CHAPTER V

EXPERIMENTS

It has been found by many investigators that the combustion efficiency in fluidized bed combustion of large particle coal (bigger than 1 mm) increases with bed temperature and with excess air for a certain range of values.(33) The combustion efficiency also decreases with calcium to sulfur ratio(34),but the available calcium used for capturing sulfur generally comes from limestone or dolomite which itself is not a heat emittable material. The idea of mixing oil shales with coals for combustion in fluidized bed comes from the relatively high calcium content of oil shales which should be as efficient for sulfur fixation as limestone or dolomite. However, very little data is available in the pullished literature in this field. The U.S. Department of Energy(14), merely disclosed that tests had been conducted to determine whether the high calcium oxide content (18%) of Colorado oil shales could be utilized for sulfur retention for high sulfur coal fluidized-bed combustion. The bituminous coal selected for testing was reported to has a sulfur content of 4.5%. When the mixtures were burned in a fluidized-bed combustion system, up to 95% sulfur retention was obtained at bed temperatures of 815 to 871°c. Furthermore, it was also found that the presence of coal can reduce the nitrogen oxide emissions considerably, to well below the 0.6 lb/million Btu EPA standard level. Another relevant article prepared by Doyle(44) also substantiated the above sulfur

Table 5.1 Fuel Analyses

Fuel	Ultimate Analysis(%)[1]					
	C[3]	H[3]	O[4]	N[3]	S[5]	Ca[5]
oil shale	15.93	1.82	7.84	0.35	0.67	4.35
lignite	41.05	2.75	26.30	1.61	1.60	1.85

Fuel	Proximate Analysis(%)		Low Heating	Theoretical
	Moisture[6]	Ash[7]	Value(cal/gm)[2]	Air(Nm^3/kg)[8]
oil shale	2.15	71.24	1,598	1.73
lignite	17.44	9.25	2,970	3.59

1 Air dried but excluding the hydrogen and oxygen in the moisture.

2 Calculated from the formula(28)

$$LHV(cal/gm) = 8,080C + 28,800(H-O/8) + 2,500S -600(9O/8 + H_2O) \quad (5.1)$$

where C,H,O,S are fractions of carbon, hydrogen, oxygen, and sulfur respectively presented in the fuel.(See Appendix A)

3 Determined by Elemental Analyser.

4 Determined by difference.

5 Determined by Atomic Absorption Spectrophotometer.

6 Determined by ASTM D 3173.

7 Determined by ASTM D 3174-73.

8 See Appendix C.

Table 5.2 Fuel Physical Properties

Fuel	Physical Properties				
	Max Size[1]	Min Size[1]	Ave Size[2]	Ave Size[3]	Density[4]
lignite	3.36	2.00	2.61	2.59	1.28
oil shale	3.36	2.00	2.67	2.61	1.75
oil shale	2.00	0.84	1.44	-	1.75

1 From sieve analysis, (mm).

2 Before entering screw feeder, (mm).

3 After passed through screw feeded, (mm).

4 Apparent density determined by simplified ASTM D 167-73.

Table 5.3 Analyses of Thai Lignite and Oil Shale in Comparison to those of the USA.

	Mae Moh lignite	North Dakota lignite	Mae Sot oil shale	Colorado oil shale
Carbon(%)	41.05	56.13	15.93	17.65
Hydrogen(%)	2.75	4.72	1.82	2.20
Oxygen(%)	26.30	14.16	7.84	10.07
Nitrogen(%)	1.61	0.25	0.35	0.74
Sulfur(%)	1.60	1.40	0.67	0.70
Moisture(%)	17.44	13.83	2.15	0.58
Ash(%)	9.25	9.51	71.24	68.06
LHV(cal/gm)	2,970	5,124	1,598	1,635

Note: All are in air dried basis.

