Chapter 5

Apparatus and Experiments

5.1 Introduction

The complex behavior occurring in the bed under certain specific conditions can be simplified by certain assumptions. Subsystems representing the phenomena in the bed are incorporated and developed into a system model. These are described in Chapter 3. The validity of the developed system model will be tested by comparing the predicted values from the system model with the experimental data.

5.2 Apparatus and Ancillaries

The apparatus and ancillaries used in the experiments are as follow. (see the photograph of the apparatus and ancillaries in Fig.5.1)

Fig. 5.2 and 5.3 show the schematic diagram of the experimental fluidized bed combustor and ancillaries which were designed[39] and have already been used in previous experiments of oil shale combustion for electricity generation as a research project for the Electricity Generating Authority of Thailand (EGAT), (detailed drawings of combustor and air plenum are shown in Fig. 5.4). These combustor and ancillaries has been suitably modified for these experiments.

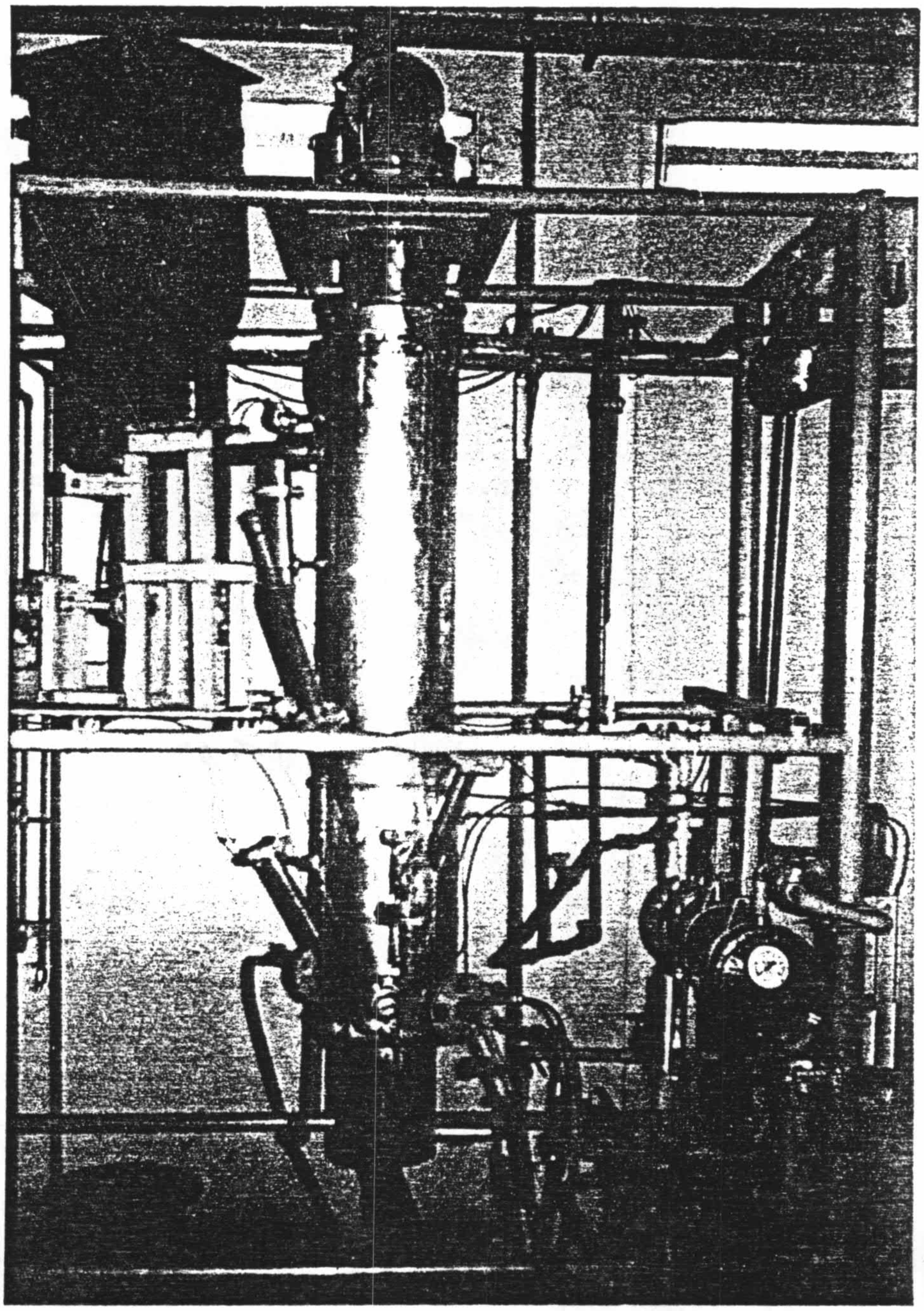

Fig. 5.1 The Apparatus and Ancillaries

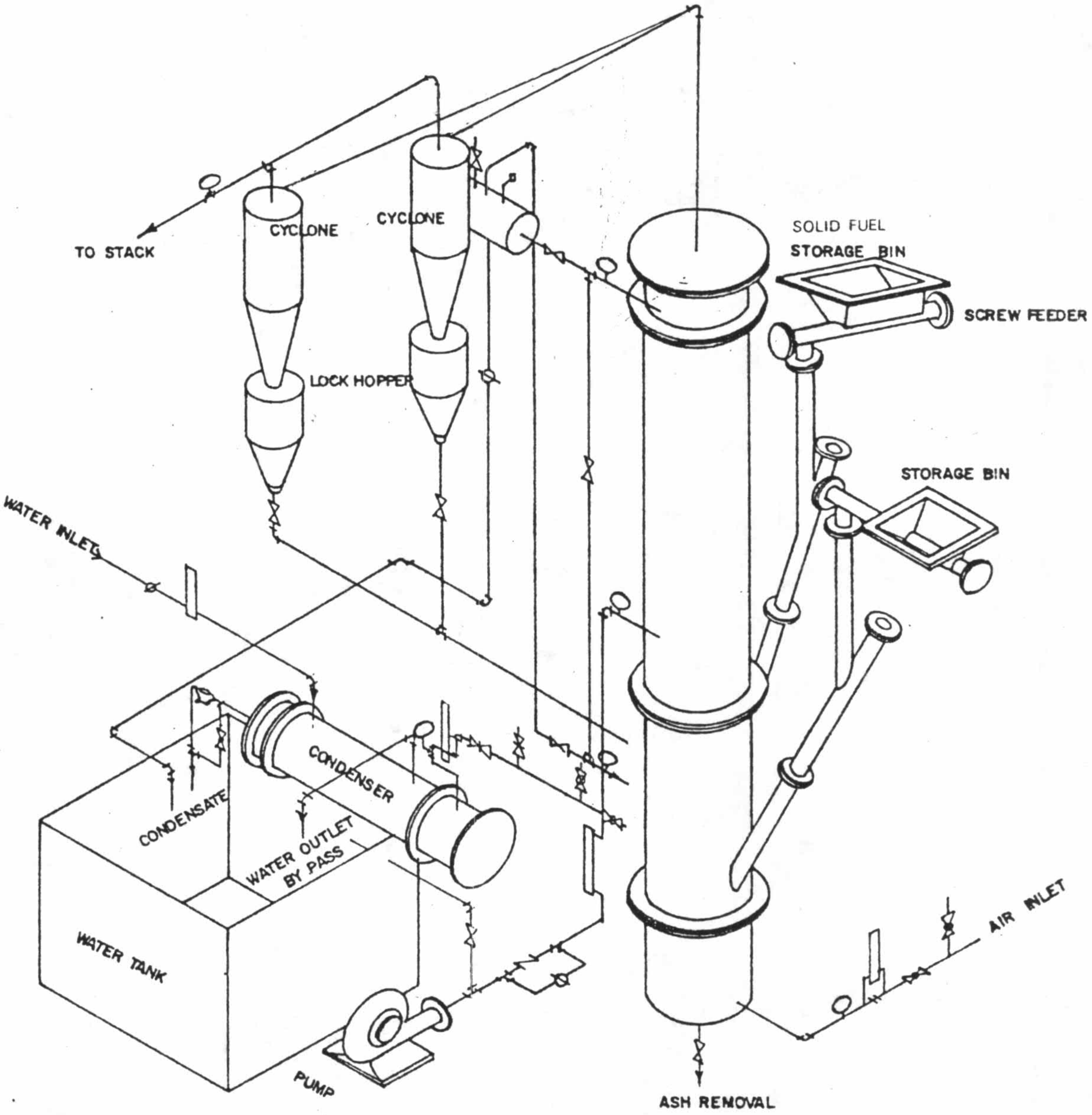

Fig. 5.2 Schematic Diagram of the Experimental Fluidized Bed Combustor and Ancillaries

