

CHAR BURN-OUT AND FLAME STABILITY
IN A
PULVERIZED FUEL FURNACE

by
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To

My wife Azza and My daughter Hanan.

Abstract

This thesis presents the results of an experimental study of the combustion of pulverized coal in a laboratory cylindrical furnace. The furnace features an industrial type double concentric burner with variable secondary air swirl. The assessment of the furnace performance is effected on the basis of the char burn-out for UK bituminous Gedling coal. For this purpose the input coal and the output char particles are characterized with respect to their ultimate analyses, proximate analyses, heating values as well as their size distributions.

A direct water quench (shower) probe is used to extract particle-laden gas samples from the combustor. After separating and drying, the particle samples are analysed for their ultimate and proximate contents.

Thermogravimetric analyses have been performed on char samples extracted from the furnace. These analyses have been used to determine the variations in volatile matter, fixed carbon and other interesting quantities along the axis of the furnace. This information enables physical deductions about the particles histories to be made. Simultaneous devolatilization and heterogeneous combustion may occurs near the burner exit. Some 3% of the original volatile matters leaves the combustor in the unburned char residual. An estimated upper limit on the 'Q' factor is 2.4

The results of on-axis char burn-out measurements for four levels of excess air, four swirl numbers and three momenta ratios of primary stream to secondary stream are presented. The mapping of the char burn-out in the flame for two levels of the secondary air swirl number are also presented. The

measurements show that there exists an optimum value of the swirl number for a fixed momentum ratio and excess air giving a maximum burn-out. The same conclusion can also be applied to the effect of the excess air level. The char burn-out, however, is insensitive to momentum ratio in the range of (0.16-0.28).

The effect of the: swirl number, ratio of primary coal and air stream momentum to secondary air axial momentum, excess air level, coal feed rate and quarl cooling on flame stability are also studied. It is observed that flame stability depends on the ratio between primary to secondary momenta, the coal feed rate, the swirl number as well as the excess air levels. The stability performance of the water-cooled quarl is significantly inferior to that of the corresponding refractory quarl. However, the elimination of the quarl slagging represents an important advantage of the water-cooled quarl.

A major attribute of the present data is their value to validation studies of mathematical models intended to assist designers of full scale equipment for which comparable data do not exist.

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Nomenclature

A	frequency factor
A_0, A_1, A_2	frequency factor
B	rate of volatile evolution
B_C	carbon concentrations in the char particles
B_H	hydrogen concentrations in the char particles
d	particle diameter
D	diffusion coefficient
D_0	binary diffusion coefficient
D_s	diameter of secondary air tube (burner throat)
E	activation energy
E_i, E_0, E_1, E_2	activation energy
FC	fixed carbon
F_{O_2}	molar fraction of oxygen
G_θ	axial flux of angular momentum
G_{ax}	axial flux of linear momentum
H_p	rate of change of the particle heat per unit mass
H_v	the total heat of volatile evaporation per unit mass of coal
H_t	total heat
$H. V$	heating value of coal per unit mass
K	rate constant

K_i, K_1, K_2, K_3	rate constant
K_c	chemical reaction rate coefficient
K_d	diffusion reaction rate coefficient
K_t	overall reaction rate coefficient
m_c	coal mass flow rate
$m_{c, p}$	coal loading in primary stream
m_p	particle mass, primary air mass flow rate
m_s	secondary air mass flow rate
M_c	atomic weight of carbon
P	pressure
P_o	reference pressure
P_{O_2}	oxygen partial pressure
R	gas constant
R_m	ratio of axial momentum of primary stream (coal plus air) to that of secondary air
$R_{m, \max}$	maximum measured value of momentum ratio R_m for stable flame
S_s	secondary air swirl number, $S_s = 2G_\theta/G_{ax} D_s$
$S_{s, \min}$	minimum measured value of swirl number, S_s , for stable flame
t	time
T	absolute temperature
T_g	gas temperature, environment temperature
T_o	reference temperature

T_p	particle temperature
V, V_i	mass of volatile released up to time, t
V^*, V_i^*	maximum volatile yield
V_p	primary air axial velocity at the burner exit
V_s	secondary air axial velocity at the burner exit
VM	proximate volatile matter contents per unit mass
VM_k	volatile matter of the coal
VM_r	volatile matter of the char
W	overall particles weight loss, desired coal feed rate
W_o	initial weight of coal in the hopper
W_{th}	theoretical weight of the coal in the feed hopper
X	axial locations
X_v	fraction of the total volatiles not yet evolved
YCH	yield of the char

Greek Symbols

α_1, α_2	mass stoichiometric coefficient
β	% release of different coal components
ΔVM	mass of volatile released
λ	excess air ratio
ϕ	mechanism factor
ω	ash weight fraction

ω_i weight fraction of the species of interest

ψ char burn-out level

Subscripts

k coal particles

x char sample

Chapter 1

INTRODUCTION

1-1 Background

The origin of the commercial use of pulverized fuel (p.f) dates back almost two centuries in the cement industry, Essenhigh (1961). The success of pulverized fuel in the cement industry was later to be emulated by its use for power generation on a substantially large scale. The present state of the world fuel market, in particular the rising cost of gaseous and liquid fuels, creates a situation in which the use of coal including low quality types, for power production becomes increasingly advantageous. In addition, large reserves of coal make it an attractive major industrial fuel.

Despite the historical dependence of industry on coal, a detailed description of the reactions the pulverized coal undergoes during combustion is still lacking. Previously, a supply of good quality, cheap coal and lenient pollution regulation precluded the need for detailed knowledge of the coal combustion process.

The characteristic of the pulverized coal combustion are qualitatively understood but not known enough for quantitative prediction of performance parameters for a novel set of constraints, regarding the adaptation to major changes of coal quality, and environmental protection requirements. The first of these constraints requires that low quality coals can be fired with adequate

flame stability and efficiency and minimum ash fouling. Environmental constraints, on the other hand, demand high efficiency coal combustion(burn-out) and a minimum pollutant emission.

The essential techniques in combustion process modification are the control of fuel mixing and flame temperature: Beer (1986). Exploration of these techniques in the design and operation of pulverized coal combustors is only possible when the various phenomena occurring during pulverized coal combustion are well understood.

1-2 Objectives and Contribution

The objective of the present study is to provide a better understanding of the physical processes which occur during the combustion of the pulverized coal. This is to be achieved through experimental measurements, which can be scaled with certain degree of accuracy to industrial furnaces, in a pulverized fuel furnace whose size allows for closer physical simulation of industrial combustion phenomena. The experimental programme aims at direct observation and inflame measurements to determine the influence of the different operating conditions of the furnace on coal burn-out and flame stability. The data obtained from these studies are also expected to be useful for the validation of prediction procedures.

The thesis contributes to the above objectives through;

- 1- Providing detailed survey of previous related work concerning the fundamental processes in coal combustion viz; coal devolatilization and char combustion as well

as studies relevant to combustion measurements in pulverized coal flames.

2- Characterization of the coal used in order to give qualitative and quantitative information for comparison purposes of the performance of different coal types used in the present study as well as other studies carried out on the same furnace.

3- Inflame axial and radial coal burn-out measurements under different operating conditions.

4- Investigation of flame stability limits in terms of the operating conditions and burner type.

1-3 Thesis Layout

In the remainder of this chapter a review of studies of fundamental processes of coal combustion is presented. The review includes coal devolatilization and char combustion, section (1.4), inflame measurements, section (1.5), and flame stability, section (1.6).

Chapter 2 is concerned with the description of the furnace and its auxiliary equipments. In section (2.2) details of the furnace structure, burner, air supply and exhaust systems are given. The description of the coal feed theory and the system are given in section (2.3), while ignition control and safety features are detailed in section (2.4).

Coal characterization and the sample collection technique are discussed in chapter 3. Section (3.2) contains details of different analyses procedures employed to define and characterize the coal. This includes particle sizing, proximate analysis, ultimate analysis and heating value calculations. The

accuracy associated with the measurements is also discussed. A critical comparison between different types of probes used in pulverized coal/air furnace is given in section (3.3). This is followed by a description of the sampling line and sampling collection technique. A critical discussion of the tracer techniques is also given.

In chapter 4, the inflame measurements conducted in the furnace are reported and discussed. The validity of the measurements together with main measurements problems are out-lined in section (4.2). The behaviour of coal particles during combustion is presented in section (4.3). In section (4.4) axial char burn-out data are presented and discussed for four excess air ratios, four levels of the swirl number, and three momenta ratios as well as the radial data for two swirl numbers. Flame stability limits are presented and discussed in section (4.5). A summary of the chapter is presented in section (4.6).

Chapter 5 provides a summary of the main findings of the thesis and suggestion for future work.

1-4 Coal Combustion

The combustion of pulverized coal (p.f.) involves a large spectrum of parallel-consecutive competitive chemical reactions resulting in coal decomposition into volatile matter which burns in the gas phase, and a solid residue which is oxidized by heterogeneous gas solid reactions. The analysis of pulverized coal combustion, therefore, has traditionally involved these two aspects of the overall process, in conjunction with the physical phenomena such as fluid-

flow and mixing , heat radiation... etc. and the change in the particle size due to swelling and fragmentation. The review given below is concerned with the two most fundamental processes of pulverized coal combustion namely devolatilization and char combustion.

1-4-1 Coal Devolatilization

When coal is heated in an inert or oxidizing environment; the particle may soften (become plastic) and ^{under-}go internal transformation. Moisture present in the coal evolves early as temperature rises. As temperature continues to increase, gases and heavy tarry substances are emitted. The extent of this pyrolysis can vary from a few percent up to 70-80% of the total particle weight and can take place in few milliseconds or several minutes. The residual mass, enriched in carbon and depleted in oxygen and hydrogen, and still containing some nitrogen, sulphur, and most of mineral matter (ash), is referred to as the char. The char particles have many cracks or holes made by escaping gases, may swell to a larger size, and can be very porous internally: Smoot and Smith (1985). In pulverized fuel flames the residual char following devolatilization, may or may not yield further volatiles in the heating processes. It is estimated that as much as 80% by weight of the feed coal may volatilize and burn in the gas phase: Badzioch and Hawksley (1970).

The devolatilization of coal is the result of a complicated sequence of phenomena, involving a wide spectrum of chemical reactions coupled with the transport of the released volatile species through the coal structure: Smoot and Pratt (1979). The consequent difficulty in collecting and interpreting the kinetic

information of devolatilization is what confronts both the experimenter and the modeller. These kinetic data are of no value unless the mechanism of devolatilization process is known. The process itself depends to a great extent on the structure of the coal, which varies greatly from one type to another, and the environment under which devolatilization occurs Jamaluddin et al (1986).

The coal structure, understandably, varies widely since it depends on the original plant structures as well as the geological conditions under which the very long process of coalification takes place. Attempts have been made to get around these complexities by postulating that the chemical properties of coal can be adequately represented by a limited number of functional groups common to all coals Gavalas (1982). A detailed discussion of the structure of these groups is given in the review of (Jamaluddin, 1985).

It is generally recognized that the parameters which significantly influence the pyrolysis process, the composition and the amount of the volatile released are: (i) the coal type, (ii) thermal history of the particles, (iii) ambient nature and pressure, and (iv) particles size (see for example Yellow 1965; Anthony and Howard 1976; Smoot and Praat 1979; and Howard 1981). The present study is mainly concerned with pulverized bituminous coals with specific particle size, namely 80% by weight under 75 μm . In the following, however, previous investigations of the above parameters and their effect on the devolatilization of bituminous and lignite coals are reviewed.

(i) Thermal History

The thermal history of a particle includes the heating rate, final, or

ambient temperature and residence time which may be defined as duration of the experiment.

Coal reaction processes are dependent on the rate at which the particles heat and on the maximum particle temperature. Chukhanov (1954) suggested that rapid heating of the coal particle causes rupture of the bonds in coal structure producing a considerable number of large radicals. Heating the particle is complicated by coal reaction processes, which initiate devolatilization at about 300 °C. As particles continue to heat, convective heating is retarded by the flow of the volatile matter from the particle. Reaction of the volatiles in gas phase changes the surrounding temperature and the heat up rate of the particle; exothermic surface oxidation of the char with the oxidizer releases energy to the particle and to the gas in the immediate vicinity of the surface. Further oxidation of the surface products causes additional heat release in the vicinity of the particle. There is no definite chronological sequence for discussion of these various events, since the particle heat up can occur simultaneously with devolatilization, phase reaction or surface oxidation Smoot and Smith (1985).

In an early study of the mechanism of rapid devolatilization, Shapatina et al (1949) devised an experiment in which a refractory tube furnace, 1.0m. high and 0.12m. internal diameter was heated electrically. The furnace temperature ranged between 250-550 °C and particle samples were collected and analysed after 0.15, 6, 30 and 300 sec. These periods were measured from the end of a heating up period of 0.45 sec. Additional data were also obtained for a decomposition period of 2 hr. The results showed that the volatile yield increased rapidly with ambient temperature, while the effect of the duration of decomposition being much smaller. They further suggested that under the

aforementioned experimental conditions, the devolatilization process may be divided into three stages; (i) rapid carbonization proceeding at a very high rate in the initial 0.1 sec., (ii) principal thermal decomposition process proceeding at a relatively low rate lasting for 2-3 min. and (iii) degassing of coal proceeding at very low rate over a much longer period (hours), and for practical purposes the evolution of volatiles ceases after 2 hours.

Kirov (1965) also suggested that the devolatilization of coal under the action of heat, although a continuous and complex process with the composition of products changing continuously with the ambient temperature, may be conveniently divided into two stages namely; (i) a primary devolatilization stage with the formation of semicoke, and (ii) a secondary degassification stage resulting in the final coke. The primary volatiles consist of tar and some gas, such as hydrogen and carbon monoxide, while the products from the secondary degassification stage are gaseous, mainly methane and hydrogen at a temperature above 700 °C.

Kimber and Gray (1967) studied the effect of thermal history of the particle on devolatilization in a laminar argon flow reactor with temperatures ranging between 1050 and 2170 K, heating rates (10^5 to 10^6 K/sec.), and residence time between 45 to 110 msec, using gravimetric method to evaluate the weight loss. Their results suggested that:

1- Devolatilization at higher heating rates appeared to be a two stages process, the first stage lasted for a period inversely proportional to the temperature(e.g. 75 msec. at 1370 K and 15 msec at 1920 K). Increasing the residence time to 110 msec. at 1370 K produced no further weight loss even though volatiles equivalent to about 20% of the original value was found during the proximate analysis of the

char. At higher temperatures the rate of the second stage increased until it was almost completed after 45 msec. at 2170 K. Extension of the residence time to 90 msec. produce only 1% further weight loss.

2- The amount of weight loss increased with increasing heating rate and the furnace temperature.

3- The ratio between the volatile yield at high temperature and that measured under standard conditions was greater than unity probably because during devolatilization at higher temperature some of the fixed carbon was carried out into the gas phase. Similar conclusion was also reached by Badzioch and Hawksley (1970), who further showed this ratio to be proportional to both the ambient temperature and heating rate.

Anthony et al (1975) studied the rapid devolatilization of lignite and bituminous coals by heating the coal particles electrically in a helium atmosphere. The devolatilization rate was measured by weighing samples before and after experiments of known durations. In contradiction to Badzioch and Hawksley (1970), they reported that for bituminous coal the weight loss increased mainly with increasing final temperature, while the heating rate had only a minor effect. This contradiction was explained on the basis that rapid heating rates were generally achieved by the use of small well dispersed particles, a condition which helped to diminish the effect of secondary reactions. Thus the associated conditions rather than the heating rate itself may be the reason for the higher volatile yield which was about 1.8 times that reported by Badzioch and Hawksley (1970) from proximate analysis. These results were further believed to include volatiles generated plus volatiles produced subsequently by prolonged heating of the char residues. Anthony et al (1975) further argued that the basis used above for reporting yields was required for inter- comparison between

different data sets since volatile content of the char residues is often not reported. This basis also provides a better indication of volatiles yield achievable in residence times of practical interest.

Suuberg (1977) studied the effect of particle thermal history on the product compositions and formation kinetics in rapid pyrolysis for lignite and bituminous coals in a helium atmosphere. The results also showed that the volatile yield increased monotonically with temperature. The evolution of different products or groups of products such as the tar and light hydrocarbon for bituminous coal and CO, CO₂, H₂O for lignite were found to occur over elevated overlapping temperature ranges. Four phases could be discerned in rapid devolatilization: (i) low temperature surface moisture removal; (ii) The evolution of the pyrolytical water (300-400 °C), (iii) a broad phase involving softening of the particles, accompanied by evolution of tar as a major product (400-900 °C); and (iv) evolution of CO and H₂ (above 900 °C). The evolution of pyrolytically formed water in bituminous coals proceeds at much lower temperature than it does in the pyrolysis of lignite, while the evolution of hydrogen was observed to occur at a slightly higher temperature than that in the pyrolysis of lignite.