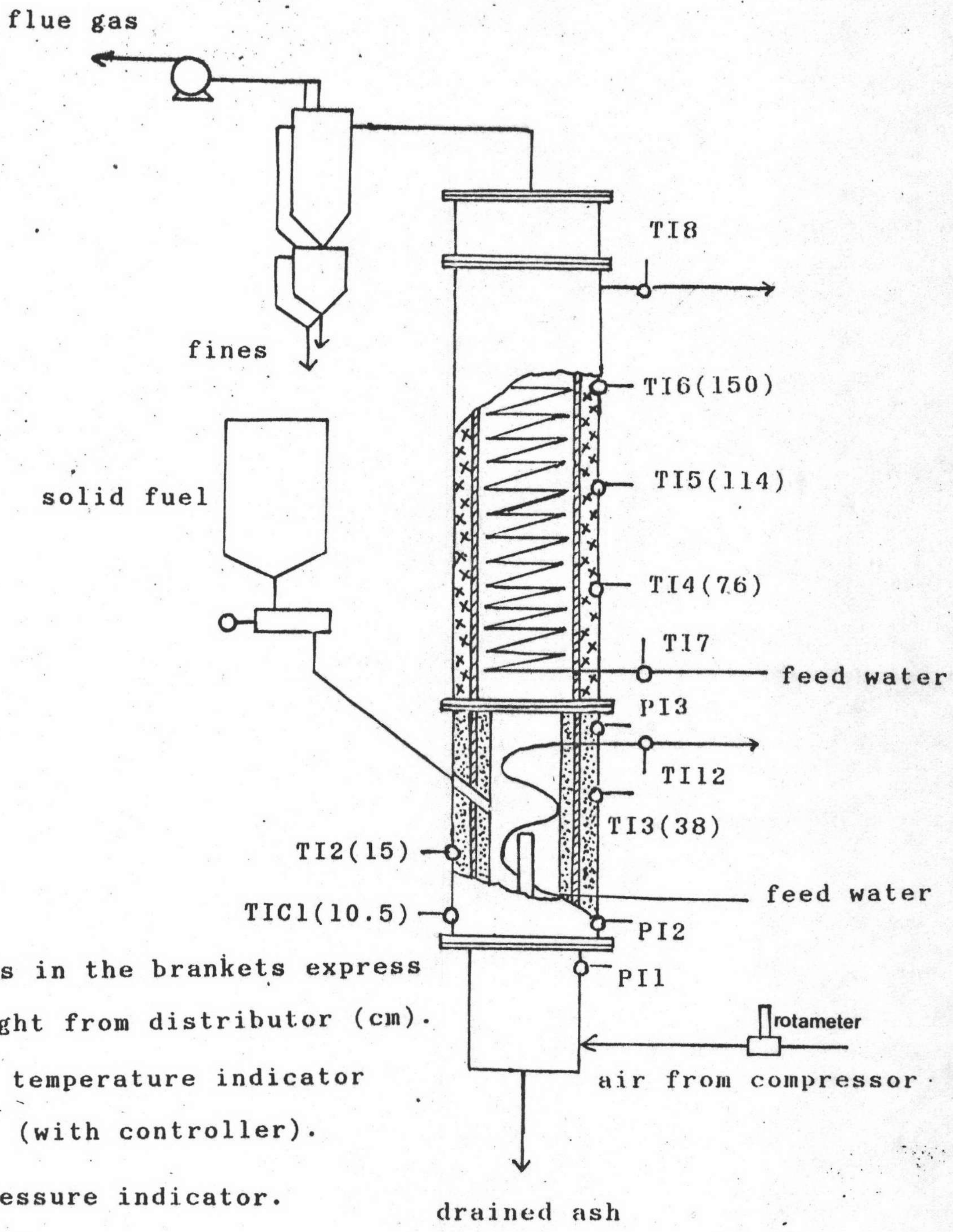
retention finding. This experiment was conducted using oil shale as a second heat generatable material and also as a calcium source. The combustion efficiency affected by bed temperatures, excess air, and oil shale to lignite ratio was analysed as well as the sulfur fixation and nitric oxide emission.