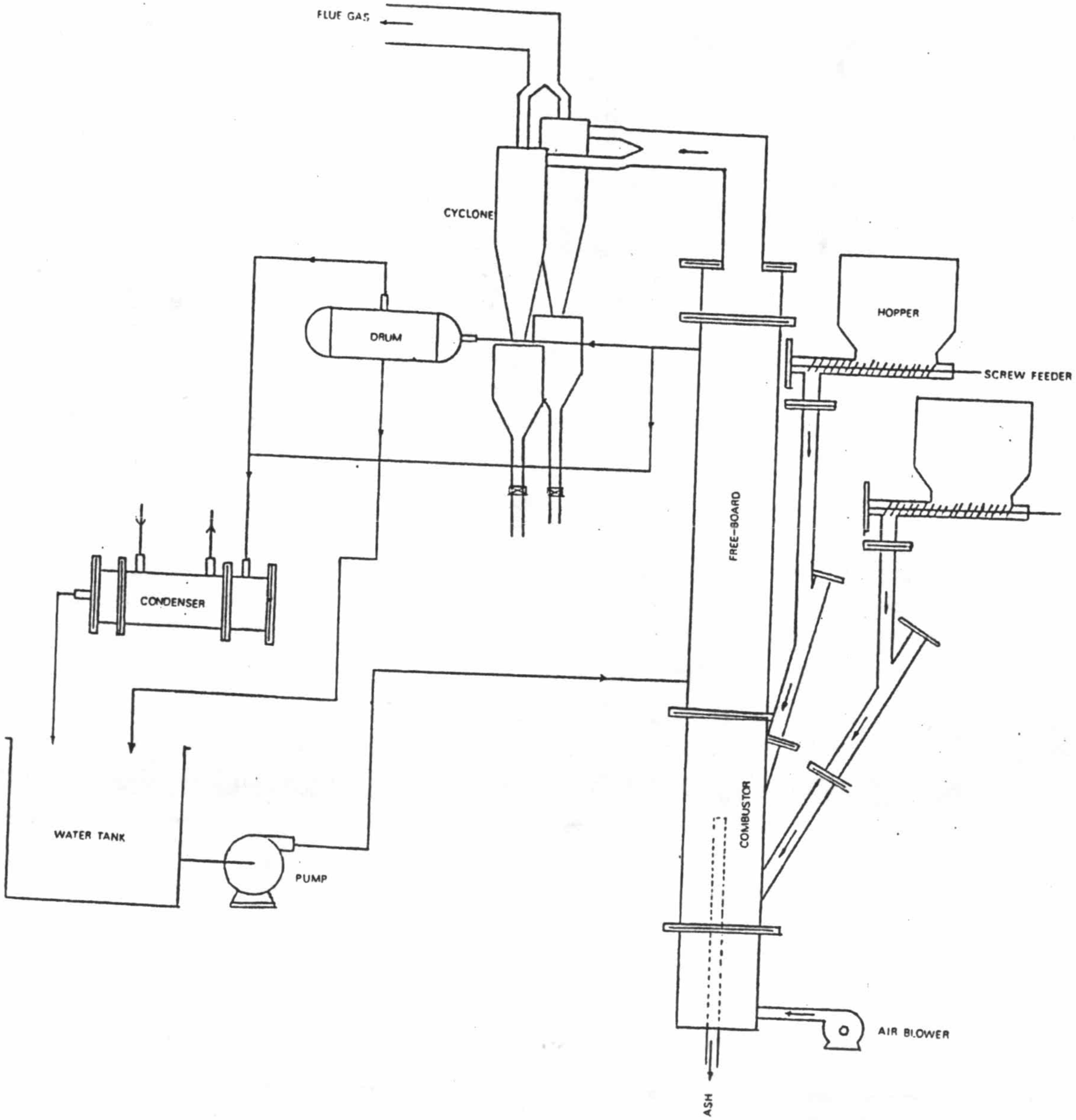

Fig. 5.3 Schematic Diagram of the Experimental Fluidized Bed Combustor and Ancillaries

The combustor is a stainless steel column of 23 cm and 23.6 cm in internal and external diameter respectively, and 2.19 m in height. The combustor is composed of 3 sections. The first section is a plenum of 30 cm in height. The second section is the bed, it is internally insulated with refractories, and the combustion bed diameter is 15 cm. The third section is the freeboard of 1.14 m in height. The freeborad is insulated externally with rock-wool. The copper heat exchanger tube of 1 cm in diameter and 4.60 m in length is arranged in the freeboard. The configuration of the exchanger tube is spiral in each horizontal plane.

The ash discharge pipe is located at the center of the bed. In a continuous operation, the raw lignite moves down while the lighter ash rises and is removed from the top of the bed by the discharge pipe. The distributor is an galvanized iron plate with 103 holes of 1.5 mm in diameter. The holes are arranged in triangular pitch of 1.5 cm in length.

The air is supplied by a centrifugal blower. Two cyclones arranged in parallel and attached to the exhaust pipe to remove the fly ash from the flue gas. The combustor is preheated by a LPG burner The raw material (mixture of Lignite and Limestone particles) is fed by a screw feeder. The mixture feed passes through the pipe and out of the pipe at the outlet port located 40 cm. from the distributor plate, down to the bed.

The temperatures in the bed are measured with thermo-couples, Chromel-Alumel type, located at TC1 and TC2 (see Fig. 5.4). The points TC1 and TC2 are 5 cm and 15 cm above the distributor plate