Solomon and Colket (1978) showed also that the similarity of the organic structure of the tar to that of the parent coal. The similarity was evident in the elemental composition. The C, H, N, and O concentration in the tar were normalized by the concentration C^o, H^o, N^o, and O^o in the parent coal. C/C^o and N/N^o were close to 1.0, H/H^o was typical around 1.2 while O/O^o was lower than 1.0.

Kobayashi et al (1977) also studied devolatilization of lignite and bituminous coals at high temperature under rapid heating conditions in a laminar flow furnace. The volatile yield was determined by both difference in the weights of the feed coal and the collected char and by the use of ash as a tracer. He concluded that the volatile yields increased significantly with ambient temperature. The same conclusion was also reached by Seeker et al (1978), Solomon and Colket (1978).

Maloney and Jenkins (1984) studied devolatilization of two eastern bituminous coals under rapid heating condition ($\approx 10^4$ K/sec) in a helium and nitrogen entrained flow furnace over a range of thermal fluxes. They used the ash-tracer technique for the analysis of the data. The pyrolysis rates were found to be dominated by heat transfer characteristics of the entraining gases and the results suggested that chemical kinetics and certain mass transport mechanisms are intrinsically coupled with the thermal transport process. Coal particle temperatures therefore were a function of the heat flux and the instantaneous pyrolysis rate, with the rate being exponentially proportional to the temperature.

(ii) Ambient Conditions

Most of coal devolatilization studies reviewed above have been carried out under inert ambient conditions to avoid complexities in the interpretation of the weight loss data due to burn-out. There are other studies however which have been carried out in pulverized coal flames, under oxidation conditions and in combustion gases ambients.

Howard and Essenhigh (1967) studied the pyrolysis of coal particles

in flames. The study was carried out in a water cooled rectangular furnace where the composition of the char and flame temperature were measured along the furnace axis.

The results suggested that:

- 1- Ignition precedes rapid devolatilization and originates on the surfaces of solid particles instead of in the gaseous volatiles.
- 2- Pyrolysis and heterogeneous combustion occur simultaneously. Volatile matter thus represents the loss from the particles by both gas evolution and heterogeneous combustion; the former process accounting for about 3/4 of the total mass loss.
- 3- Pyrolysis is slow enough in the tail of the flame such that about 5 % of the original volatile matter leaves the combustion chamber in the unburnt residue.
- 4- Pyrolysis occurs as though volatile matter exists in coal as two different components, one evolving very rapidly and the other very slowly. The slowly evolving component appears to represent about 15% of the total volatile matter.

An experimental and analytical study of the rapid devolatilization of bituminous coal injected and entrained in hot gases with the temperature ranging between 1500 and 2000 K has been carried out by Ubhayakar et al (1977). They observed an increase in the volatile yields of up to 74% of the original dry ash.

Badzioch and Hawksley (1970) carried out experiments in a nitrogen atmosphere in the presence of some oxygen concentrations below those required to promote ignition of the volatiles. These were made alternately with measurements in nitrogen at each temperature and transit time. No difference was detected between the decomposition rate in nitrogen and in oxygen-nitrogen mixture. They also reported that to prevent ignition, the oxygen concentration employed had to be decrease from about 20% by volume at 550 °C to about 2% at

900 °C.

Jost et al (1984) studied coal oxidation in a flow tube reactor . The gas temperatures were varied between 1300 and 2000 K and the oxygen concentration between 7 and 16 %. They reported that at high temperature or high O₂ concentration, particle luminosity (ignition) was apparent in less than 5 msec, and 70 % carbon loss was measured prior to 30 msec of residence time. The observed rapid carbon conversion at early times was attributed primarily to oxidation of the volatiles. For a given gas temperature, devolatilization rate increased with increasing oxygen concentration. Energy from oxidizing volatiles appeared to be fed back to the coal particles, increasing their temperature and thereby volatile release rate and yield.

With respect to the ambient pressure, it seems that there are very few quantitative investigations of its effect on coal devolatilization. It is generally accepted that the volatile yield decreases with increasing the ambient pressure, see for example (Howard 1963; Anthony et al 1975; Howard 1981). Suuberg (1977), however, showed that the volatile yield decreases by 15% for bituminous coal, and 5 % for lignite when the pressure increases from 0.0001 to 69 atm. This was attributed to the large decrease in the tar yield and liquid hydrocarbons, Ko et al (1988).

(iii) The Particle Size

Howard and Essenhigh (1967) found devolatilization to be independent of the particle size for conventional pulverized coal flame (80% by

weight less than 74 μm). Badzioch and Hawksley (1970) also observed no significant effect of size on devolatilization (up to 60 μm .) and this is attributed to the fact that the heating rate of the particle was controlled mainly by the heat flux from the carrier gas, so that the coarser particles were heated only by slightly lower rates than for the finer particles. The same conclusion was early reported by Kimber and Gray (1967). Jost et al (1984) showed that, for bituminous coals finer particles devolatilized faster than the larger ones, while the particle size have a little effect on the product yield.

Seeker et al (1981) examined the physical, thermal, and chemical behaviour of coal particles during thermal decomposition for five coal types, and two particle sizes for one bituminous coal. Particles were injected axially into lean (35%) methane/air mixture flat flame with nominal peak temperature of 1750 °C. They classified their observations by three time scales: (i) particles heat to the gas temperature in less than 10 msec., (ii) devolatilization occurs between 10 and 75 msec., and (iii) the formation and growth of large soot particles for time exceeding 75 msec. They argued that for 80 μm particles a significant volatile fraction is ejected from the particle as a jet, which reacts close to the surface producing a trail of small solid particles. The local heat released during the reaction of the volatile, in combination with heterogeneous oxidation, increases the particle temperature and raises it above that of the bulk gas stream. At later times, growing soot structures were formed and were attributed to the agglomeration of small, homogeneously formed soot on the volatile trail structures. Small bituminous coal particles 40 μm were found to burn with a higher intensity (i.e more rapidly and producing higher temperatures) with few trails and do not produce soot structures, probably because of the more diffusive nature of the

devolatilization process.

Devolatilization Models

Several proposals have been made to model the volatile release for numerical prediction purposes. A complete pyrolysis model should be able to describe all stages of devolatilization, the composition and physical state of the coal dust as well as the composition and evolution rate of volatiles. The theoretical formulation must be sufficiently versatile to accommodate the coal type, particle size and the surrounding local condition. In case the solid phase reacts with volatile products, these secondary reactions and their rates should also be taken into consideration. Clearly the quest for a universal model formulation is a difficult, if not impossible, one. In the following review the available models are classified into two categories according to the number of reactions involved in devolatilization, namely;

- 1- Single reaction models.
- 2- Multiple reaction models.

Some of these models are summarized below on basis of their simplicity and wide popularity. .

1- Single Reaction Models;

(i) Constant Evaporation Rate Model;

This is probably the simplest devolatilization model, and was proposed by Baum and Street (1971). It assumes that the evolution of volatiles does not take place below temperatures of 600 K and the rate of devolatilization is

determined by the total heat of evaporation of the volatiles and the heat available from the environment such that ;

$$\text{Coal } \underline{\text{heat}} \text{ Volatile+ Char}$$

A maximum rate of evolution is permitted, while the surplus heat, over and above this maximum is consumed in raising the temperature of the particles. Mathematically, these conditions are expressed as;

$$d x_v / d t = 0 \qquad T_p < T_g \quad \text{or} \quad x_v = 1.0 \qquad 1.1$$

$$d x_v / d t = (H_p / H_v, B) \qquad T_p > T_g \quad \text{and} \quad x_v < 1.0 \qquad 1.2$$

Where x_v , t , T_p , T_g , H_p , H_v , B are the fraction of total volatile not yet evolved, time, the particle temperature K, the environment temperature K, rate of change of the particle heat $\text{J kg}^{-1} \text{ sec}^{-1}$, the total heat of volatiles evaporation per unit mass of coal J / kg , and the maximum rate of volatile evolution, Sec^{-1} respectively.

The value of B is to determine by trial and error by matching the predicted and experimental results. Baum and Street suggested a value of B as high as 10 Sec^{-1} while Lockwood et al (1984) reported an improved accuracy for B of 30 Sec^{-1} .

(ii) Single Reaction Model.

Badzioch and Hawksley (1970) assumed devolatilization to be a

first order reaction process, with the reaction rate being proportional to the amount of volatile matter yet to be released: i.e.,

$$dV/dt = K(V^* - V) \quad 1.3$$

Where

$$K = A_0 \exp(-E/RT) \quad 1.4$$

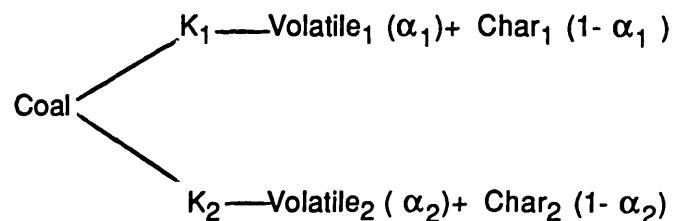
and V^* , V , A_0 , E , R , T are the mass of volatiles per unit mass of original coal evolved at time t , the value of V at $t = \alpha$ (i.e. the value of the yield of volatiles determined experimentally), the apparent frequency factor, the activation energy, the gas constant, the absolute temperature of the particle respectively.

One of the most serious shortcomings of this model is its inability to predict dependence of volatile yield V^* on the final temperature Rizvi (1985).

2- Multiple Reaction Models;

(i) Two Competing-Reaction Model.

Kobayashi et. al.(1977) suggested that pyrolysis could be modeled with two parallel, first-order, irreversible reactions:



Where K_1 and K_2 are the pseudo rate constants given by;

$$K_1 = A_1 \exp (-E_1 / R T) \quad 1.5$$

$$K_2 = A_2 \exp (-E_2 / R T) \quad 1.6$$

and A , α , E are the frequency factor, mass stoichiometric coefficient, and activation energy respectively.

The first reaction is assumed to be dominating at relatively low temperatures producing the volatile yield, (α_1) , while at higher temperatures the second reaction is more effective and produces the volatile yield (α_2) . The first reaction has a lower activation energy than the second reaction accounting for the faster and higher yield in the latter.

The overall particles weight loss equivalent to the volatile yield given by;

$$W = \int_0^t (\alpha_1 K_1 + \alpha_2 K_2) \exp \left(-\int_0^t (K_1 + K_2) dt \right) dt \quad 1.7$$

This model enjoys wide popularity and satisfactorily correlates the data of Kimber and Gray (1967), Badzioch and Hawksley (1970), Kobayashi et al (1977) and Jamaluddin et al (1986).

(ii) Multiple-Parallel Reaction Model

Anthony and Howard (1976), assumed that the overall thermal

decomposition of coal molecule may be described by a large number of independent chemical reactions. Differences in the strength of chemical bonds through out the molecule will cause marked difference in temperature at which various bonds rupture. Since the thermal decomposition of single organic species is typically described as a simple first order irreversible reaction, the rate of contribution to devolatilization by a particular reaction, within the coal structure is given the simple form;

$$d V_i / d t = K_i (V_i^* - V_i) \quad 1.8$$

Where

$$K_i = A_o \exp (-E_i / R T) \quad 1.9$$

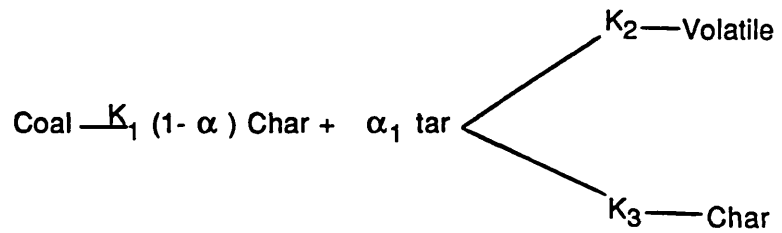
$$\text{and} \quad V_i^* - V_i = V_i^* \exp (- \int_0^t A_o \exp(-E_i / R T) d t) \quad 1.10$$

The values of A_o , E_i , V_i^* cannot be predicted a priori, and must be tuned in accordance with the experimental results.

The merit of the model lies in the fact that it needs only one more adjustable parameter than the single reaction model Jamaluddin et al (1986).

(iii) *Consecutive-Competing- reaction Model*

This model proposed by Wen and Dutta (1979) . It consist of three parts representing devolatilization, cracking, and decomposition. The devolatilization products are tar, gases, and char. The tar fraction further decomposes to form volatile matter and additional char.



Many other complex and detailed models to describe the devolatilization process have been proposed see for example (Nsakala et al 1977; Suuberg et al 1978; Solomon and co-workers 1979, 1980, 1982; Gavalas 1983; Howard 1981 and Niksa 1988).

1-4-2 Char Combustion

The char remaining after devolatilization consists of carbon, and ash together with some remaining volatile matter. heterogeneous gas-solid reactions involving a single char particle are governed by on intricate coupling of transport phenomena and chemical kinetics. The overall reaction scheme usually involves Rizvi (1985):

- (i) Diffusion of mass (reactant and product gases) and heat across the boundary layer surrounding the particle.
- (ii) Diffusion of mass and heat through the porous structure of the particle.
- (iii) Reaction of gases with external and internal solid surfaces exposed by particle.

The combustion of char may be viewed as a combination of three steps Jamaluddin (1985):

- (i) Transport of oxidant from the ambient gases to the particle surface across the

"stagnant" boundary layer.

(ii) Chemical reaction on the surface of the particle involving chemisorption of oxidant onto the active sites of the particle surface, and desorption of the product gases from the surface.

(iii) Diffusion of the reaction products away from the surface.

Large number of chemical reactions with oxygen, carbon dioxide and water vapour may take place Bradley et al (1984) on the particle surface and in the surrounding boundary layer. Since char particles are porous, it is possible for reactant to diffuse into the particle and to react on internal surface Rizvi (1985). Young and Niksa (1988) suggested that carbon conversion to CO₂ at the char surface arise from the catalytic impurities in the char. Mitchell (1988) concluded that for particle temperatures in the range 1600 to 1700 K, as much as 15% of the carbon content of the particle could be converted to CO₂ at the particle surface. At 1800 K, heterogeneously formed CO₂ was negligible.

The overall rate of char combustion is controlled by two rate-limiting processes Field (1969); namely the chemical kinetic rate (R_c) of oxidizer and the diffusion rate (R_d) from the ambient to the particle surface. These may be expressed respectively by Walker et al (1959). Mathematically, these rates are;

$$R_c = K_c (P_{O_2})^n \quad 1-11$$

$$R_d = K_d ((P_{O_2})_\alpha - (P_{O_2})_o) \quad 1-12$$

where K_c is chemical reaction rate coefficient of order (n), given by;

$$K_c = A \exp (-E / RT)^n \quad 1-13$$

and, A and E are the frequency factor and apparent activation energy respectively while $(P_{O_2})_o$ and $(P_{O_2})_\alpha$ are the partial pressure of oxygen at the particle surface and in the ambient gas respectively, K_d the diffusion reaction rate coefficient is given by Field et al (1967);

$$K_d = (D_c)(M_c)(\phi) / ((R_d / 2)(T_p + T_g) / 2) \quad 1-14$$

where D_c is the diffusion coefficient and is given by;

$$D_c = (D_o)(P_o / P)(T_g / T_o)^{1.75} \quad 1-15$$

where P_o and T_o are the reference temperature and pressure. D_o is the binary diffusion coefficient (m^2/sec) for O_2-N_2 mixture, M_c is the atomic weight of carbon, and ϕ the mechanism factor whose value is 2 if CO is main product and 1 if CO_2 is main product, being driven away from the particle boundary layer. T_p and T_g are the particle and gas temperatures respectively.

Field (1969 & 1970) studied the combustion kinetics for various size graded char particles (28 to 105 μm) in a range of temperatures between 1200 and 1700 K, and for oxygen concentration levels of 5 and 10%. The major

findings of this study showed that the char particles are attacked by the reactant both externally and internally. The combustion rate was found to be directly proportional to the oxygen partial pressure (P_{O_2}) while the primary combustion product was CO. Moreover at the highest temperature, the combustion rate of coarser particle reaches the theoretical maximum, given by equation (1.1).

Smith (1978) provided a useful comparison between the intrinsic (chemical) reactivity coefficient of 32 porous and 17 non porous types of carbon in temperatures ranging between 580-2200 K. A regression analysis of the reactivity data produced the following correlation;

$$K_c = 3050 \exp (-179.4 / (RT)) \quad 1-16$$

The differences in reactivity that still remained between different carbon types, were attributed to the differences in atomic structure, the carbon contents, and to the different levels of catalytic inhibiting impurities in the solid and gaseous reactants.