5.1 Materials

Table 5.1 gives the analyses of Mae Moh lignite and Mae Sot oil shale used in the experiments, while Table 5.2 provides their physical properties. Moreover, Mae Moh lignite, North Dakota lignite, Mae Sot oil shale, and Colorado oil shale properties are presented in Table 5.3 for comparisions. North Dakota lignite was of the Beulah Mine, in Mercer County and Colorado oil shale was of the Piceance Creek Basin section of the Green River formation, which is the world's largest oil shale deposit. Oil shale received was in big-lump form which must be crushed and screened to the desired sizes. The shale was crushed by a jaw crusher.

The lignite received was also in big-lump form, but prolonged outdoor storage caused spalling and fracturing of the coal which, in turn, made the lignite screen readily, without the need of crushing, from the stock pile.

Lignite and oil shale used in the present experiment was brought from surface mining only. Thus, the fuel properties represented herein are not the indication for the whole resource ones.



Numerals in the brankets express the height from distributor (cm).

TI(C) = temperature indicator
(with controller).

PI = pressure indicator.

Figure 5.1 Schematic Diagram of the Experimental Apparatus.

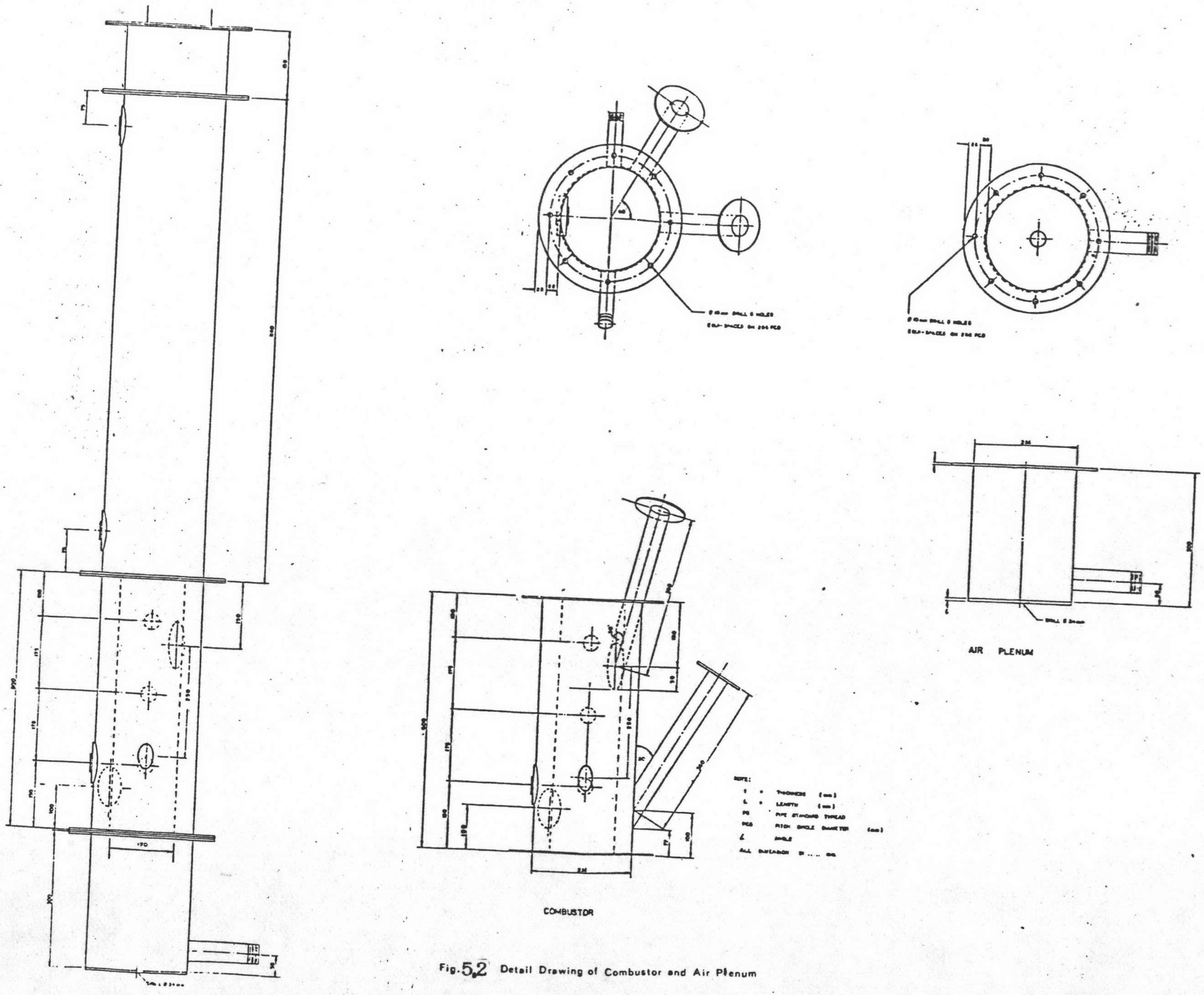


Fig.5.2 Detail Drawing of Combustor and Air Plenum

5.2 Apparatus

A partially broken off schematic diagram of the experimental apparatus is shown in Figure 5.1, while Figure 5.2 is the combustor drawing. The FBC column comprises three cylindrical section, i.e. a plenum, a firebox, and a freeboard, all of which are made of stainless steel. The firebox is a 23-cm in diameter and 60-cm high cylinder lined with refractory cement to provided the final inside diameter of 15 cm. Copper tube of 0.94 cm outside diameter and of about 88 cm in length is provided within the bed in helical form adjacent to the inside wall. The external surface of the bed is insulated also with refractory cement which, in turn, is wrapped with aluminun sheet.

