted heterogeneously with the fuel reducing CO_2 to CO by the reduction reaction. Far from this region unreacted oxygen escaped with the other flue gas components resulting in a lower actual A/F ratio. At a higher A/F ratio of 11.0 there was sufficient amount of oxygen reacting with the fuel resulting in an oxidation of carbon rather than a reduction of CO_2 to CO.

However, the difference in efficiency between both levels of A/F ratio is noticeably higher at 180 L/min, than at 260 L/min. The much smaller difference in combustion efficiency between A/F ratio levels at 260 L/min showed that better mixing of fuel and sand inside the reactor was a very important factor in the efficient combustion of fuel in fluidized bed. This result supports the finding of Ketley, et. at. as reported by Skinner that CO content of the flue gas showed the tendency to rise as the A/F ratio fell.

Bed depth

On the average, higher combustion efficiency is attained at 9 inches than at 6 inches although the difference is not much. This is true for both levels of A/F ratio. The difference is much noticeable at higher air flow , i.e. combustion efficiency is higher at bed depth of 9 inches than at 6 inches. Similar results were observed by Ketley, et.al. of BCURA in their pilot-scale combustor. The efficiency at higher bed depth improved because of an increase in residence time for the oxidation of CO. This not quite evident at 180 L/min due to lower fluidization velocity.

Bed temperature

The combustion efficiency at lower temperature level, 820°C is almost always higher than at higher bed temperature, 910°C by a very slim margin. At higher temperature the particles near the feed point where combustion was taking place was already pyrolyzing prior to reaching the bed.

Factors Affecting Thermal Efficiency

Thermal efficiency follows the same pattern as combustion efficiency as mentioned earlier. This is so because both measures of performance require common factor used in their calculations and this is the number of moles of dry flue gas produced which has a direct effect on mass of flue gas components. Both combustion and thermal efficiencies are higher as greater number of moles of dry flue gas is produced. The weight of burned carbon which also affects the number of moles of dry flue gas and hence the efficiencies, hardly played a significant role as almost all carbon (about 95%) in the fuel reacts based on the percentage of carbon in refuse.

The thermal efficiencies are higher at higher air flow (260 L/min), A/F (11.0) and bed depth (9 in.). The results are shown in Fig.4. Thermal Efficiencies are higher at higher bed temperature level. Sensible heat gains of flue gases having direct effect on rate of heat output hence on thermal efficiency are higher at higher bed temperature due to higher temperature rise (T).

Statistical Analysis

The analysis of variance shows that variability in the bed performance (combustion and thermal efficiencies) is explained by the independent variables used in the study. This is based on high R-square values of 0.9968 and 0.9955 for combustion and thermal efficiencies respectively. This implies that no other significant on major factors had been overlooked in the selection of design parameters.

The regression models are about 90 percent linear since both quadratic and interaction effects contribute less than 10 percent of the total effect. Lack of fit test shows that there is no reason to doubt the adequacies of the regression models as revealed by the large mean squares of 1.604 and 3.154 for thermal and combustion efficiencies respectively.

Effect of factors on combustion efficiency

The main effects of all the factors on combustion efficiency are significant except bed depth. Combustion efficiency is most sensitive to A/F ratio and least sensitive to air flow. The regression equation shows that the effect of the three significant variables are additive meaning that combustion efficiency increases with these factors. Canonical analysis of the response surface regression shows that the stationary point is a saddle point.

The regression equation for combustion efficiency is

$$\begin{aligned} Y2 = &- 4242.34 + 9.6395\ X_1 + 14.025\ X_2 + \\ &0.408X_3 - 1.155\ X_4 - 0.00557\ X_1^2 \\ &- 0.00067\ X_1X_2 - 0.000053\ X_1X_3 - 0.0315 \\ &X_2X_3 - 0.00099\ X_1X_4 - 0.0169\ X_2X_4 \\ &+ 0.015604\ X_3X_4 \end{aligned}$$

Effect of factors on thermal efficiency

The R-square characterizes the relation to be more linear than quadratic. Interaction effect is less significant and contributes only about 0.14 percent.

The main effects of all the factors on thermal efficiency are significant except bed depth. Thermal efficiency is least sensitive to air flow having the smallest regression coefficient and most sensitive to temperature. The prediction equation shows that the effects of bed temperature, A/F ratio air flow were additive with bed depth providing the opposite effect on thermal efficiency.

The fitted equation for thermal efficiency is :

$$\begin{aligned} Y1 = &- 4798.453 + 10.9754\ X_1 + 7.3522\ X_2 + \\ &0.1895\ X_3 - 2.69496\ X_4 - 0.00632\ X_1^2 - \\ &0.002557\ X_1X_2 - 0.00000937\ X_1X_3 - \\ &0.002031\ X_2X_3 + 0.004083\ X_1X_4 + \\ &0.084069\ X_2X_4 - 0.002323\ X_3X_4. \end{aligned}$$

Optimum operating condition

Table 3 shows that the optimum operating condition occurs at bed temperature range of 902°C to 910°C, A/F ratio of 11.0 to 11.6, air flow of 260 to 285 L/min, and bed depth of 9.0 to 11.1 inches. The estimated combustion and thermal efficiencies under this condition ranged from 96 to 100 percent and 64.2 to 68 percent, respectively. These conditions are however based on the minimum estimated performances of the unit of about 5 percent less than the estimated maximum performance. the estimated maximum combustion and thermal efficiencies are 99.93 percent and 67.97 percent, respectively.

Table 3. Fitted output from regression equations

PARAMETERS				FITTED OUTPUT	
Temp. °C	A/F kg/kg	Air Flow L/min	Depth inch	C.Eff. %	T.Eff. %
910	11.0	260	9	96.15	64.21
902	11.0	260	9	99.93	67.97
910	11.6	260	9	99.92	67.36
910	11.0	285	9	99.99	67.66
910	11.0	260	11	99.96	67.03

CONCLUSIONS

It has been shown that minimum fluidizing velocity is dependent only on particle size irrespective of particle density and bed height; bed pressure drop is however higher at higher static bed height; the "best" particle size of coal feed is - 1/16 + 40 mesh; the two major causes of agglomeration are poor mixing of air and LPG during the preheating and operating at temperature above 950°C; both combustion and thermal efficiencies increases with A/F ratio, air flow and bed depth; and the optimum thermal performance or the system is expected at bed temperature range of 902 to 910°C, A/F ratio of 11.0 to 11.6, air flow of 260 to 285 L/min and bed depth of 9.0 to 11.1 inches.

The results of the study provided the information necessary to understand the fundamental processes governing combustion behavior in fluidized beds and model these processes for scale up. This will further provide baseline informations for future studies of the technology and establish the conditions under which continuous operations could be maintained.

It shows that low quality coal such as Semirara is a viable fuel in fluidized bed combustor. This could trigger an investigation on combustion of local coal on a larger scale and use the technology to substitute local coal and other low-grade fuels for oil and gas. This will provide option for conventional coal-fired systems.

RECOMMENDATIONS FOR FUTURE WORK

As follow-up activities, it is recommended that the following be undertaken:

- Use of multi-point screw feeding system or pneumatic feeding to correct uneven fuel distribution.
- For good solid mixing, both vertical and horizontal, spouted bed may be tried for investigation.
- Other air distribution system such as bubble-cap type will provide an advantage.
- A diesel injected start-up system is recommended to reduce the preheating time and allow early feeding.
- A similar study using light feed materials and those containing high volatile matter.
- A similar study but on gasification of local fuel that will measure the effectiveness of the gasification process.
- This requires some studies on the proportion of limestone needed for a certain sulphur present in the feed.

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