Some studies on char combustion (Lester et al 1981; Young and Smith 1981; Mitchel and McLean 1982; Mitchel 1987 and Patel et 1988) indicate that the apparent reaction order, n , is close to 0.5 rather than 1.0 as earlier observed by Field et al (1967) and Baum and Street(1971). Moreover, Young and Smith (1981) argued that the reaction order was a complex function of temperature, carbon type, and oxygen partial pressure. This agrees with the observations made by Essenhigh et al (1965), Gray et al (1974) and Essenhigh (1977), who suggested that the reaction order rises from zero at about 1000 K to

unity at about 2000 K. Young and Smith (1981) also re-analysed the data of Field (1969) in the light of their new finding regarding the reaction order, taking the apparent reaction order as 0.5. This resulted in no significant difference in the goodness of fit to the original experimental.

Based on high temperature (1300- 2000 K) char combustion study using a drop tube furnace, Wells et al (1984) found the reaction order to be near unity. Also Lockwood et al (1984) suggested that for modeling purposes, the assumption of a unity reaction order is as good as any other in the range from 0 .0 to 1.0; an assumption which was conformed in the results they obtained.

Essenhig(1981) argued that the Chemical rate coefficient , K_c , is a complex function of the particle temperature, oxygen concentration, particle size, particle heating rate, devolatilization environment and char properties such as char porosity, the structure pores and the chemical structure of the coal .

As far as the diffusion rate of reaction is concerned, a distinction should be made between the bulk diffusion of oxygen to the particle surface and the pore diffusion, which is usually coupled with intrinsic char reactivity to give the overall chemical reaction rate.

Field et al (1967) and Gray et al (1974) recommended the use of an overall rate coefficient, K_t , which is a combination of the chemical kinetic rate coefficient, K_c , and the diffusion rate coefficient , K_d , such that;

$$K_t = 1 / ((1 / K_c) + (1 / K_d))$$

It may be noted that when one of the terms is much smaller than the other, the overall reaction is dominated by that term. The char burning rate could thus be written as Field et (1967);

$$dm_p / dt = -K_t \pi d^2 P (F_{O_2})_\alpha \quad 1-18$$

where P is the ambient gas pressure and $(F_{O_2})_\alpha$ is the molar fraction of oxygen in the combustion gases.

Walker et al (1959) and Hampartsoumian et al (1988) have postulated the existence of the three main different temperature dependent regimes, which determine the overall reaction rate.

Regime I: At low temperature chemical reactions are sufficiently slow so that there is no restriction on the transport of oxidant to the particle, or through its porous structure. The concentration of the oxidant inside the pores remains about the same as that in the ambient, and any reaction that may take place involves the entire internal surface area of the particle. The diameter of the particle, therefore, remains unaltered while its density gradually decreases.

Regime II: As the temperature increases, the chemical reactions become sufficiently rapid for the diffusion of oxygen through the pores to exert a notable rate- limiting effect, so that the oxygen concentration is reduced to zero before, or at the centre of, the particle. During combustion both the density and particle size

reduce due to the burn off. Oxygen concentration gradients thus exist within the pores and across the particle boundary layer.

regime III: Further increase in temperature eventually causes chemical reaction to become so fast that all the oxygen is consumed as soon as it reaches the outer surface of the particle. In this regime the rate of reaction is controlled by diffusion of oxidants from the ambient to the particle, and chemical reactivity of the particle has no effect on the burning rate.

Laurendeau (1978) argued that the overall char reactivity is dependent mainly on the: chemical or (intrinsic) reactivity, oxygen, and hydrogen contents, presence of inorganic impurities and the porosity of the particle.

Chemical reactions are favoured at the reactive sites which have surface faults and irregularities. In a char particle, such surface faults, impurities and the presence of oxygen or hydrogen functional groups provide the active sites Walker et al (1959). While the active sites are necessary for oxygen to react with carbon, Blackwood and McTaggart (1959) and Rosner and Allendorf (1965 & 1968) observed that free radicals like O, H and OH react with any carbon site. The purpose of active sites, therefore may be seen as to dissociate molecular reactants. This conforms to dissociative chemisorption of carbon dioxide and oxygen evidenced by Mentzer and Ergun (1973).

Convincing evidence of catalytic effect of mineral matter on the combustion rate was obtained by Walker et al (1975), who de-ashed char using HCl and HF solutions, and found that the de-ashed char particles had similar reactivities despite the wide variation in coal ranks. The higher reactivity

observed in smaller particles Field et al (1967) was attributed to their higher mineral matter content. The effect of mineral matter, was further found to reduce at high temperatures.

A detailed analysis of the diffusion and reaction within porous char was presented by Mulcahy and Smith (1969) who suggested that for small pulverized bituminous char particles of 40 μm mean diameter, combustion predominantly occurred within the pores, so that discussion of the kinetics must be based on penetration, complete or partial, of the particle by oxidant. They pointed out that for particles larger than 100 μm the combustion would be mass-transfer controlled in temperatures ranging from 1200 to 2300 K. It was emphasised, however, that the rate of combustion becomes increasingly dependent on the chemical kinetic reaction rate as the particle diameter is decreased below 100 μm .

The severity of devolatilization is another factor affecting the char reactivity. Radovic et al (1983) reported that significant de-activation of char may be caused by devolatilization at high heating rates and high temperatures. Similar de- composition at high temperatures was also observed by Sy and Calo (1983). This however, is contrary to the belief Jamaluddin (1985) that chars produced by rapid devolatilization are more reactive on account of their higher porosities.

The heating rate was also found to contribute to the char reactivity. Ashu et al (1978) observed an increase in the reactivity of lignite char when the parent coal was devolatilized at 8000 K/sec, compared to the reactivity at a heating rate of 10 K/sec. At heating rate of 10^6 K/sec Farzan and Essenhigh (1982) observed an order of magnitude increase in the reactivity as compared to

that at a heating rate of 10^4 K/sec.

1-5 Inflammation Measurements

It may be concluded from the previous section above that most devolatilization and char combustion investigations have been carried out under controlled laboratory conditions. Although such investigations help to understand the mechanism of devolatilization and char combustion, they do not fully represent the actual operating conditions prevailing in pulverized coal flames. Pulverized coal combustion in furnaces involves many complex aerodynamic and physicochemical phenomena. These include, to name but a few, heat transfer, turbulent fluid motion, coal devolatilization, volatile oxidizer reaction, char reaction, particle dispersion, slag and ash formation. Which of these processes occur, and more importantly, which dominate the coal reaction processes differ depending on the type of flame, combustor, and operating condition Smoot and Smith (1985).

The present study is mainly concerned with pulverized coal diffusion flames in which the fuel and oxidizer, not completely premixed, are delivered to the reactor vessel. The common practice in these flames is that coal is pneumatically conveyed with a small air fraction (primary air) into the furnace through one or several ducts. The larger percentage of the total air (secondary air), which usually is preheated, enters through different ducts placed close to the primary inlet(s). In order for the coal to burn efficiently, the coal/air "primary" stream and the heated "secondary" stream must mix efficiently. Accordingly the turbulent mixing processes together with gas kinetics, particle kinetics, and heat

transfer, that occur in such flames have a major impact on the efficiency of coal combustion.

Most of the experimental investigations of the characteristic of pulverized coal combustion on industrial scale combustors emanate from the International Flame Research Foundation (IFRF). The studies reviewed below are divided into two categories in relation to their effect on combustion efficiency;

- (i) Furnace aerodynamic
- (ii) Coal characteristics

1-5-1 Aerodynamic Studies

Hubbard (1960) described a performance trial in which the effect of primary and secondary air, coal fineness and thermal load were studied. This investigation was conducted at IFRF on a horizontal furnace 1.5 x 1.5 m. cross section and 10 m. long. He showed that when volatiles were evolved, it is possible that cracking and soot formation occur if there is insufficient air available. After the evolution of the volatiles the char is surrounded by a cloud of volatile matter. This cloud burns and fresh supplies of oxygen diffuse through it and through the products of combustion before the combustion of the char can begin. The results also indicated that 95% of the volatile have evolved in 50 msec. and 90% burn-out of the char took place in about 350 msec. Hubbard (1960) further reported that when the primary air quantity was high the volatiles burnt as soon as they evolve and combustion of the char began sooner. He concluded that the combustion rate-controlling processes was the physical mixing of air and fuel.

Beer (1962) studied the effect of mixing in a model furnace where

measurements of gas concentration and velocity distributions were performed for the primary, secondary and recirculating fluids. The results showed that buoyancy in the furnace affects the mixing pattern near the burner region. Beer (1964) also reported that the heat transfer was mainly influenced by recirculation of the hot products.

Michel and Payne (1980) reported detailed measurements in long pulverized flames for the characterization of pollutant formation. The data were obtained in a refractory tunnel furnace 2x2 m. cross section and 6.25 m. long with a double concentric parallel flow burner system. Several long flames were studied for various air and fuel input velocities, and temperatures. The measurements included the determination of local gas/solid concentration and composition, temperature and radiative heat transfer and aerodynamics. Their results indicated that in agreement with earlier conclusion of Hubbard (1960) mixing is the rate-determining mechanism for the overall combustion process.

Thurgood et al (1980) investigated the extent of gas mixing in a laboratory scale combustor. The effect of secondary air velocity, injection angle and coal particle size were studied by measuring the mixture of gaseous species, particle flux and char burn-out. They concluded that the combustor could be divided into an early mixing region where gas mixing took place and subsequent reaction regions where particle combustion occurred. The aft-regions of the combustor exhibited some premixed like flame characteristics. Moreover gas mixing rates were found to be significantly enhanced by increasing the secondary air velocity, while changes in particle size and injection angle had a little influence on the mixing rate.

Rees et al (1981) used the same combustor and investigated the effect of stoichiometric ratio on nitric oxide formation. The results showed that the nitric oxide showed a marked increase as the stoichiometric ratio increased. Nitric oxide formation was associated primarily with near ignition zone and occurred rapidly presumably during devolatilization. A similar conclusion was also reported by Chen et al (1981).

Harding et al (1982) extended the investigation of Thurgood et al (1981) and Rees (1981) to study the effect of swirl, primary velocity and the coal feed rate, coal size and secondary air temperature on pollution formation. It was observed that the nitric oxide decreases as primary air decreased. This is probably due to an increase in the mixing of fuel and oxidizer and the enhanced oxidation of HCN and NH_3 . The rate of gas mixing with swirl appeared to be comparable to that determined in the absence of swirling secondary flow. The data also showed that particle dispersion is a slower process than gas mixing in these swirling flames. Finally, the use of swirling secondary flows changed the mixing patterns and caused the onset of combustion of coal dust at the air duct inlet. Asay et al (1983) showed that a change of swirl intensity caused dramatic changes in the flow structure of the flame caused marked change in NO_x concentration.

Hazanov et al (1985) investigated the possibility of achieving higher combustion efficiency under conditions of stable burning in an opposed flow combustor. For this purpose measurements of temperature, pressure, gas concentration and velocity were carried out. Particle size distribution, ash, and volatile matter content were also measured at the impingement point in order to determine locally the extent of the devolatilization and reaction zones. The

measurements again showed that an improved mixing of fuel and air was required for better ability to control combustion.

Hirji et al (1989) studied the effect of swirl number, air fuel ratio and momentum ratio on nitric oxides formation. The study showed that the emission increased with the increase of air/fuel ratio. For a given value of air/fuel ratio and momentum ratio, R_m , there existed an optimum value of swirl number at which the NO_x emission was a minimum. Furthermore NO_x emission was found to decrease rapidly in the range $0.12 < R_m < 0.16$ but was insensitive to higher values of R_m up to 0.28.

Measurements in the present furnace, details of which are given in chapter 2 were performed by Hassan et al (1985) and Godoy et al(1988). Hassan et al (1985) measured temperature, gas concentration and char burn out for Grimethope bituminous coal and the data obtained were mainly used for the validation of a computer prediction code. Godoy et al (1988) studied the effect of two excess air levels and swirl numbers on the concentration measurements and temperature. The results suggested that increasing the swirl and excess air produced a rapid evolution of volatile due to an improvement of air fuel mixing.

1.4.2 Coal Characteristics Studies

Hubbard (1960) reported that smaller particles release their volatiles more quickly and, if there is sufficient oxygen available, the combustion and temperature rise of char would be faster. The effect of volatile and ash contents on the combustion performance was studied by Loison and Kissel (1962).

The investigation showed that with higher volatile content the ignition distance was considerably shorter than that for low volatile content coal. This was attributed to the much slower combustion rate of char in the latter due to the higher proportion of solid matter.

Beer (1964) observed that the flame front moved nearer to the burner and the flame length shortened when coal with greater fineness was burnt. The mechanism of solid particle combustion with simultaneous gas-phase volatile combustion was investigated by Howard and Essenhigh (1971). The experimental measurements included collection of samples of solid and gaseous material along the axis of propagation of the flame. Measurements of flame temperature were also performed to provide information on the ignition, pyrolysis and combustion of the coal particles. They observed that ignition occurring at temperature of about 1100 °C precedes significant volatile evolution. This rapid volatile evolution appeared to influence the combustion process by decreasing both the partial pressure of oxygen at the solid surface and flux of oxygen available for heterogeneous reaction.

Thurgood et al (1980) reported that the percentage of particle burn out was greater for smaller particle-size coal dust, which may be due to the increase in the residence time for such particles. Gas mixing was further found to be nearly complete before coal reaction started. This occurrence resulted principally from the relatively slow particle heat up in this combustor in the absence of swirling motion.

Nitric oxides formation was studied by Chen et al (1982) with respect to coal type. They concluded that the coal rank and nitrogen content were

more significant than the origin of the coals and that control of nitrogen oxides can be achieved through control of the pulverized coal combustion as well as the mixing process as mentioned earlier.

Farzan and Essenhigh (1982) investigated higher intensity combustion and reported that the volatile release in early stage of combustion was about 1.8 times higher than that obtained from standard proximate analysis. Near exit measurements of NO, NCH, NH₃ and coal burn out were performed by Asay et al (1983) to study the effect of coal moisture on NO_x formation. They used the same combustor used by Thurgood et al (1980). Combustion characteristics of undried (25 % moisture) and dried (4 % moisture) subbituminous coal were investigated and the measurements revealed that substantial decrease in coal moisture caused a little change in NO_x level and the burn out values.

Wall et al (1985) Investigated burn-out in a 2.5 MW pulverized coal furnace fitted with a swirl burner. They reported that the properties affecting coal particles burn-out are: (i) high volatility which had a primary influence in determining flame temperature and (ii) char reactivity.

1-6 Flame Stability

A stable flame is defined as that which initiates at or very near to the burner exit. The relative lack of stability of the pulverized coal flames, and the consequent possibility of the flame failure or blow-off, is due mainly to two factors. Firstly high axial momentum of the incoming coal particles which can

result in their fast penetration of the near burner zone. Secondly, a significant heat addition is required to release the volatile matter of the particles (assuming the coal has a useful volatile content) and the release may not occur soon enough for the disengaged gases to enter the near burner region. Given sufficient incident radiation from the hot refractory walls the coal particles may ignite farther downstream to give a lifted flame. A flame of this type would however be regarded as dangerously unstable in combustors with little or no refractory lining such as that of the modern front wall fired combustors.

For good flame stability the aerodynamics of near-burner field should be such that the particle residence times, heating rate, and the availability of oxygen be maximised within the primary reaction zone. This is usually achieved by creating a strong recirculation zone near the burner which carries the hot combustion products back towards the burner exit to establish a temperature high enough to ignite the coal volatiles and a reasonable proportion of the char. This recirculation zone, usually referred to as the inner recirculation zone (IRZ) can be created by means of either imparting swirling motion to the incoming air or immersing a bluff body in the air to create wake eddies in the near-burner region. From a recent visual observation of various industrial flames, Schimed et al (1987) classified five main types of flames. These flame types, shown in Fig. (1.1), broadly illustrate whether an (IRZ) is present or not. The present study is mainly concerned with swirl generator burners. In the following, previous investigation of the different parameters affecting the stability of pulverized coal flames are reviewed with special reference to this type of burners.

Beer and Chigier (1969) studied the effect of swirl and impingement of flames in a tunnel furnace 10m long and 2 x 2m cross-section.

This investigation showed that application of swirl to secondary air caused a pronounced improvement in the stability of the flame and led to a reduction in the distance between burner and flame front. This was attributed to the creation of a toroidal vortex type recirculation zone in the central region of the swirling jet close to the burner exit. This zone constituted a well mixed zone of hot combustion products acting as a storage of heat and chemically active species. Heat and mass are then transported effectively from combustion product to fresh particles by the high levels of turbulence intensity prevailing in the vortex region. They further showed that application of the swirl to the primary air had a comparatively little effect on the flame stability. Moreover, fitting a divergent extension to the burner was found to increase both the size, and strength of the central recirculating vortex and improve the stability of the flame.