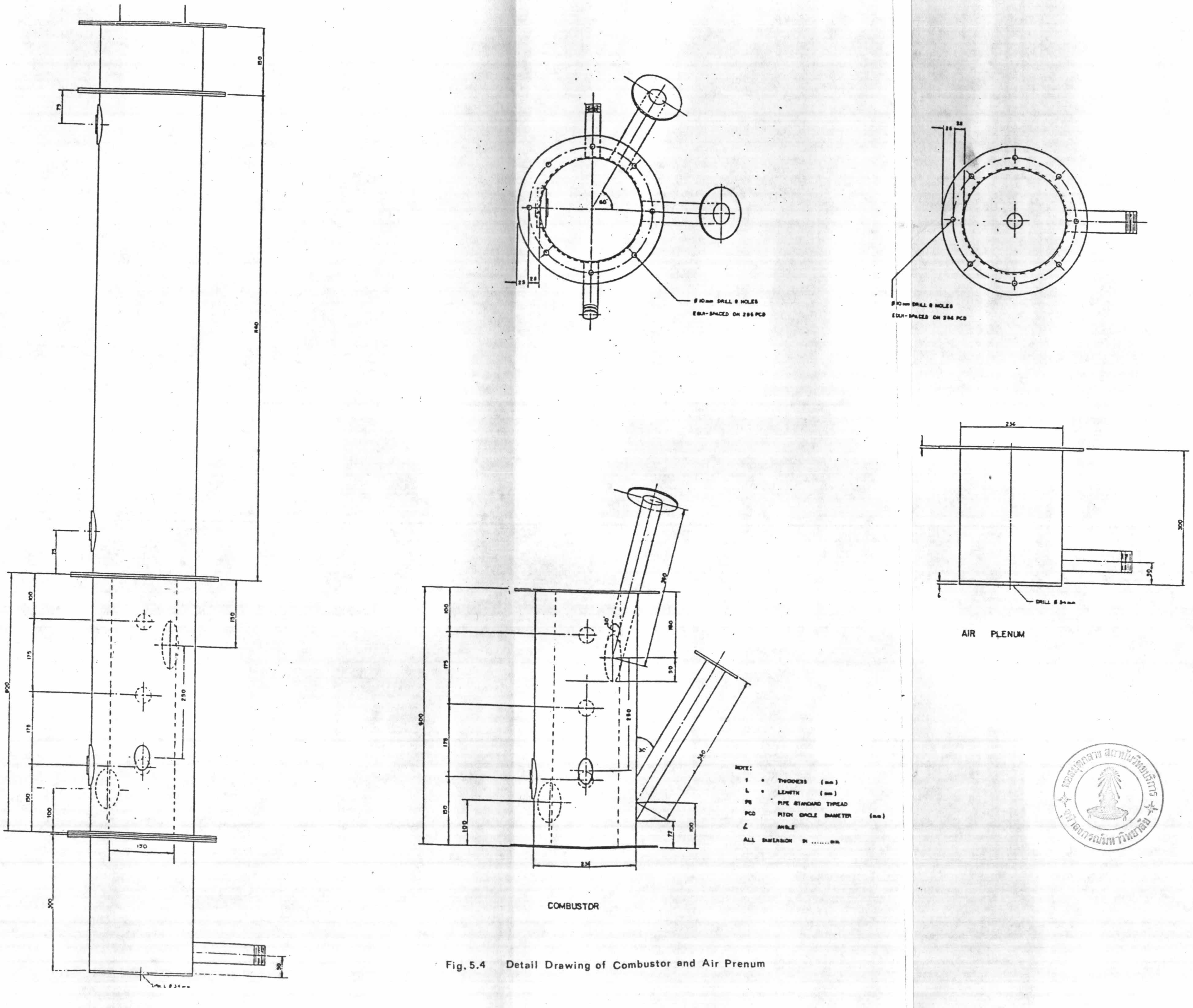

Fig. 5.4 Detail Drawing of Combustor and Air Prenum

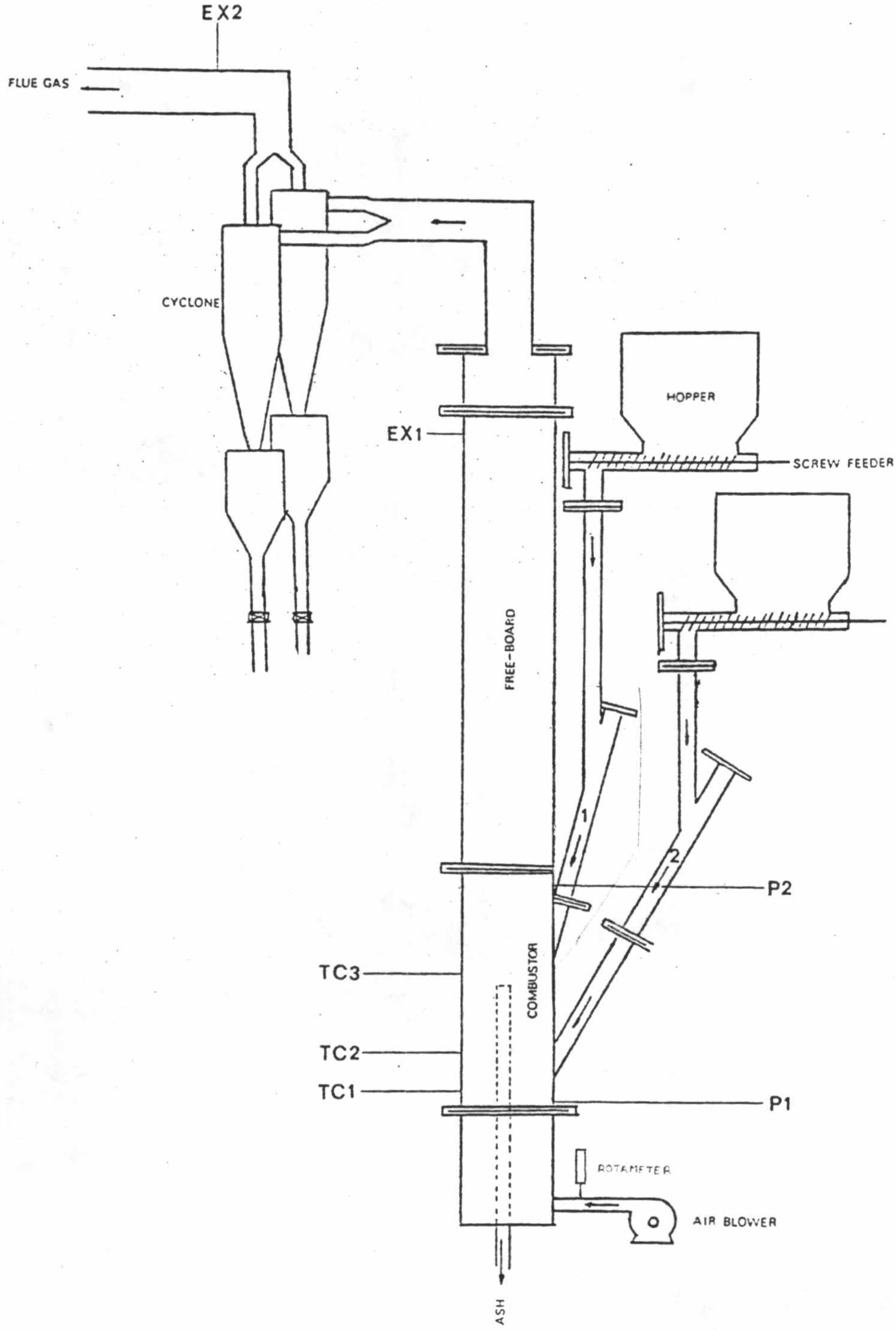

Fig 5.5 Measuring Positions of Temperature, Pressure drop and Gas Analysis

respectively. Another thermocouple is located at TC3, 37 cm above the distributor plate. The flue gas over the bed is collected at the point EX1 in the free-board for O_2 analysis by an orsat analyzer. The flue gas from the cyclone is collected at Ex. 2 for the analysis of CO_2, NO_x, CO and SO_2 using Infared Gas Analyser. The pressure drop across the bed (the point P1 and P2 in the Fig. 5.4) are measured by a manometer. Air flowrate is measured by means of a Rotameter (see Fig. 5.4).

Bed height is controlled by a 2.54 cm diameter ash discharge pipe located at the center of the bed (see Fig. 5.4). In these experiments, the bed height is 30 cm. The solid fuel feed rate is controlled by a variable speed motor. The calibration Table for controlling feed rates is shown in Appendix G. The air flow rates supplied to the bed are controlled manually by adjusting Rotameter readings.

5.3 Materials

The materials used in the experiments are lignite coal and limestone.

5.3.1 Lignite

The lignite used in these experiments as solid fuel is from the Mae Moh reserve, Lampang province. From proximate analysis shown in Table 5.1, the average heating value is 4166 calories/gm, the average fixed carbon is 23 %, the average volatile matter is 34 %, the average moisture is 28 %, average sulphur is 2.7 % and the average ash content is 14 %. From ultimate analysis as shown in Table 5.2, the average