The freeboard section, located above and connected to the fired box by bolt-nut assemblies, has inside diameter of 23 cm and 114 cm in height. The copper tube of the same diameter as in the bed provided within this cylinder is 46 m long, with typical hairpin with encircling ring arrangement. The external surface of the freeboard is covered with asbestos board which in turn is wrapped with aluminum sheet.

A perforated-plate air distributor made of 0.3 mm galvanized steel sheet with two high temperature resistance gaskets disposed above and beneath the plate is located between the lower end of the bed and the upper end of the plenum. The distributor has 103 one and a half mm perforations arranged in triangular pitch with the pitch of 1.5 cm which comprise 1 percent open area. The upper end of the plenum, the distributor plate, and the lower end of the firebox are fastened together by bolt-nut assemblies.

Along the longitudinal axis of the bed a bed-drain pipe was provided. The pipe has 2.5 cm inside diameter and is made of stainless steel. It is divided into upper and lower sections. The lower section is attached axially to the bottom of the plenum whereas the upper end is just below the distributor plate and the lower end is extended through the plenum bottom. The upper section of the length according to the bed height required is pierced through the distributor plate and threadedly connected to the upper end of the lower section.

For the fuel supply system, fuel mixture stored in the hopper can be introduced into the combustor by a variable speed screw feeder through a gravity drop pipe with a fuel entrance port center located about 35 cm above the distributor plate.

A rotary air blower is provided to supply fluidizing air, and air used for the gas ignition system. The fluidizing air flow rate can be measured by a 20-90 Nm^3/hr rotameter.

The ignition system is composed of two propane-butane (LPG) gas burners connected to individual gas cylinders. The air supplied to the burners is introduced from a by-pass manifold of the air line leading to the plenum. The two burner inserting ports open into the bed tangentially to its internal circumference. The port centers are 9 cm above the distributor plate and opposite to each other.