In an investigation of the process of coal dust flame stabilization by means of bluff-bodies Wolanski and Wojcicki (1974) observed that the evolution of volatiles from the coal dust particles and ignition by hot combustion gases filling the recirculation zone were essential for the mechanism of flame stabilization. The emission of volatiles from coal particles already takes place during the mixing with hot combustion gases from the recirculation zone. They further showed that the size of the bluff body, fuel and oxidizer concentration, and their initial temperatures were also important in the devolatilization process, as explained earlier (see section 1.4), and so to flame stability.

Wroblewska et al (1976) correlated, in isothermal flow, the mass of recirculating flow with the swirl number and the ratio of axial momentum of the primary air to that of the secondary air. They used the isothermal mixing data to predict the performance of a full scale coal burner and observed an optimum value

of the recirculating mass flow, depending on the coal type and the operating conditions for flame stability of low calorific value coals.

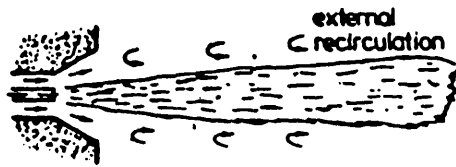
Godoy et al (1986) examined the effect of operating conditions and coal particle size on the stability limits of an industrial pulverized coal combustor. They reported that at lower feeding rate stability could be maintained at higher values of momentum ratio, due probably to the longer residence time in the near-burner zone resulting from the lower inlet velocities as compared with those of the higher feeding rates. Increasing the amount of excess air enhanced stability by causing more air to be available for early combustion in the fuel-rich recirculation zone. The fineness of the particles was found to enhance stability limits and this was attributed to the fact that the finer particles follow the gas flow more readily. This in turn led to a longer residence time and faster and higher rate of volatiles release in the near-burner region. For finer particles, heterogeneous ignition is also possible in the recirculation zone, and their ignition time is of course shorter compared with that of the coarser particles. The effect of coal type was found to depend mainly, and as expected, on the amount of volatile matter and ash content. The results further showed that flame stability was enhanced when the diameter of the primary air tube was increased, presumably because of the lower inlet velocities and accordingly the longer residence time near the burner.

Lockwood (1985) reported combustion trials on two different coke samples with very low volatile content. He concluded that in order to achieve stable flame and good burn-out, high swirl numbers, low fuel pipe velocities, and refractory surface adjacent to the quarl were necessary. He also concluded that solid fuels of low volatile content would be difficult to stabilized and that grinding

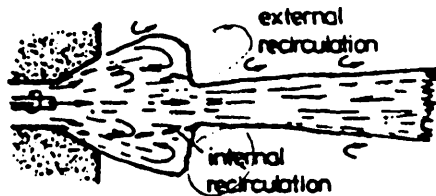
to very fine sizes could overcome this difficulty and promote flame stability. The results however clearly indicated that this kind of coal had in general a poor flame stability performance.

In a study of the effect of feeding rates and operating conditions on stability limits Godoy et al (1986) classified their flames, according to an earlier classification by Bortz(1985), into either "type II" or "type III" . The type "II" flames, which are characterized by a strong near burner IRZ occurred for high swirl combined with low momentum ratios. In flame type "III" the IRZ is suppressed by low swirl and high momentum ratios and the transition from type "II" to type "III" as function of momentum ratios and swirl numbers was found to be gradual rather than sudden. They concluded that flame lift-off occurred when the ratio of the primary to secondary air momenta exceeded an upper limit and when the burner swirl fell below a certain lower limit. The upper limit of the momentum ratio was found to increase dramatically with high feed rates, whereas at low feed rates the heat loss from the near burner zone to the surroundings was relatively greater and adversely affected the flame stability.

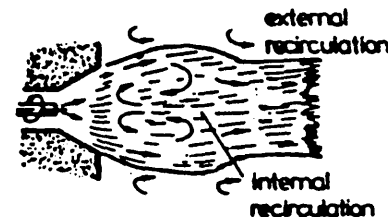
Hirji (1986) also reported that the micro fine coals exhibited superior stability performance at low loads, while the performance of the char coke was found to be inferior at all loads due to its very low volatile content. In agreement with previous investigation he concluded that the single most important factor influencing burner flame stability was the particle residence time in the inner recirculation zone.



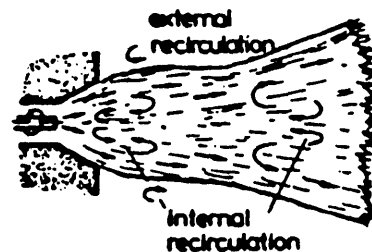
Type 0: long jet flames stabilised on the fuel injector or downstream, produced with no secondary air swirl and axial fuel injection, used typically in corner fired boilers.



Type 1: a combination of a long jet flame (Type 0) and a quarl stabilised, closed IRZ, flame (Type 2) where the fuel jet penetrates through the IRZ, used occasionally as a low NOx emitter.



Type 2: short intense flames stabilised on the quarl with closed IRZ, produced with relatively high secondary air swirl, used in wall fire boilers and many industrial process heaters.



Type 3: longer, but still intense, flames stabilised on the quarl with a second IRZ downstream, produced with very high secondary air swirl and a high furnace confinement, not frequently identified in industrial situations.

Fig. (1.1): Schematic of Various Industrial Flame Types

(after Schmid et al 1987).

Chapter 2

THE TEST FURNACE AND ANCILLARIES

2.1 Introduction

The design of pulverized coal combustors requires that various phenomena occurring during combustion be taken into consideration in order to provide the necessary data and information related to various processes such as gas and particles mixing, devolatilization, char combustion etc. Such information may further establish the data base for the development of computer-based mathematical models.

The test furnace used in the present investigation is large enough to emulate the combustion behaviour in industrial applications. The design of the burner is typical of those used in power stations for wall-fired boilers. Its main practical advantage however is that reliable inflame measurements are possible, a daunting task if they are to be conducted in large boilers.

The present chapter describes the details of the furnace and its ancillary equipments. In section (2.2) details of the furnace structure, burner, air supply and exhaust systems are given. Section (2.3) deals with the coal feed theory, feed system and coal conveying line. Finally the ignition system, safety features and precautions are presented in section (2.4).

2-2 The Furnace and Ancillary Equipment

2-2-1 The Furnace

The furnace is cylindrical, vertically-oriented, to minimize the asymmetric effects due to particle setting and natural convection, and fired from its top to facilitate particulate and ash removal. A diagram of the furnace and its auxiliary equipments is shown in Fig. (2.1), while the principal dimension and design details are illustrated in Fig. (2.2).

The furnace has a uniform inside diameter of 0.6 m and consists of ten water-cooled, 0.3 m long, segments. As it is presently arranged, the upper five segments, Fig. (2.3), and the roof, Fig. (2.4), are water-cooled and lined with bricks of high quality castable refractory cement. These bricks can stand a maximum operating temperature of 1700 °C and their function is to stabilize the flame. Platinum/Platinum-10% Rhodium thermocouples are installed along the walls of the first three segments of the furnace, to measure the wall temperatures. To reduce conduction error, the thermocouples beads with 2 cm. length of wire are buried approximately 0.2 cm. deep in the walls. The wall temperatures are displayed on a digital voltmeter (type advance DPM 300 series) and are used to determine the steady state operating condition when data collection could begin.

The bottom five segments are only water-cooled, Fig. (2.5). High temperature gaskets interface the ten segments and completely eliminate all leakage of gas/air from/to the furnace. Observation of the flame and probe access are facilitated by pairs of a diametrically located ports in the first nine segments

while the tenth segment is fitted on one side with an explosion vent.

The cooling water is distributed to individual segments at a constant rate through a high pressure cylindrical water distributor, Fig. (2.1). The total flow rate is metred, prior to the distributors, by a calibrated rotameter. The flow of the cooling water input to individual segments, is measured by separate rotameters, while its temperature is recorded by an electronic Nickel-Chromium/ Nickel-Aluminum thermometer (Comark Electronics Ltd Sussex England) at the exit of each segment.

2-2-2 Primary Air System

Compressed air at 7.5 bar is used as the primary air supplied by a dedicated 7.5 kw air compressor (Model Hydrovan 43, Hydrovan Ltd. Redditch, Worces, England) through a copper tube 26 mm. inner diameter. The flow rate is measured by a rotameter calibrated for various pressures and temperatures. The copper tube is heated electrically by two heating tapes, 850 Watts each (type GW Hotfoil Ltd.) controlled by a variac transformer. To minimize the heat loss to the atmosphere, the tube is insulated by a non-combustible rock fiber material. The primary air could be heated up to 100 °C and its temperature is monitored by a Nickel-Chromium/ Nickel-Aluminum thermocouple placed just before the burner gun. All the primary line is electrically earthed to eliminate the risk of the built-up of electro-static charges within the line which could cause particle accumulation and hence irregular coal feed rates.

2-2-3 Secondary Air System

The secondary air is supplied by a 7.5 kw forced draught fan (type MC. Addays, Peacock Co. Ltd.) as shown in Fig. (2.1). The air flow is measured by an orifice plate on the inlet side of the fan. To improve the symmetry of the secondary flow as it enters the furnace a manifold of square cross-section surrounds the burner and the air is admitted at four equally spaced radial locations from the manifold to the burner ports as shown in Fig. (2.6).

A 21 kw electric heater (Eltron london Ltd.), controlled by a variac transformer, is used to preheat the secondary air whose temperature is measured by four Nickel-Chromium/Nickel-Aluminum thermocouples located at the four inlet ports of the burner as shown in Fig. (2.6). The secondary air duct from the exit of the heater up to the quarl is completely insulated by rocksil insulating materials.

2-2-4 The Burner

The coal/ primary air stream is injected into the furnace through a concentric burner gun made of straight stainless steel pipe of 22.2 mm. inner diameter and 35 mm. outer diameter Fig (2.6). An IFRF swirl generator provides swirling motion to the secondary air in the range of swirl numbers of $S_s = 0.0$ to $S_s = 1.45$.

Where the swirl number S_s is defined by:

$$S_s = G_\phi / G_x R_e \quad 2.1$$

where: G_ϕ is the axial flux of the angular momentum, G_x is the axial flux of the axial momentum and R_e is the exit radius of the burner nozzle.

The design of the swirl generator possesses the following advantages:

- 1- The facility to change swirl intensity during furnace operation.
- 2- The air pressure required to achieve a given level of swirl is relatively modest.
- 3- High swirl numbers are attainable.

The swirl generators was calibrated with the aid of the honey-comb device shown in Fig. (2.7). The Calibration curve is shown in Fig. (2.8) and is valid irrespective of the secondary air temperature Hassan (1983). The swirl generator is followed by an interchangeable cylindrical duct which leads the combustion air into the burner quarl. In the present study two geometrically similar quarls are used, a cement refractory quarl and a water-cooled quarl, to study the effect of cooling on the flame stability and char burn-out as further discussed in section (2.2).

2-2-5 The Exhaust system

An exhaust system is incorporated to deal with the flue gases and fly ash particles produced by coal combustion. The exhaust system consists, as shown

in Fig. (2.9), of a nozzle scrubber with an accompanying exhaust pipe line, cyclone separator and induced draught fan. The scrubber unit is water cooled. At the throat water spray sheets are injected through four nozzles situated at right angles to trap and decelerate the particles, and also to reduce the exhaust gases temperature. The finer ash particles retained by the exhaust gases and escaped the nozzle scrubber is trapped in the cyclone separator. These particles are collected in a tank placed under the cyclone separator, and removed manually. The exhaust gases are discharged through the induced fan to the laboratory extraction system.

2-3 The Coal Feed System

Accurate control of the coal feed rate is essential in order to enhance combustion efficiency and regulate pollutant levels Smoot (1981) as well as for obtaining reliable data . Considerable technical difficulties are usually encountered in trying to control the flow rate of fine coal powders due to the variation in their local density, moisture content and particle size. There are two main coal feed system types: (1) volumetric feed system and (2) gravimetric feed system. The latter is widely popular in industry and preferred to the former because it accounts for local density variation and the possible subsequent fluctuations in the feed rate. The gravimetric feed system employed in the present design, and shown schematically in Fig. (2.10), is based on the so called "Loss-in weight " principle.

The loss-in weight technique relies on the recognition of the fact

that the weight of the powder in a hopper is proportional to its mass. Thus keeping the weight loss rate constant results in a constant mass flow rate. The rate of weight loss can be determined by measuring the change in weight of the hopper contents over a specific time interval and control over this can be achieved by varying the speed of the screw feeder at the base of the hopper, Fig. (2.10). The feed hopper is mounted on a weight-bridge, and coal in the feed hopper is weighed by a load cell. The signal from the load cell is amplified and fed into a microprocessor.

The loss in weight is measured every few micro-seconds and the information is averaged and stored by the microprocessor as the rate of weight loss. This rate is compared with a preset feed rate stored in the microprocessor according to the furnace operating condition. Differences between the two rates are used to speed up or slow down the screw feeder in order to make the two rates identical. Fig.(2.11) shows the weight-time graph for the loss-in-weight technique. The dashed line represents the theoretical weight of the coal in the feed hopper, W_{th} , at a specific time, t and is obtained from :

$$W_{th} = W_0 - W \times t / 3600 \quad 2.2$$

where W_0 is the initial weight of coal in the hopper at $t = 0$, and W is the desired feed rate.

The theoretical weight loss is calculated as the difference between

the theoretical weights at times t_1 and t_2 , while the actual weight loss in the same period is determined by the difference between the measured weights at t_1 and t_2 respectively. The difference between the latter and the former values at any particular time is defined as the error which is fed into the control system for correction. When the weight of coal in the feed hopper reaches a lower limit, the microprocessor calls for a refill and automatic filling valve is activated for a short period to replenish the supply.

2-3-1 The Weight System

A Rospon (SODEC Ltd) loss-in-weight feeder based on the above theory is employed in the present design. It comprises 5 main units:

- 1) The controller
- 2) The weight platform unit
- 3) The signal conditioner
- 4) The feeder
- 5) The material hopper and product transfer system.

1) The Controller consists of a wall mounting sheet steel dust-protecting enclosure which houses the microprocessor unit. It also contains power supplies and switching to control the feeder and a digital indicator for the feed rate in kg/hr and the total weight in kg.

2) The Weight Platform Unit consists of a rigid frame supporting one load cell onto which are bolted the weighting platform, screw feeder, vibratory trays and a cylindrically angled chute.

- 3) The Signal Conditioner converts the analogue signal generated by the load cell to an industry standard 4 to 20 mA output ranged to suit the microprocessor controller.
- 4) The Feeder consists of a conditioning chamber which contains a slowly turning agitator to de-aerate powders and keep sticky powders free. Below the conditioning chamber is the variable speed arhimedean screw feeder.
- 5) The Material Hopper is of 4 kg capacity and has a side angle of 70° from the horizontal to allow a smooth outflow of the coal powders without 'bridging' or 'rat-holding'. The feeder is connected to the conical feed hopper through a flexible connector.

2. 3. 2 The pneumatic coal conveying system

Preliminary coal firing trials by Hriji (1986) indicated unacceptable combustion instabilities. The cause was traced back to coarse fluctuations of coal feed rate at the burner resulting from coal settling in the horizontal length of primary tube which was periodically re-entrained by the primary air stream. This phenomenon also resulted in back pressure at the injector body which in turn affected the weight-bridge load cell signals. It was clear therefore that for the present study, the exiting pneumatic conveyor had to be redesigned.

Two of the most important inter-linked features of the pneumatic coal conveying system had to be considered. Firstly the pressure drop in the conveyor pipe and secondly the ropping and subsequent settling or drifting of coal

particles in the horizontal pipe runs. Since the air/coal ratio, the coal feed, the mean particle size and the coal type were already selected for the experimental program, attention was focused on the pipe line configuration. It was observed that the worst coal drifting occurred in the horizontal stretch of the conveying pipe which was 3m long. Therefore this length had to be reduced to minimum length dictated by space limitations. The redesigned system, shown in Fig.(2.12), consisted of a vertical 3m downwards pipe after the injector, the 1m horizontal pipe, followed by a 4m vertical pipe leading to the burner gun. These pipes are all 26 mm inner diameter.