Table 5.1 Composition of Lignite

Proximate Analysis

As-received Basis

Sample No.	Fixed Carbon %	Volatile Matter %	Moisture %	Ash %	Sulfhur %	Heating Value calories/gm.
1	22.10	33.90	31.91	12.09	4.09	4163.2
2	19.09	33.46	30.55	16.09	4.40	4065.5
3	25.80	34.72	28.52	10.96	3.82	4376.4
4	14.31	37.01	19.84	28.84	2.59	3205.8
5	21.71	36.87	25.28	16.14	2.45	4130.9
6	28.91	29.11	33.43	8.55	2.39	4383.6
7	17.53	39.90	23.85	18.72	2.30	3958.3
8	30.17	31.67	27.85	10.58	2.26	4358.7
9	25.68	32.86	33.58	7.88	1.76	4597.1
10	29.27	30.46	30.74	9.53	1.12	4416.7
Average	23.00	34.00	28.00	14.00	2.70	4166.0

Table 5.2

Lignite Analysis*

Sample No.	% N	% C	% H
1	2.06	50.98	3.44
2	2.04	50.45	3.36
3	1.88	48.57	3.24
4	1.81	48.88	3.27
Average	1.95	49.72	3.33

*Ultimate Analysis

As-Received Basis

Table 5.3

Lignite Analysis

Sample No.	% Ca
1	1.60
2	2.10
average	1.85

*Chemical Analysis

As-Received Basis

total carbon is 50 % and the average nitrogen is 2 %. Calcium element in lignite is 1.85 % from chemical analysis (see Table 5.3). The density of lignite is 1.5 gm/cm^3.

5.3.2 Limestone

Limestone is used as a bed absorbent for reducing SO_2. This limestone is from an area of Saraburi province in the central part of Thailand. From chemical analysis the chemical composition of this limestone is

Calcium Oxide (CaO)	44 % by weight
Magnesium Oxide (MgO)	8.8 % by weight

The limestone density is 2.71 gm/cm^3.