The points of temperature and pressure measurements are shown in Figure 5.1 where parenthetic numerals represent the distance above the distributor plate. All thermocouples are chromel-alumel type(type K) three of which are attached to the firebox, three to the freeboard, and the other three to the water loops. All thermocouples are wired to the selector switch which is attached to a control pannel. The temperature corresponding to the switch position is displayed on a digital monitor. Furthermore, the thermocouple at TIC1 is also connected to a single-pen chart recorder in order to determine temperature-time variations. Pressure differences across any two levels, e.g. PI2 and PI3, can be measured by a manometer.

The bed temperature can be controlled by adjusting water flow rates in the copper tube. But for this stage of research, it is unnecessary to use so efficient a controller and the controller used was an ordinary on-off type which is commercially available as RKC controller model PF-4. The water flow rate is also measured by a rotameter.

Hot gas leaving the firebox with fine particles will be cooled by water travelling in the freeboard tube prior to flow through two cyclones in parallel to remove fines from the gas. Afterward, the gas will go throgh the stack to be dispersed into the atmosphere. A draft fan is provided for use in case of start up the combustor to draw the smoke up through the stack.

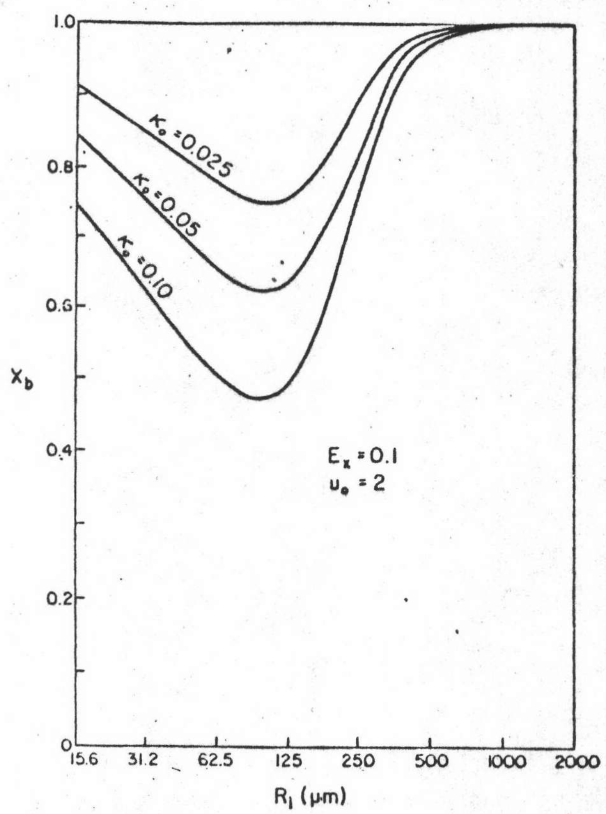


Figure 5.3 Conversion of Char in the Bed as a Function of Size of Coal Feed and Elutriation Constant(35)