As a consequence of the change in the pipe configuration the injector had to be modified to adjust the line back pressure. The injector-coal feed chute linkage could not be sealed because the suction would induce load on the weight-bridge. Therefore the design of the injector had to meet the most basic requirement that it should not allow any secondary entrainment. Thus the injector and the coal feed chute are linked by a flexible bellows to prevent secondary entrainment and allow the chute to vibrate freely. The injector is mounted in such a manner that it could swivel about its axis and be adjusted to blow air towards the pipe wall permitting the excess momentum, if any, to be dissipated by friction keeping the pressure upstream of the injector at the ambient values. This pressure is also adjusted by by-passing some of the primary air to the top of the injector as shown in Fig. (2.12). The pressure upstream of the injector is carefully monitored through the shown pressure tap.

The present system operated satisfactorily for coals with a nominal

size distribution of 70% to 80% by weight smaller than 75 μm . For micro-fine coal of 80% less than 40 μm , coatings of the particles were observed even on the vertical pipe wall. A similar behaviour was also observed by Yang et al (1980) when transporting very fine nuclear powders. This behaviour is believed to be due to an increased cohesiveness associated with small particle sizes. Higher levels of turbulence had to be introduced in the pneumatic conveying line to reduce this phenomenon. This was achieved by replacing the conveying pipe described above with a 22 mm inner diameter corrugated flexible hose. This modification proved to be satisfactory for conveying micro fine Gedling coal which had a mean size of 11 μm .

2-4 Ignition Control and Safety Features

2-4-1 Ignition System

The ignition system (developed by industrial Automated Systems Ltd.) used to light-up the furnace comprises : (i) a torch igniter, (ii) an air/gas premixing unit and (iii) electronic ignition and control unit.

(i) Torch igniter

The incoming fuel is initially ignited by a natural gas/air premixed flame provided by an energy torch igniter system (P44 pulse). This is a one metre long high quality steel tube housing a concentric conductor rod supported on special insulators, attached to its firing end is a stainless steel burner head. An ignition coil is supported in gun metal casting at the out board end as shown in Fig. (2.13). The conductor rod performs two functions simultaneously:

- 1) Conveying the voltage from the ignition coil to a head resistance spark electrode.
- 2) Serving as the return path for the flame current via a secondary coil to the flame current amplifier.

(ii) Air/Gas Premixing Unit

A mixture of air and natural gas is provided by the premix unit (type MK6) through a flexible hose to the torch as shown in Fig.(2. 13). Compressed air is used for combustion to achieve a hard stable flame of maximum heat release. The air pressure is adjusted through a jet and nozzle mixing arrangement, which controls the size of the pilot flame, and the resulting high velocity flow entrains a regulated amount of gas as air passes on its way to the torch.

(iii) The Electronic Ignition and Control Unit

An ignition and detection device for providing a spark and detecting the pilot flame is used (IAS, type CU3). The (CU3) unit provides a continuous low voltage, low current oscillating pulse signal which when applied to the ignition coil, produces a high voltage to produce a continuous spark for ignition. The unit is energized manually, and during ignition the start button is pressed to provide an output which opens a normally close gas/air mixture solenoid valve (Dewra Switch Ltd.) prior to the torch. In case of an ignition failure, and to achieve immediate pilot ignition, the button is released and a sufficient time is allowed for purging the furnace with secondary air before attempting re-ignition.

The pilot flame detection circuit utilizes part of the spark generation circuit and a common torch electrode is used for spark and pilot detection. It should be noted that the detection circuit functions only when the start push button is released. Once a flame is established, the torch ignition is switched off to avoid any disturbance to the main flame.

2-4-2 The Main Flame Supervision System

(i) Flame Scanners

Flame scanners are used for monitoring the main burner flame, that is to terminate the fuel supplies on loss of ultraviolet signals from the flame using normally closed solenoid valves. Two ultraviolet scanners (type UAIA 6) are sited in such a manner that none of them see the igniter flame. They also view two areas in the first one third of the flame, taken from the point where the flame begins, for maximum ultraviolet radiation signal from the flame. This arrangement provides a reliable and sensible detection of the main burner flame.

Because it is necessary to keep the scanners cool and clean to avoid nuisance shut-down, the special mounting arrangement shown in Fig. (2.14) is employed. It consists of:

- 1) An insulating union to reduce conduction heat.
- 2) A quartz window union to seal off the furnace pressure.
- 3) Cooling air (1500 cc/min.) to reduce the site pipe temperature and push the combustion gases out of the scanner arrangement.

(ii) The Control Unit

The fire eye burner management control (Series D 41) is used to provide ignition and flame failure protection from the manually ignited gas, gas/coal flames. The flame failure response time of the unit is one second. Additionally, it accommodates momentary power loss for approximately two seconds, and permits the burner to continue to fire provided the flame remains normal.

(iii) Furnace Operation Procedure

The sequence of the flame ignition operation can be summarized in the following steps:

- 1- Turning on cooling water to all segments, venturi scrubber unit and its water showers.
- 2- Switching on the air compressor, the induced draught fan and the secondary air forced fan.
- 3- Supplying the necessary cooling air to the flame scanners.
- 4- Purging the furnace with the secondary air for about 15 minutes.
- 5- Igniting the pilot flame.
- 6- Pressing the manual push button. This immediately energizes the main fuel valve, an indication lamp lights when the scanner sees the flame, the button is then released and the flame relay then holds the fuel valve open.
- 7- When successful ignition on gas is achieved, a small amount of primary air is admitted to the primary line.

These steps are followed during preheating the furnace by firing

natural gas until a steady refractory wall temperature (1100 °C) is reached. The primary air heater, the secondary air heater, and the coal feed system are switched on when the refractory wall temperatures reached 800 °C. Once the refractory walls, primary air and secondary air temperatures reached 1100, 100 and 250 °C respectively, the primary air flow is increased to the desired value. The natural gas supply to the furnace is reduced and coal plus natural gas are fired simultaneously. Once a stable, anchored coal flame is established the natural gas supply and the ignition are turned off while the secondary air flow is adjusted to the required rate. The coal/air flame is allowed to burn for additional time to establish the required inlet conditions. After a steady coal flame and adequately steady wall temperature are attained, the data collection procedure begins.

2-4-3 Safety Features

- 1- A ball valve is fitted on the primary line just before the burner gun to isolate the coal feeding system from the rest of the furnace during light-up on gas to avoid any possibility of flash back.
- 2- Once successful ignition on gas is achieved, a small amount of the primary air is admitted to the primary line to prevent the combustion gases migrating into coal feeding system as well to clear the primary line of residual coal particles from the previous run.
- 3- A flame trap is fitted to the gas line prior to the igniter burner premix unit to prevent any possibility of flash back through the igniter air/gas mixture supply.
- 4- A control unit is used to supervise the presence of the main flame which shuts down the fuel supplies in the event of flames failure.

5- An adjustable photo-electric alarm (Fisher control Ltd.) is mounted on the main cooling water supply rotameter to close the fuel valves if the flow rate of cooling water falls below a certain minimum value.

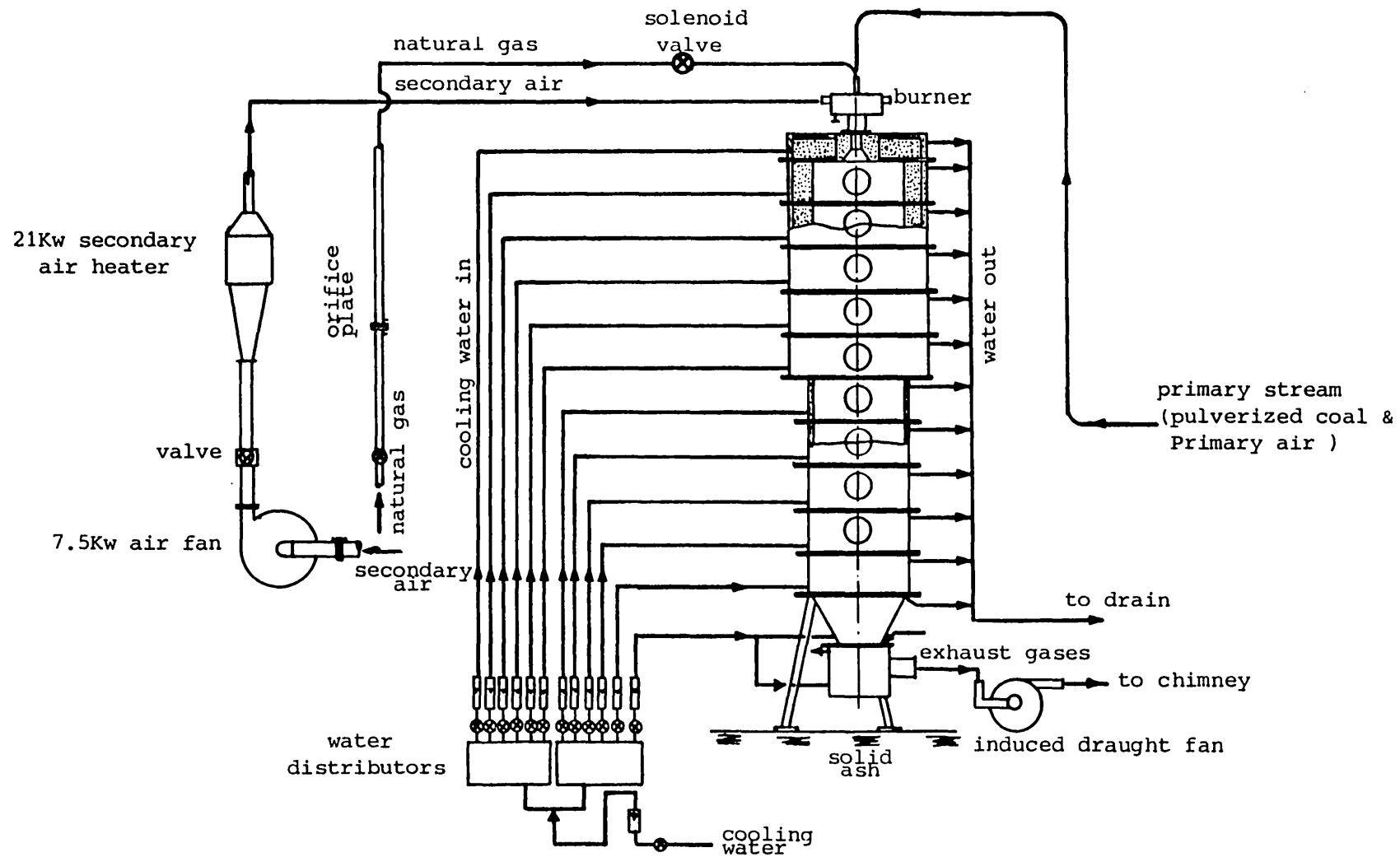


Fig. (2.1): Details of the Furnace Arrangements.

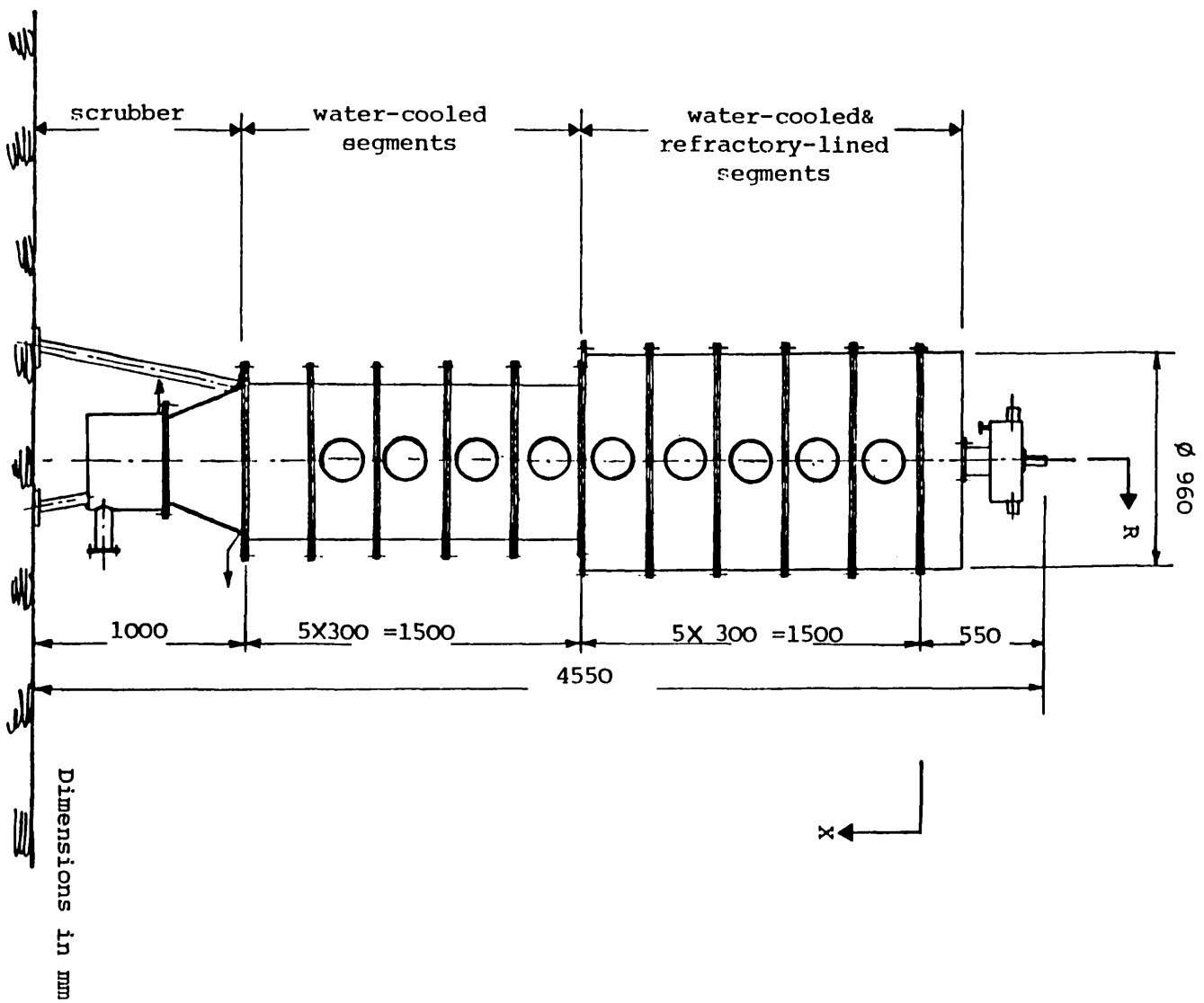


Fig. (2.2): The Furnace.

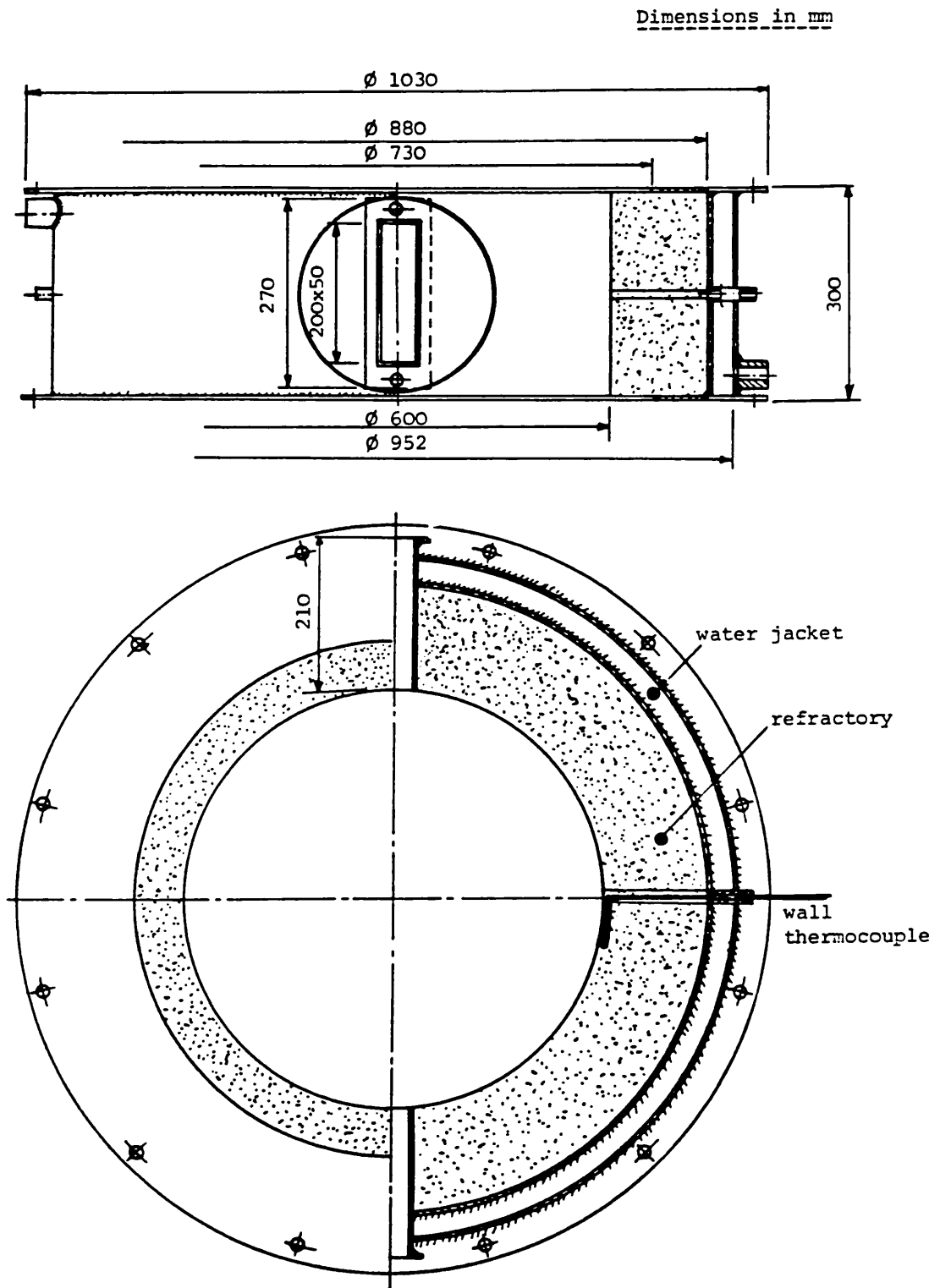


Fig. (2.3): Details of Refractory-Lined and Water-Cooled Segments.