5.3.3 Lignite and Limestone mixture

Lignite and limestone particles of similar fluidising velocities are mixed together and kept in the hopper. Due to initial design Lignite and limestone can not be fed separately to the bed, although there are two screw feeders, and two hoppers. An outlet of the feeding port of a feeding line is at the bottom of the bed , during fluidization, the particles in the bed will flow back into the feeding pipe (2) (see Fig. 5.4) and obstruct the particles flowing down from the screw feeder. This feeding line would be available if it was fed by the screw feeder directly to the bed without the feeding pipe (2).

Lignite and limestone are mixed in a certain ratio. This ratio depends on the quantity of SO_2 emission and the capability to reduce SO_2 using limestone properties.

5.4 Design of Experiments

The validity of the system model for predicting carbon combustion efficiency is tested by comparing the experimental carbon combustion efficiencies with the prediction of the system model. The experiments will cover the effects of operating variables on the carbon combustion efficiencies.

The important operating variables are particle size, feed rate, fluidizing velocity and bed temperature.

These operating variables are limited by certain conditions.

From Geldart particles classification shown in Fig. 3.4.4, for density of lignite, 1.5 gm/cm^3, the lower range of large lignite particle size (type D) is about 1 mm. The upper range of large lignite particle size is generally not larger than 5 mm. Hence the range of lignite particle sizes is 1 mm $< d_p <$ 5 mm. The lignite particles will be screened by mesh No. 4 sieve with 4.7 mm. opening and held on mesh No. 10 sieve with 1.7 mm. opening. The calculated average particle diameter is 2.41 mm. (see Appendix D).

In addition, lignite particles passing through mesh No. 10 sieve and held on mesh No. 20 with sieve openining 0.84 mm., are also used in experiments in order to test the validity of the system model for the smaller particles size. The average particle diameter of these smaller particles is 1 mm. The size distribution of the larger particles size and the smaller particle size are shown in Fig. 5.5 and Fig. 5.6 respectively. Two average sizes of lignite particles are used in the experiments.

Limestone particle sizes of approximately the same U_{mf} of lignite particles are mixed with lignite particles for reducing SO_2 occuring in the bed. The limestone particles sizes are from the particles screened by mesh No. 10 sieve and held on mesh No. 20 sieve for the larger lignite particles, and from the particles screened by mesh No. 20 sieve and held on mesh No. 35 sieve, for the smaller lignite particles. The calculated aveage limestone particles sizes are 1 mm. and 0.6 mm. in diameter respectively.

The mixing ratio of limestone and lignite depends on the capability of limestone to reduce SO_2 emission. In this experiment, the mole ratio of Ca:S used is 12:1. According to this ratio and the composition of Ca and S mentioned above, the mixing ratio of lignite and limestone is 1:1 by weight.

The bed temperature is not controlled at a fixed temperature level, but it can change to any steady state level under certain conditions. However, in practice the bed temperature is not lower than 650°C, otherwise sectional fluidization will occur in the bed, and finally the bed will stop burning.

Screw feeder controlled by variable speed moter can feed the mixture of limestone and lignite at rates between 50 gm/min. and 700 gm/min. The calibrations of the numbers of speed motor variables and the mixture feed rate are shown in Appendix G. However from experience at handling the combustor at this certain mixing ratio of fuel mixture , the fuel mixture feed rates