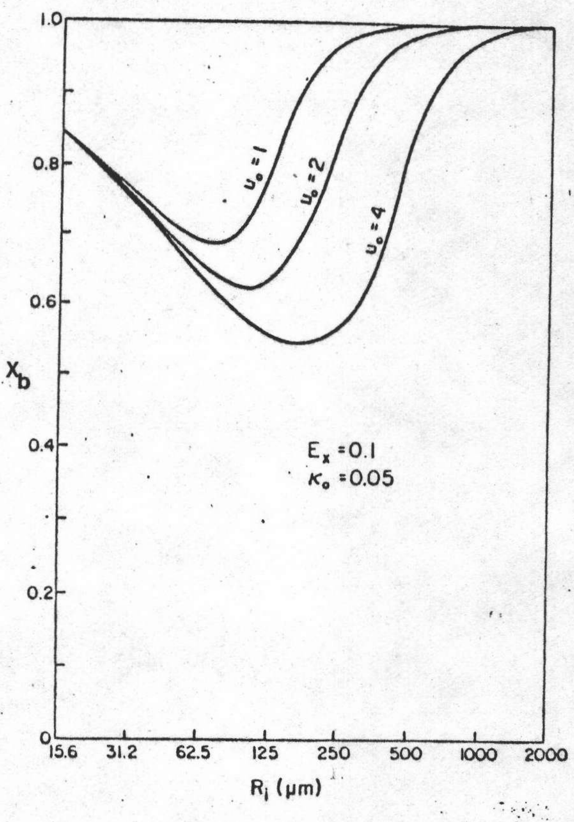


Figure 5.4 Conversion of Char in the Bed as a Function of Size of Coal Feed and Superficial Gas Velocity in the Bed(35)

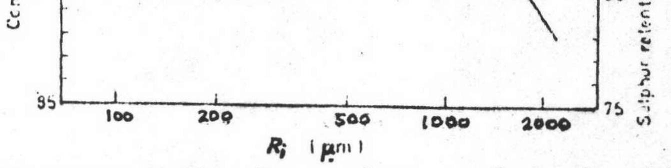


Figure 5.5 The Dependence of Combustion Efficiency and Sulfur Retention on the Particle Size of Coal Feed at Ca/S = 3(34)

K_o = elutriation constant

u_o = superficial gas velocity(

R_i = particle radius

X_b = conversion of char in bed

E_x = excess air ratio

5.3 Experimental Approach

The first thing to be performed before doing combustion was particle size selection. Figure 5.3 and 5.4 show the effect of different superficial gas velocities(u_o) and elutriation rate constants(k_o) on char combustion efficiency in the bed which is fed different sizes of coal particles at a bed temperature of 1116 K(35), as calculated by the Plume Model. The figures show that the lowest carbon efficiency always comes with an intermediate size of feed coal, say 30-250 microns, not with very large or very small feed sizes. Thus, the coal feed to the AFBC should try to avoid this critical size. Nevertheless, according to Chen and Saxena' model(34), the combustion efficiency is a maximum at an initial value of large particle size region for fixed feed rate and Ca/S ratio, as shown in Figure 5.5. This is so because at high values of particle radius the particle surface to volume ratio decreases resulting in a decreased reaction rate. Elutriation losses increase for intermediate value of particle radius which also reduces the combustion efficiency. For very small sizes, as can be seen in Figure 5.3 and 5.4, the combustion efficiency is increased again. This may be because the tiny sizes have very short burn out times and low fluidizing velocities are possible. The particles thus can be burned to a great extent before they come out the combustor.

In another aspect, the sulfur retention simply increases with the coal size as shown in Figure 5.5. Hence, to gain advantages both from combustion efficiency and sulfur retention aspects, lignite and oil shale sizes were selected to be 2.59 mm for the former, and 1.44 and 2.61 mm for the latter, which are large particles, as shown in details in Table 5.2.

It can be derived easily from Table 5.1 that the Ca/S mole ratio of pure lignite is 0.925 while that of pure oil shale is 5.194. These figures give respectively minimum and maximum Ca/S for the experiment. Thus, the weight ratio of oil shale to lignite used was chosen, at first, to be zero, one, three, seven, and infinite for attaining Ca/S of 0.925, 2.185, 3.114, 4.018, and 5.194 respectively.

For the fuel of relatively large size, a 30-cm bed drain pipe was installed to provide sufficient residence time for fuel combustion within the bed. Higher bed, i.e. longer pipe, was not suitable because the bed top level might be close to or beyond the fuel introducing port (35 cm above the distributor plate) which, in turn, could cause problems in material dissipation or, in other words, fuel particles dropped along the gravity drop pipe may be retarded at the port vicinity from circulation throughout the bed which causes local hot spots and, in turn, ash fusion there. For this bed height 67 cm of heat transfer tube was immersed within the bed.