Dimensions in mm

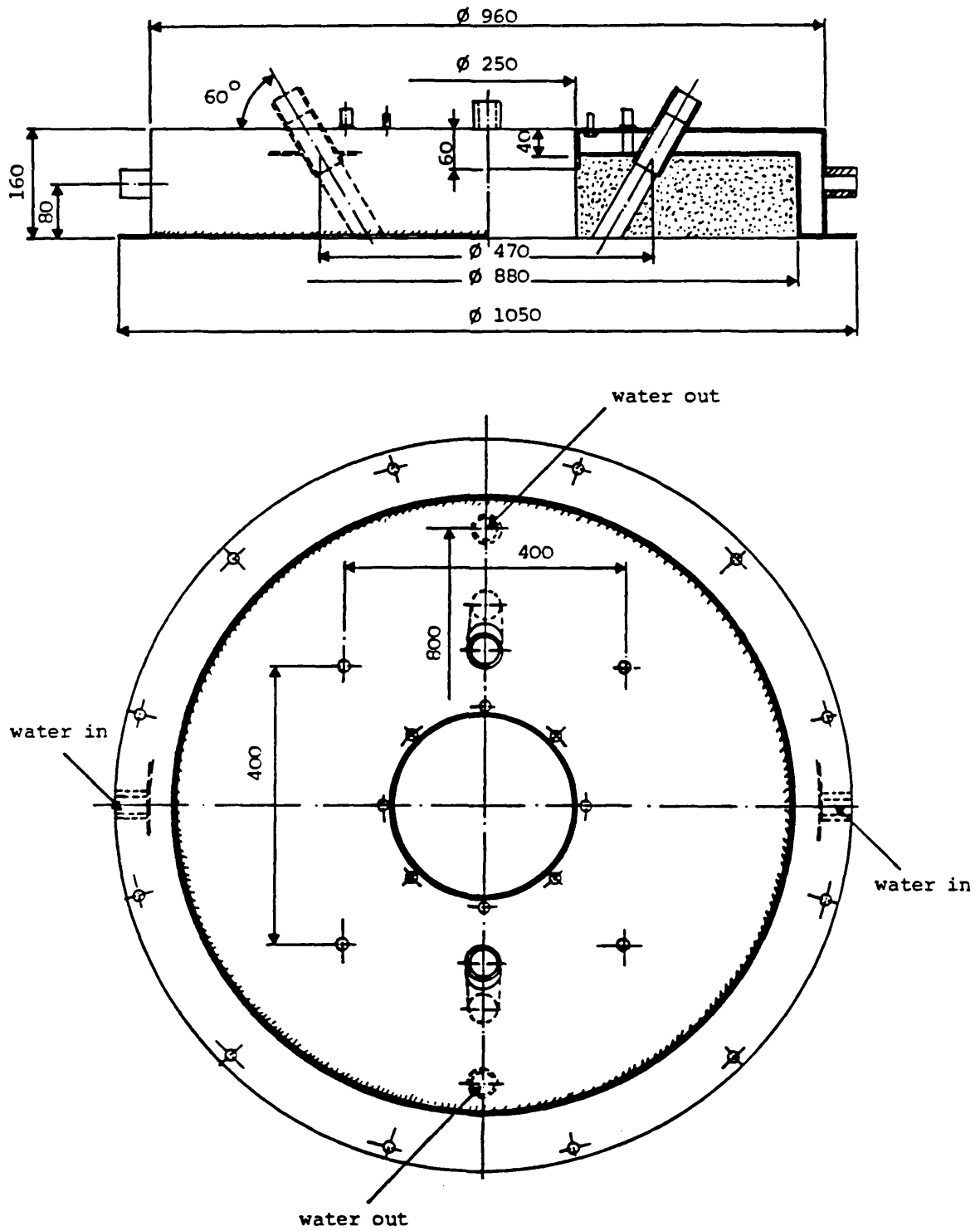


Fig. (2.4): Details of the Furnace Roof.

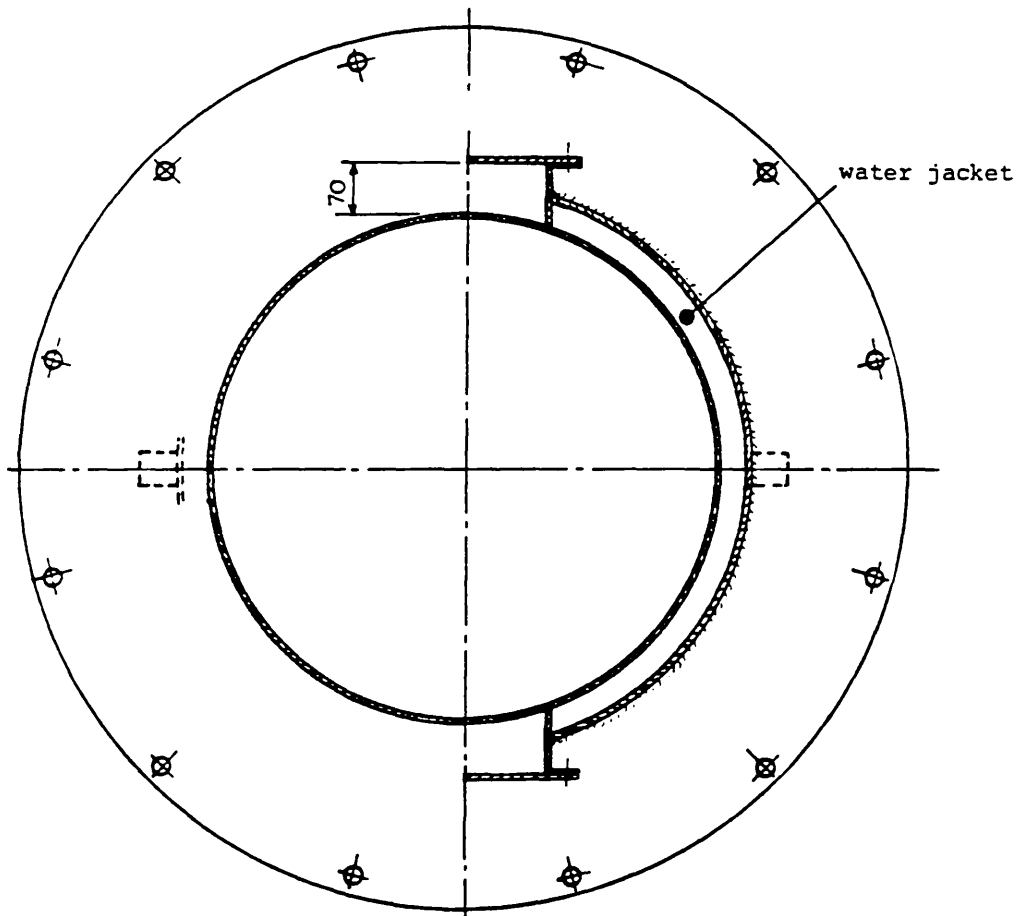
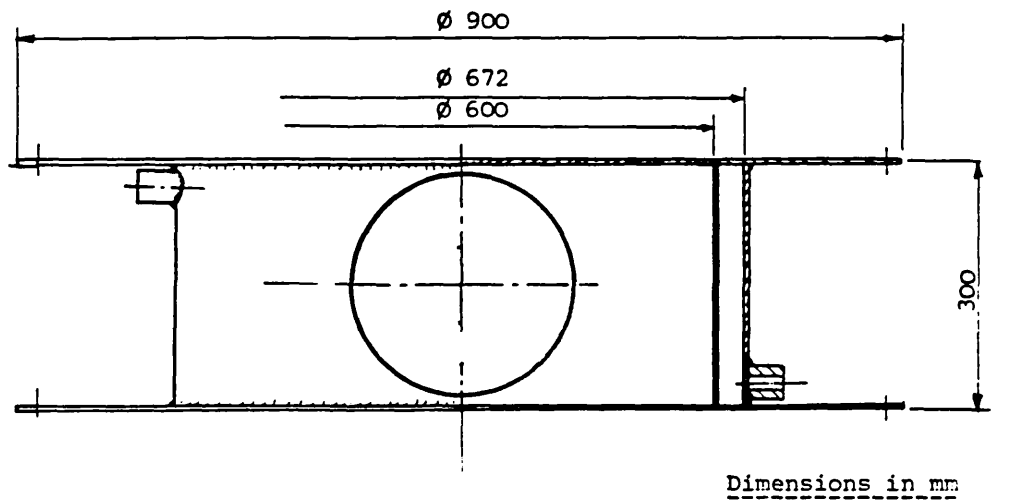


Fig. (2.5): Details of Water-Cooled Segments.

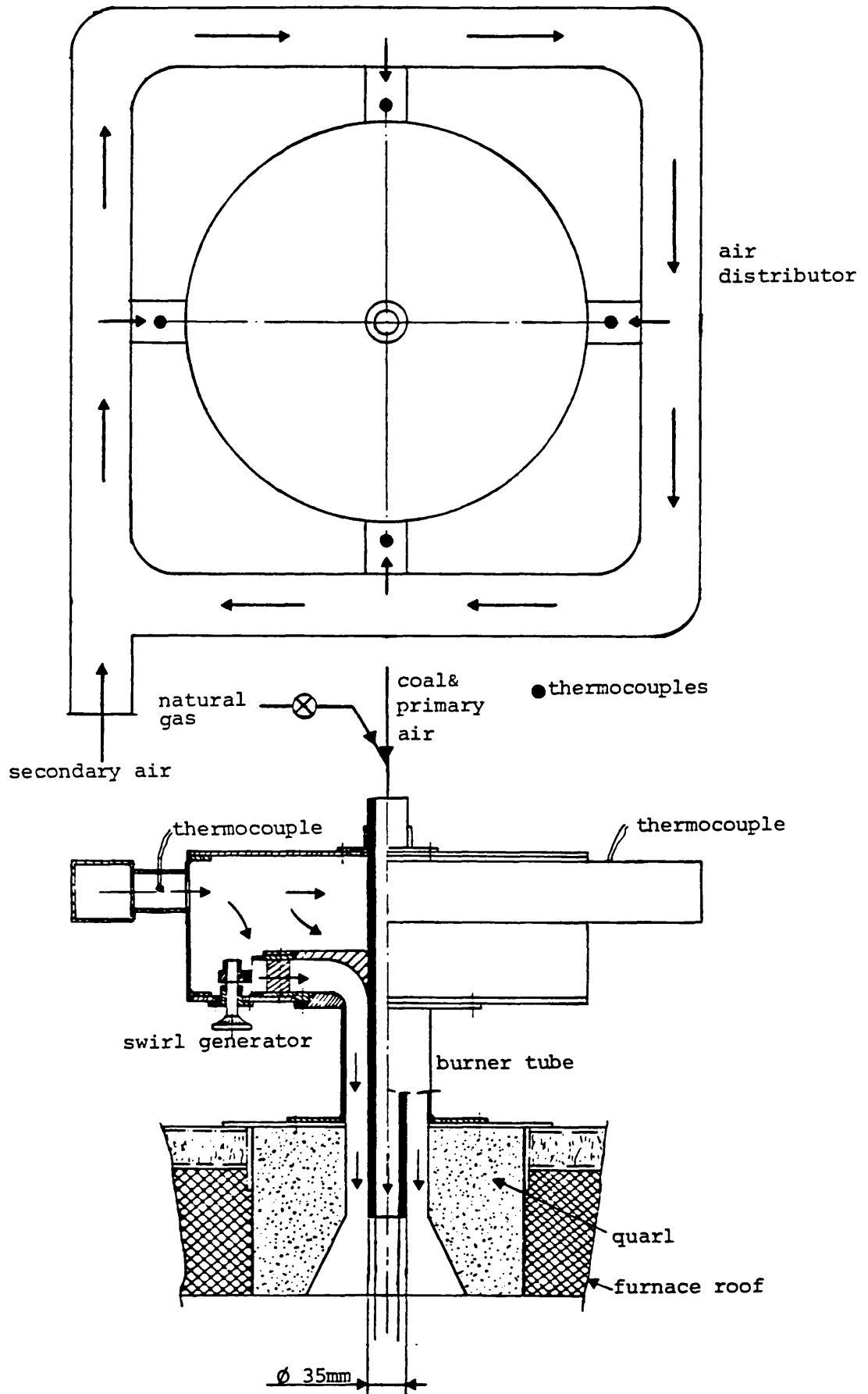


Fig. (2.6): Schematic Diagram of Coal Burner.