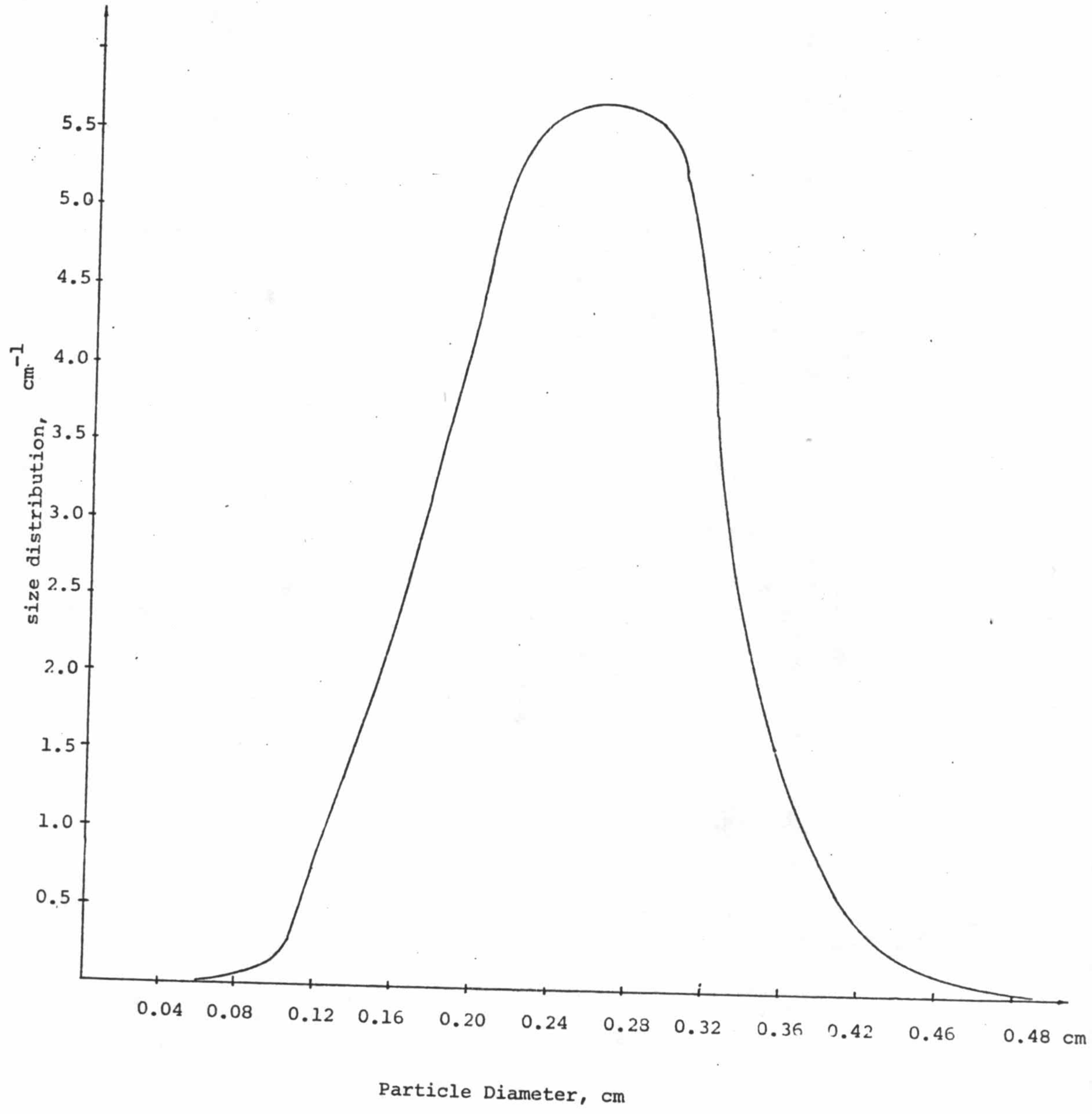

Fig. 5.6 Size Distribution of Coal Feed

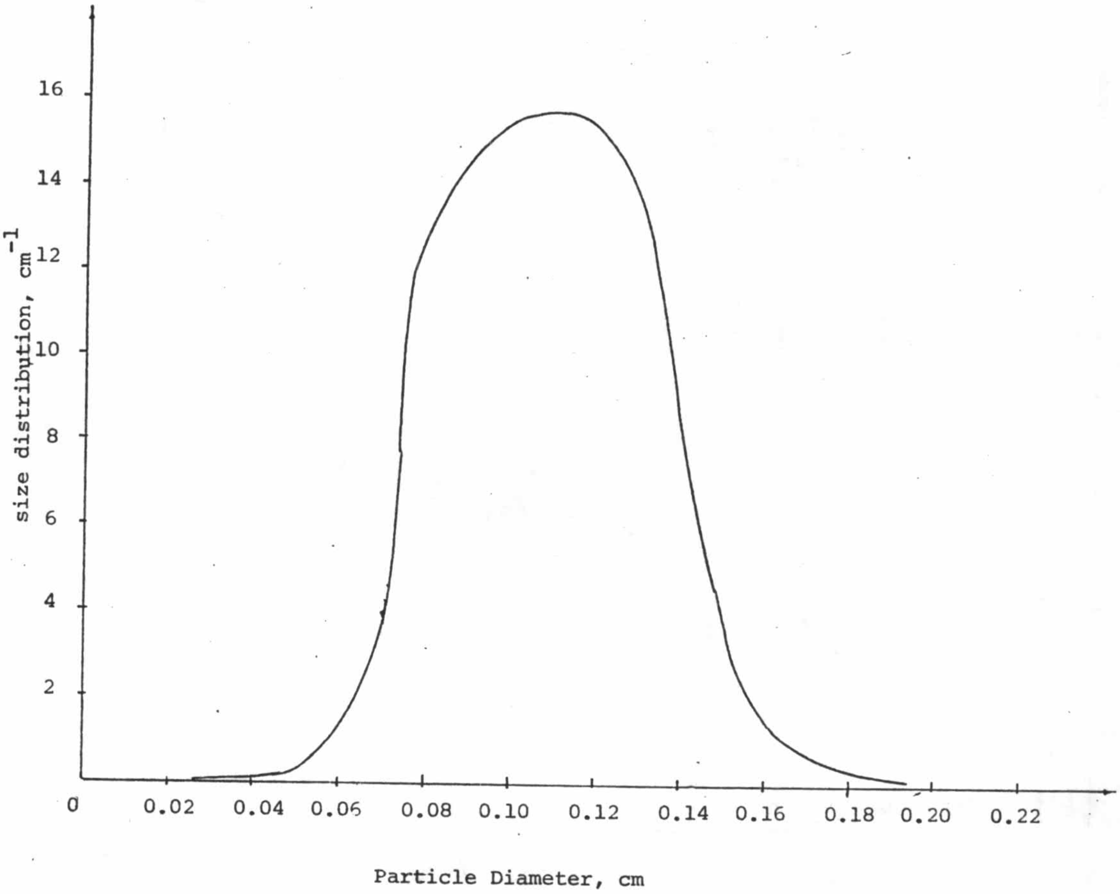

Fig. 5.7 Size Distribution of Coal Feed

are between 70 gm/min and 350 gm/min. If the feed rate is outside this range, the bed temperature will be lower than 650° C. In this range , fuel mixture feed rates of 145 gm/min and 200 gm/min were selected for the large lignite particles, and a feed rate of 118 gm/min was chosen for the smaller lignite particles.