5.4 Experimental Procedure

1. To start up the combustor, firstly, the combustor was heated by an LPG burner for about 20 to 30 minutes during which time its refractory wall absorbed the supplied thermal energy. About 670 gm of lignite was, then, dumped into the firebox and the burner was cut off. The retained heat in the refractory wall transferred to the

coal and made it volatilized. Since volatilization is an exothermic reaction(36), the bed temperature was gradually increased.

2. Fluidization air was fed to the combustor and gradually increased until the burning particles coming out ofthe drain pipe was noticed (this implies the existence of a state of fluidization).

3. Thereafter, 2.59-mm lignite particles was fed by the screw feeder into the bed at a rate capable of maintaining the combustion process. To this end, the system was left to attain steady state, while the temperatures were recorded sequentially.

4. After steady state had been attained, the minimum fluidizing velocity was determined by pressure drop across the bed versus superficial gas velocity plot.

5. The air flow rate was adjusted to two times that of the minimum fluidizing velocity in order to assure good solid mixing, while lignite feed rate and water flow rates were adjusted to give the steady state bed temperature of about 800 to 900°c of which has been found by many investigators(30-32) to be the efficient temperatures for both combustion and sulfur capture processes. The water flow rates in the freeboard and the bed loops were kept constant for all experiments and were set high enough so as to prevent steam formation and thereby obtain a smooth flow of water from which heat transfer data could be obtained. It was found later, in this circumstance, that the required lignite, freeboard water, and bed water feed rates had to

be 5.814 kg/hr, 3.0, and 0.8 liter/minute respectively.

6. Ash, fly ash, and flue gas were collected for analyses.

7. Another two gas flow rates were respectively set at 2.3 and 2.6 times of the minimum fluidizing velocity while other parameters were kept constant. Step 6 was repeated again when steady state was reached.

8. The experiments were also performed using other fuel mixtures. The start up method was similar to that mentioned in steps 1 and 2. The difference was that lignite culm was used instead of the individual mixed fuels because of the difficulty of oil shale to ignite. Low ash content, small particle size, and relatively high attrition rate of the start-up lignite culm made it elutriate out of the combustor easily and, thus, did not disturb the bed performance. The fuel mixture feed rates were predetermined by the quantities that generate the same amount of heat as the pure lignite in step 5 (see Appendix B). Afterward, step 4 was carried out in which minimum fluidizing velocities of the mixtures were obtained and, subsequently, the fluidization air was adjusted to two times of the minimum fluidizing velocity of individual mixture. Then, step 6 and 7 were repeated.

9. The experiments were still performed in the similar manner as step 8 except that the bed temperatures were maintained constant around 850°c instead of the heat generating rates.

5.5 Experimental Conditions

The experimental conditions are summarized in Table 5.4. The fixed variables were lignite size, bed height, and water feed rates; the manipulated variable is mixed-fuel feed rate; the controlled variable is the bed temperature; while the independent variables are fluidizing velocity, oil shale size, and oil shale to lignite ratio by weight, i.e. Ca/S.

Table 5.4 Experimental Conditions

Particle Size(mm)		O/L	Ca/S	Fluidizing Velocity	Water Flow(l/min)	
O	L				bed	freeboard
1.44	2.59	0	0.925	2.0u_{mf}	0.8	3.0
2.61		1	2.185	2.3u_{mf}		
		3	3.114	2.6u_{mf}		
		7	4.018			
			5.194			

Bed Height (cm)	Bed Temperature (°c)	Fuel Feed Rate (kcal/hr)	Fuel Feed Rate (kg/hr)
30	not controlled	varied	varied
	fixed(850°c)	17,291	5.814
			7.564
			8.904
			9.769
			10.820

Symbols: O = oil shale, L = lignite
O/L = oil shale to lignite weight ratio
Ca/S = calcium to sulfur mole ratio