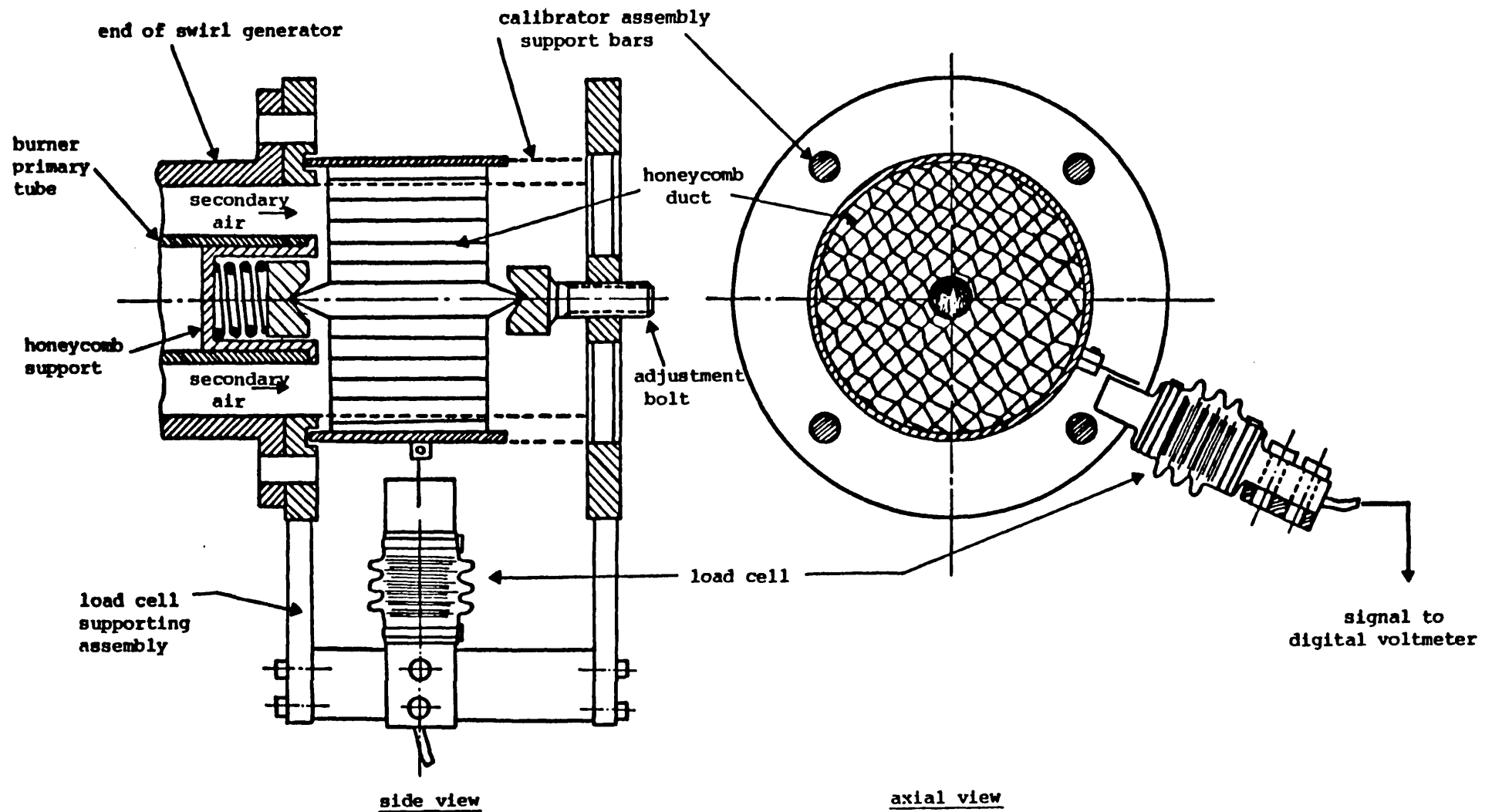


Fig. (2.7): Diagram of the Swirl Meter.
after Hassan 1983

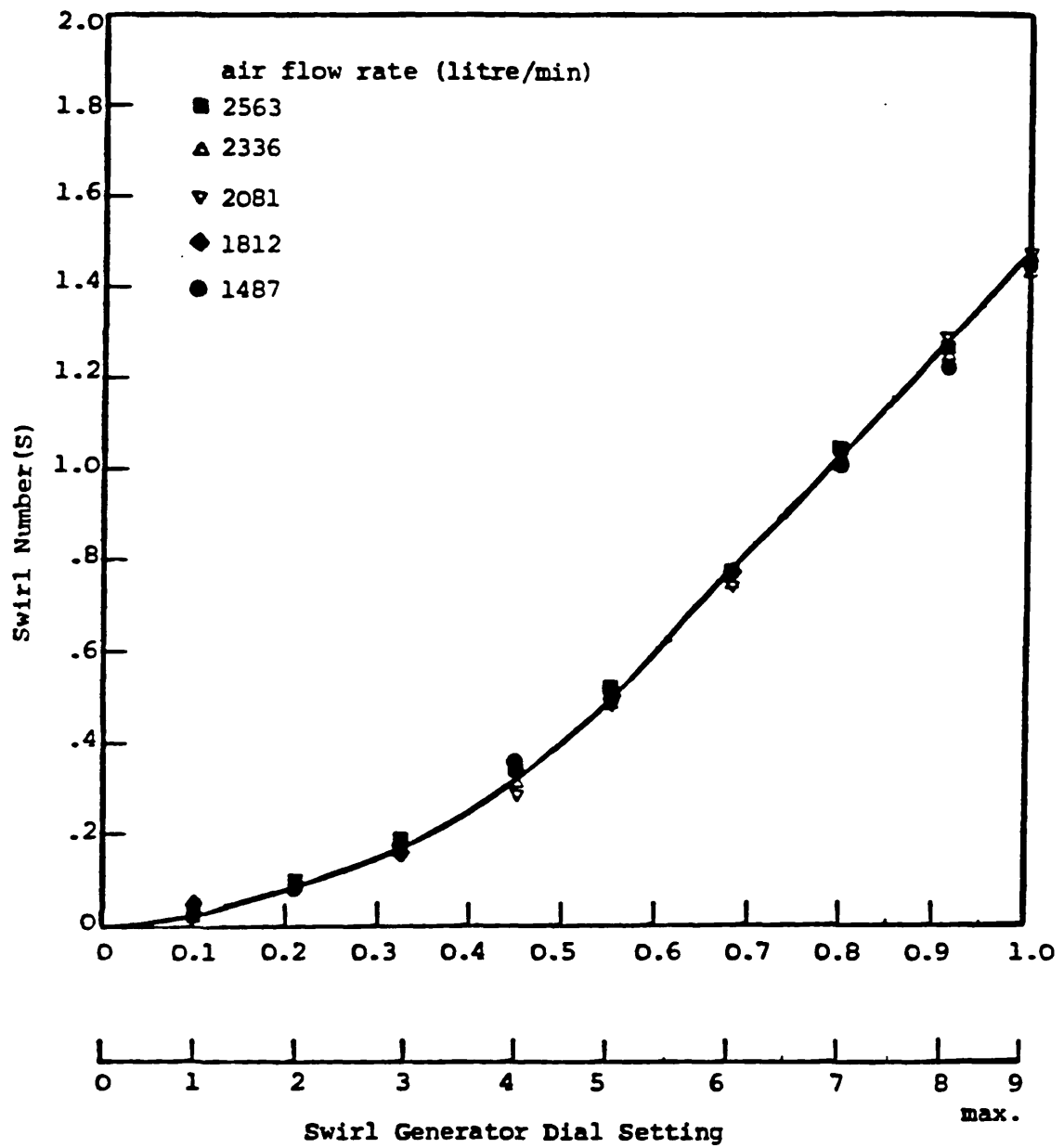


Fig. (2.8): Calibration Curve for the Swirl Generator.

after Hassan 1983

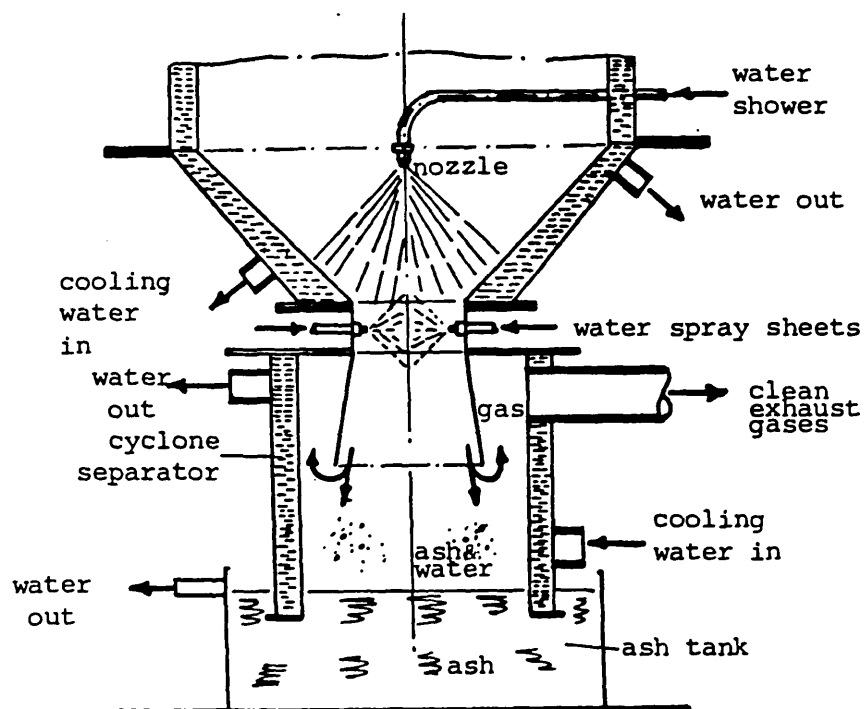


Fig. (2.9): Details of the Scrubber.

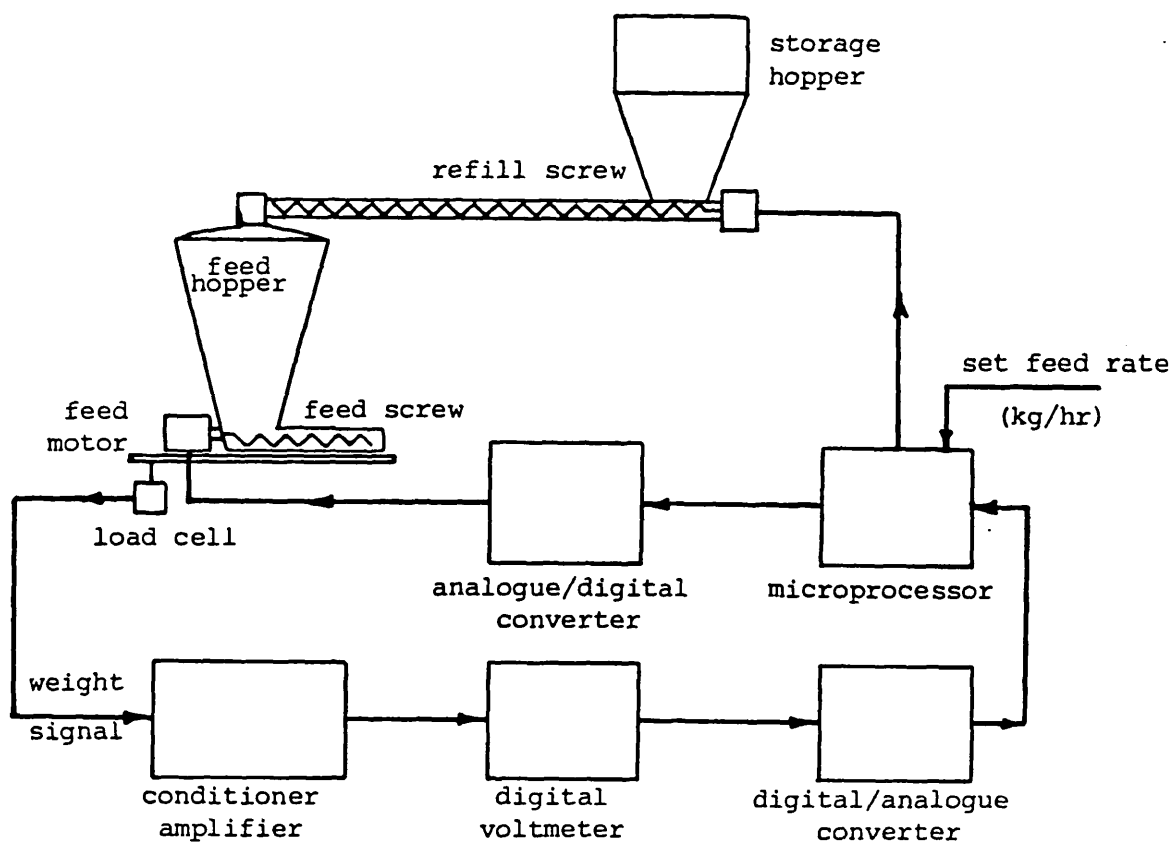


Fig. (2.10): Schematic Diagram of Loss-in-Weight Control System.

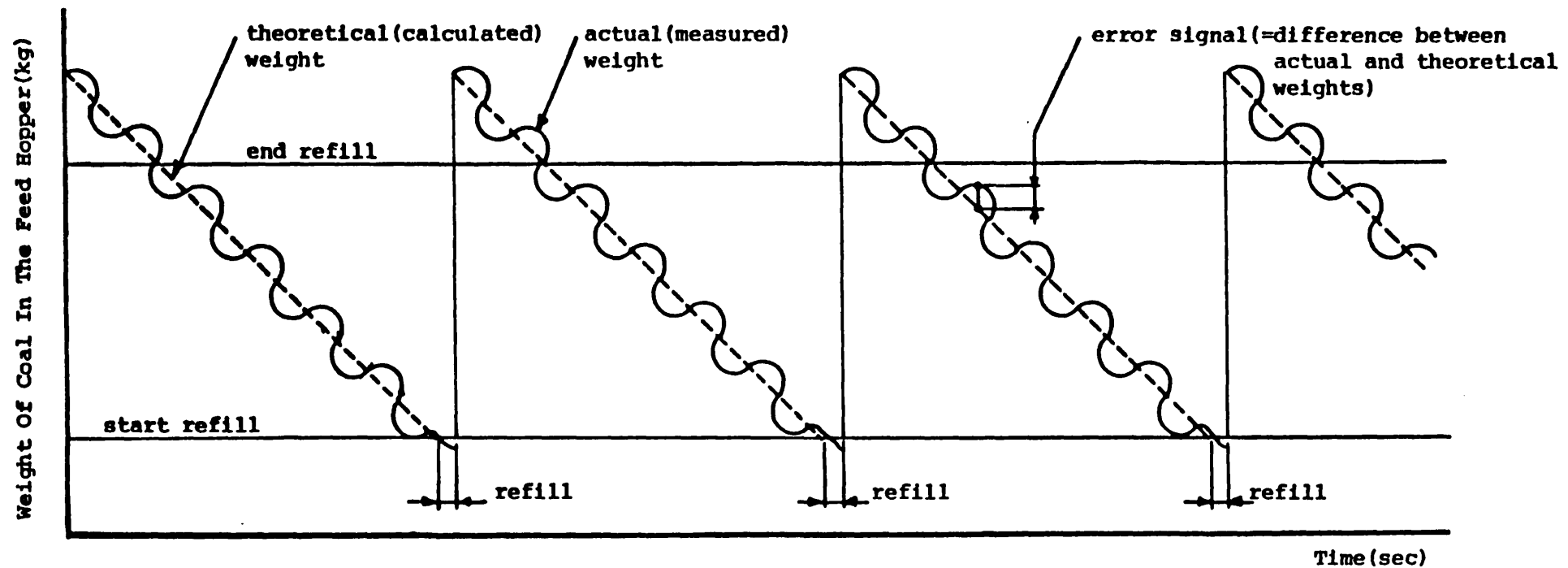


Fig.(2.11): SchematicDiagram of Weight-Time Graph
for the Loss-In-Weight Technique.

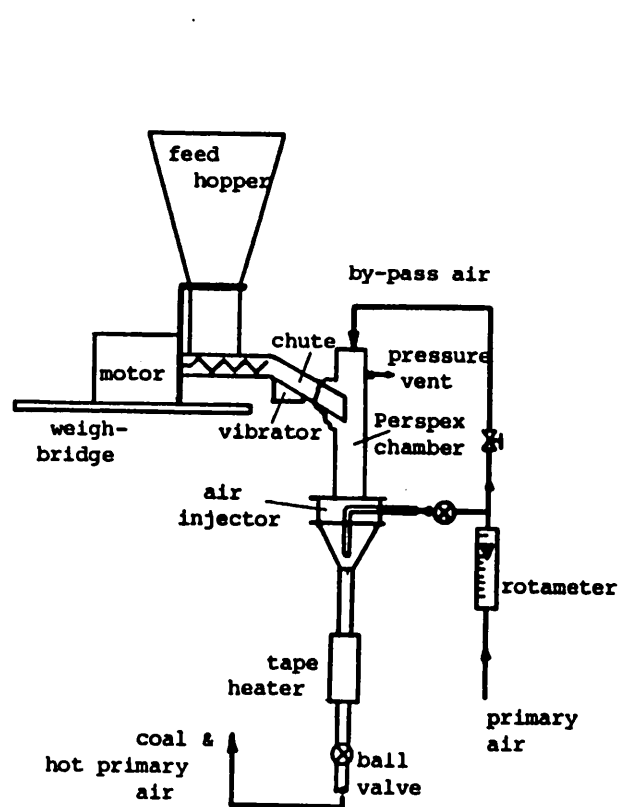


Fig. (2.12): Schematic of Coal Feed System.

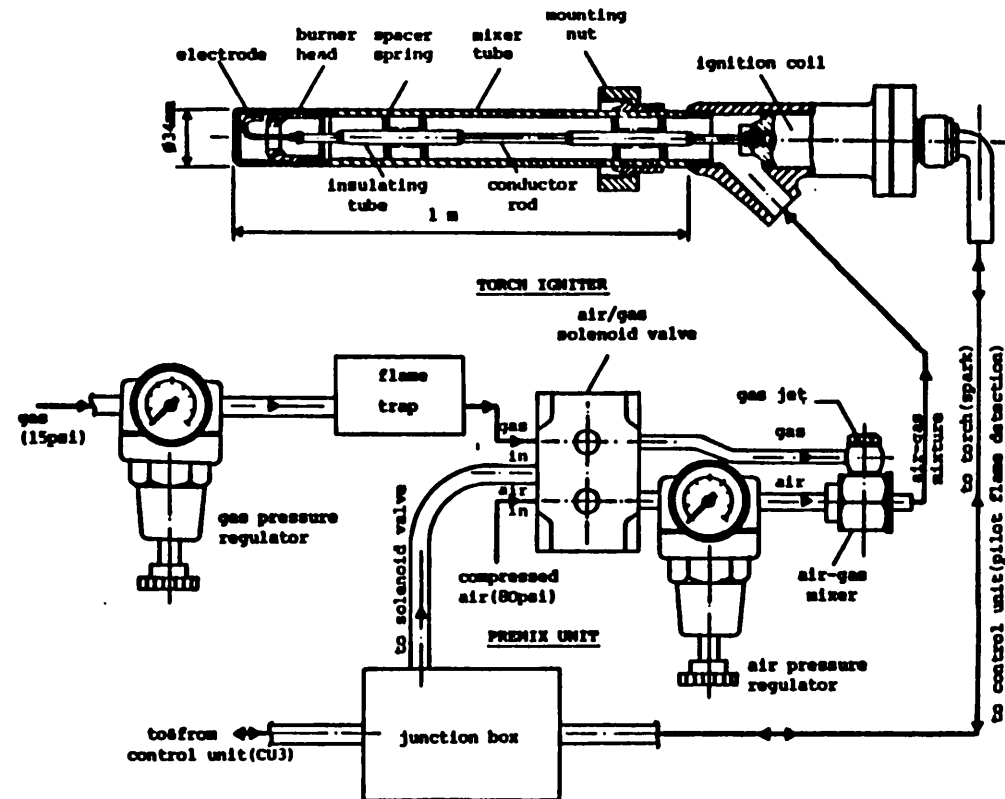


Fig. (2.13): Pilot Ignition System.