The air flow rates supplied to the bed are in a certain range. The lower limit of air flow rate should be slightly superior to the air flow rate for minimum fluidizing velocity (U_{mf}) at combustion bed temperature. This minimum limit in practice can be determined from manometer measuring the pressure drop across the bed. However the U_{mf} can be calculated by the Ergun equation shown in Table 3.2. The upper range of air flow rate must not be more than the air flow rate of the terminal velocity of the average limestone particle size at a bed temperature of about 750°C. In this range, at each feed rate, five air flow rates were used. Consequently, the summary is that 15 different operating conditions were performed in the experiments.

5.5 Experimental Runs

To carry out the experiments on fluidized bed combustion, two step are necessary . The first step is to start up the combustion. After the first step the experiments under various specific operating conditions according to the experimental design mentioned above will be carried out without returning to the start-up step again.

5.5.1 Start-up

In starting-up the fluidized bed combustor , a recurring problem is agglomeration of solids in the bed. This can be prevented if the bed is in the fluidizing state. But the bed has to be stagnant during heating from the refractory combustor wall to the solids in the bed and the bed temperatures has to increase ignition point. If the air is not supplied on time and the bed temperature increases rapidly over 900°C, the solids will agglomerate. If the air is supplied before hand in order to have the bed in a fluidizing state, the heat transfered from the refractory combustor wall will be removed by the air and the bed temperature cannot reach the ignition point. Hence the timing in supplying the air to the bed is critical for start-up.

The following procedures have been found suitable for start-up of the fluidized bed combustor.

1. Preheat the combustor with LPG burner for about 40 minutes or until the combustor temperature is between 900°C and 1000°C, then cut off LPG supplied to the burner.

2. Feed the fuel mixture of lignite and limestone particles until the estimated bed height is 5 cm, then stop feeding.

3. Let the bed be stagnant for a moment to affect heat transfer from the refractory combustor wall to the fuel mixture. The bed temperature decreases rapidly to a certain temperature about 400-600°C. Then the bed temperature increases gradually and then rapidly because of gasification occurring in the bed. Now it is the critical step of start-up operation because of the agglomeration of lignite occurring over 900°C when the particles are stagnant.

4. Decrease the bed temperature and fluidize the particles by opening the valve supplying the air to the bed at the air velocity which is higher than U_{mf}. The minimum fluidizing velocity, U_{mf}, can be determined from noting the pressure drop across the bed monitored on the manometer. The fluidizing air velocity should be generally 2 times the U_{mf} for insuring fluidization and good mixing of particles in the bed so as to prevent agglomeration. At the same time feed limestone by hand to keep the bed temperature below 900°C, then feed the fuel mixture gradually. When the coal is combusted throughout the bed and the bed is in a fluidizing state, this means that we have passed the critical start-up procedure. Then increase the fuel mixture feed rate to the point that the coal is well combusted and adjust the air-flow rate. Leave the combustion continuing for about 1 hour.

5.5.2 Verification of operating variables

When the combustion is started up and can sustain itself without coal clinker formation, verification of operating parameters for various specific operating conditions is performed.

1. Vary feed rate to a required point

2. Air is supplied and the bed is left for about 40 minutes or until the bed temperature is steady. Record the bed temperature, overflow rate of ash and elutriation rate of fly ash. Collect the ash samples and keep them for subsequent analysis. Collect the flue gas from the free-board for O_2 analysis by orsat. Collect the flue gas from the cyclone, this flue gas will be analysed for concentration of NO_x, SO_2, CO, and CO_2 by infared gas analyser.

3. Vary air velocities with fixed coal feed rate. For each variation of air velocities, the experiment is carried out following 2. The five air velocities variations are performed for each feed rate, and the air velocities are in the range according to the experimental design.

4. Vary feed rate and perform 2 and 3.

5. Change from the larger particles sizes in the experiments to the smaller size and perform 2,3

The specifications of the operating variables in the experiments are shown in Table 5.4.

Table 5.4 Table of Experiments

Average Lignite particles diameter, mm.	Fuel mixture feed rate, gm/min.	Experimental Run No.	Volume air flow rate at STP, m^3/hr
2.41	145	1	40
		2	45
		3	50
		4	55
		5	60
	200	6	40
		7	45
		8	50
		9	55
		10	60
1.00	118	11	32
		12	35
		13	40
		14	45
		15	50