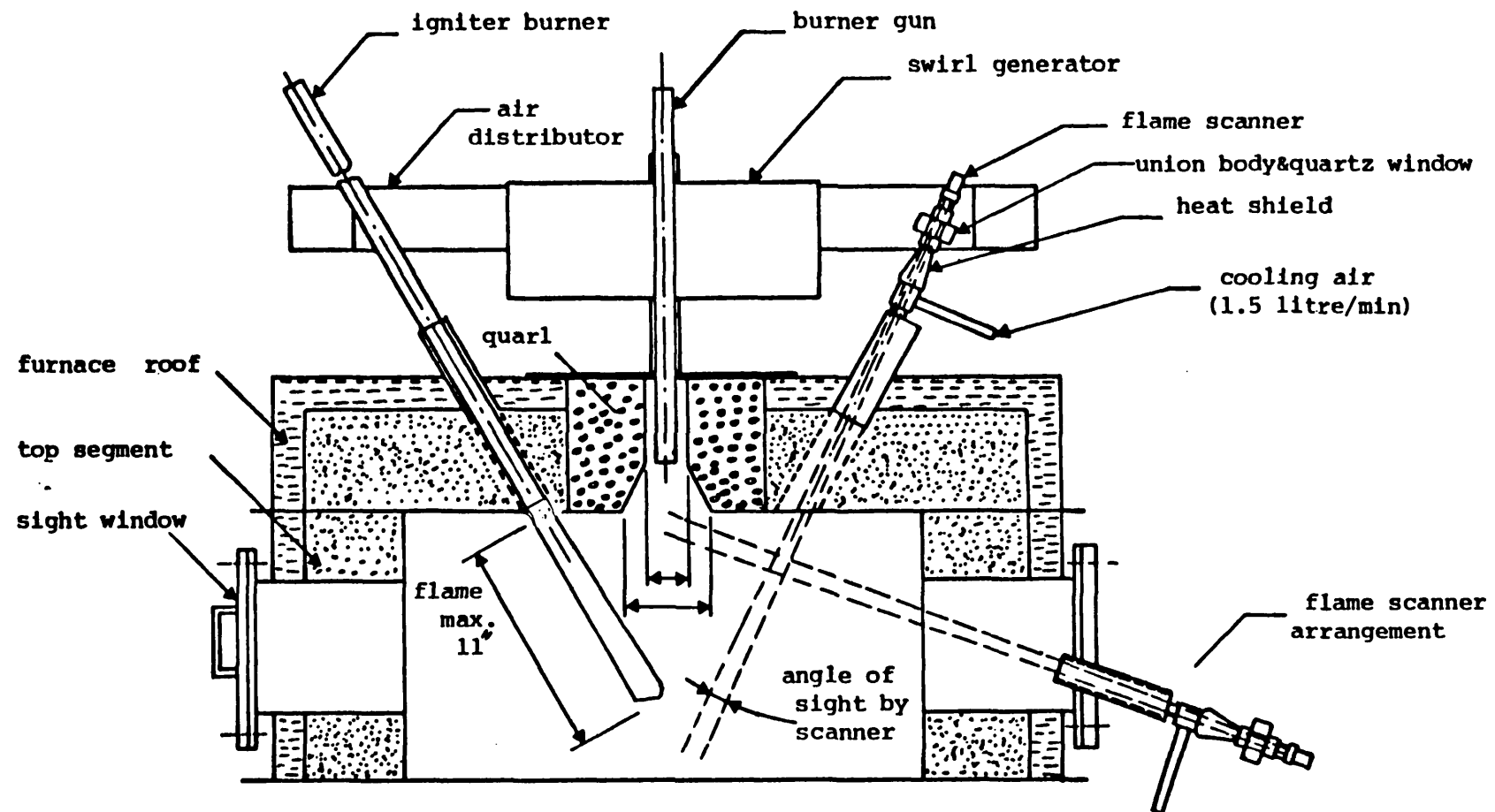


Fig. (2.14): Details of Furnace Top Firing End.

Chapter 3

MEASURING TECHNIQUES

3.1 introduction

It is a well known fact that coal is a difficult fossil fuel to consume efficiently and cleanly. It is a very complex heterogeneous substance whose structure varies greatly from one type to the other according to its age, the location and depth at which it is found. Its behavior is, therefore, highly variable and not well known under different combustion conditions. The clean and efficient combustion of coal can be increased through improved technology based on a thorough understanding of fundamental physical and chemical processes that occur during combustion. Thus the characterization of coal and char has been one of the main objectives in the present study. The key factor in achieving this objective was the production of well-defined and reliable laboratory data by easy, simple and accurate measurements of coal characteristics prior to, and after, combustion.

This study presents the current effort to produce general characteristics and properties for 7 different coal types, as well as char burn-out measurements. Section (3.2) contains in detail the different analyses procedures employed to define and characterize the coal. These include particle sizing, proximate analysis, ultimate analysis and heating value calculations. Some principal variables in terms of which coal quality is expressed are also determined

by empirical tests that do not directly measure variables themselves, but rather the behavior of coal under fixed standard conditions. Standardization of these condition is essential for obtaining comparable results between determinations performed within this study and those performed by different laboratories.

In section (3.3) a critical comparison between different probe types used in pulverized coal-air furnaces is given and a selection is made for the probe type to be used. This is followed by a description of the sampling line and the sample collection technique. A critical discussion of tracer techniques is also presented and a selection is accordingly made on the basis of economy, simplicity and accuracy. The accuracy associated with measurements is also discussed in both sections.

3. 2 Coal Characterization

The combustion of coal is a complex process which cannot be clearly defined by a set of simple parameters because of the wide range of physical and chemical properties of coal. However, several characteristic coal properties may provide an indication as to the performance of coal burning under specific operating conditions. Additionally, slight variations in the coal composition, for example in the concentrations of sulphur and nitrogen, can have a marked influence upon the species and quantities of pollutants formed during the devolatilization, pyrolysis and final combustion of the coal particles.

Numerous analytical techniques are available to quantify these properties. These analyses may be performed on: as-received, moisture-free

(dry), or ash-free basis. The as-received analysis is used for combustion calculations e.g. to determine the air required for complete combustion for a given feed rate, as well as for modelling purposes in numerical predictions. On the other hand, the dry and ash-free analyses are mainly performed for classification purposes.

Coal characterization is usually done through size distribution, proximate and ultimate analyses, heating values, coal rank, and free swelling index. A brief description of each of these is given below.

A- The Size Distribution is used to obtain a complete size range for different coal grinds, which helps in determining the means of handling and transportation of the coal particles from the main hopper to the burner pipe. It also gives an indication of the relaxation time (the time required for the particles to reach dynamic equilibrium with the gas flow).

B- The Proximate Analysis involves determining the moisture, volatile matter, ash, and fixed carbon content in a coal sample. These are defined as follows:

1- **The Moisture (Free-Water) Content** is the loss in weight when the coal sample is heated in inert ambient at a temperature set by standards. It is to be noted, however, that moisture does not represent all the water present in the coal sample.

2- **The Volatile Matter** is that portion of coal driven off as gas vapour when a coal sample is heated to a standard temperature. Volatile matter consists mainly of a variety of organic gases, resulting generally from distillation and decomposition.

3- **The Fixed Carbon** is the combustible residue left after volatile matter is driven

off. In general the fixed carbon represents that portion of the fuel that must be burned in solid state.

4- The Ash is the non combustible residue remaining after complete combustion, as the final form of the mineral matter present in the coal.

C- The Ultimate Analysis involves the determination of coal composition by weight of carbon, hydrogen, nitrogen, sulphur, and oxygen.

D- The Heating Value is the total heat produced upon complete combustion of a coal sample of a given weight.

E- The Coal Rank is an empirical method for classifying coal by certain properties, including apparent age, fixed carbon, volatile matter, inherent moisture, oxygen, agglomerating and non weathering indices Meyers (1981). This obviously means that no single property completely defines coal rank.

F- The Free Swelling Index Analysis gives a measure of the extent of swelling of a coal and its tendency to agglomerate when heated rapidly according to standard procedures.

Because coal is highly nonhomogeneous in both its chemical and physical properties Smoot and Smith (1985) it is very important therefore to carry out any characterization study on a representative coal sample. It was believed that such a sample could be obtained by carefully preparing the coal sample in the following steps:

- 1- Coal bags were chosen randomly from the batches received from the suppliers.
- 2- Coal samples were taken individually of approximately equal weights from each

of the chosen bags by collecting the sample from different locations within it.

3- The samples collected above were mixed thoroughly and divided into sub-samples kept in labelled containers for different analyses.

4- Samples were also collected frequently from the coal feed system during the particular run condition of the furnace and then treated in the same way as for the above step.

Moreover coal tends to change its chemical composition when left in air for long periods. At a certain stage in the present work this posed a major problem and was resolved by keeping the samples in an inert ambient, e.g. nitrogen Kandiyoti (1986), prior to analysis.

In the following the techniques and results of particle size distribution, proximate analysis, ultimate analysis and heating value are represented for different coal types considered in the present study namely: U K Grimethorpe (normally ground), UK Grimethorpe (microfine), South African (A), South African (B), UK Gedling (normally ground), UK Gedling (microfine) and Low Volatile Char (BLVG). For easy reference these types were assigned numbers as shown in Table (3.1).

3. 2.1 Particle Size Distribution

Extensive particle size distribution analyses were carried out for the different types of coal studied. Most of these types were pulverized by the suppliers, and came in sealed bags of approximately 25 Kg. each.

The particle size distribution was performed on a number of

samples each weighing approximately 100 gm., taken from different coal bags in the fashion explained earlier. These samples were run through the air jet sieve (type 200LS, Alpine process Technology Limited) shown in Fig. (3.1), and a particle size analyzer (Malvern 3600, Malvern Instruments, Malvern, England).

In the air jet sieve the sample was screened in a series of micro-sieves (Haver and Boecker, Germany), ranging in size from 25 to 710 μm , (25, 32, 40, 45, 63, 75, 90, 106, 125, 150, 212, 250, 425 and 710 μm). The screened samples were 5 gm. each and the percentage weight of the particles passing through a particular sieve was determined as the average of at least three samples. This averaging was mainly due to the irregularity of the particles shape which also dictated a relatively long sieving time of 4 minutes. The sieving vacuum pressure ranged between 250 and 1000 mm. H₂O in proportion with the sieve size . Between sampling the sieves were cleaned using an ultrasonic cleaning device (Sanorex Compact Unit, type R K, Alpine Process Technology Limited).

For sizes below 25 μm a different optical method was used in which the powder sample was dispersed in a suitable liquid . The size distribution was determined as a function of the light scattered by the suspended particles . A major advantage of this method was the ability to use ultra sound to assist the break up of cohesive materials into their constituent particles . Its main disadvantages was that the powder can have chemical change or interactions with the dispersant liquid that can cause them to coagulate. In this technique the liquid type can be any clear (633 nm. wave length) optically homogeneous liquid that does not interact with the sample so as to change its size. In the present study coal was dispersed in

methanol as suggested by Smith (1985).

Based on this concept is the Malvern 3600 particle analyzer which was used in the present analysis. The analyzer consists of a laser source, sample cell, a lens system, and an array of concentric diodes, all mounted upon an optical bench, Fig. (3.2). The particles in suspension in the sample cell diffracts incident light through an angle, θ . This angle is related to the particle size; and the intensity of the diffracted light at any given angle is related to the proportion of this particular particle size in the sample.

The diffracted light is collected and focused upon the diode array by the lens system which is interchangeable depending upon the required range of particle size as shown below;

Focal length	Particle size range
F . L mm	μm
300	5.8- 564.0
100	1.9- 188.0
63	1.2- 118.0

For most tests in the present study the 63 mm F . L lens was use.

The light signals from the diode array were analysed using a modified computer (Commodore PET). The computer estimates an initial size distribution from which it constructs a corresponding light energy distribution. This estimated distribution is then compared with the measured one and the initial particle size distribution is progressively refined by least squares technique to obtain a best fit. This process terminates when adjustments to size distribution become smaller than the fundamental resolving capacity of the instrument .

The sample concentration was adjusted for obscuration* (0.25-0.5). The results gave a log difference** of (3.5 - 5.5), which shows a good level of accuracy, when compared with the (4.0 - 5.5) range recommended by the manufacturer.

The particle size of coal dust varies greatly, depending upon the grinding technique and desired application, which in the present study required a particle weight mean size of around 45 μm , (80% under 75 μm). Typical average size distributions for different coal types are shown in Figs. (3.3) to (3.9). These results, which are also summarized in Table (3.2), demonstrate good agreement between air jet sieve and Malvern 3600 analyzer. Furthermore Fig. (3.10) shows the particle weight mean size distribution, and indicates good grinding consistency for coal types 1, 3, 4 and 5, and compatibility with the furnace project requirements. Coal types 2&6 however show smaller particle weight mean size as they represent the micro fine coals. Coal type 7 shows much coarser particle weight mean size and this is believed to be due to the fact that it was ground locally at Imperial College (Dept. of Mineral Resources Eng.), where it was obviously difficult to maintain the required size distribution.

* Obscuration is a measure of the optical intensity of the sample, i.e. the amount by which an incident beam is attenuated or obscured, and defined by:

$$\text{Obscuration} = (\text{Light intensity with the sample} / \text{Light intensity without the sample})$$

** Log difference measures the goodness of least square fitting process. It is defined as:

$$\text{Log difference} = \text{Log } \Sigma (\text{Light calculated} - \text{Light measured})^2$$

3. 2. 2 Proximate Analysis

The proximate analysis refers, as mentioned earlier, to the process determining the percentage contents of water vapour, volatile matter, fixed carbon, and ash in a coal sample. One of the methods employed here for proximate analysis in the present study is that described by British Standard (BS 1016, 1977). Briefly, the procedure begins by placing a 1.0 gm sample in a silica crucible and leaving it in a drying oven maintained at 105 -110 °C in a current of nitrogen for about one hour. Measuring the weight loss determines the moisture content of coal. Likewise, volatile matter is determined by establishing the weight loss in the sample when heated at 900 °C for seven minutes. This latter weight loss minus the moisture content, determined earlier, represent the volatile matter. Ash is determined by measuring the residue remaining after gradually heating the sample to 815 °C. This heating takes place as follows, the sample is first heated in air from ambient temperature to 500 °C in 30 minutes; from 500 to 815 °C in 60 to 90 minutes and then kept at 815 °C until a constant weight is reached, usually within 45 to 60 minutes. Finally the fixed carbon is determined by difference. This process usually takes about 4 hours.

The results of this analyses are shown in Fig. (3.11), and summarized in Table (3.3). The same analysis was carried out by BP research centre for coal type 3, the results of this analysis are shown in Table (3.4) in comparison with the present one. The agreement between both sets of results is seen to be reasonably good to within 7%, 4%, 1% and 1.5% difference in moisture, volatile matter, ash, and fixed carbon respectively.

The second proximate analysis method employed was the Thermo-gravimetric analysis (TG), in which the sample's weight is continuously monitored as its temperature increases gradually under controlled ambient conditions. The instrument used for this purpose was the Thermo-Balance (Perkin-Elmer Model, TG1) Fig. (3.12).

A sample of 5 to 10 mg is loaded in the electric furnace and set to represent 100% on the recorder chart, a typical example of which is shown in Fig. (3.13). Dry nitrogen is purged into the thermo-balance system at a rate of 300 cc/min for about 10 minutes, to remove all traces of oxygen. After all oxygen has been removed the flow of nitrogen is reduced to 100 cc/min. Moisture content is first removed by heating the sample at a rate of 40 °C/min. up to 110 °C; a temperature which is held for 5 minutes. Heating is then resumed at a rate of 80 °C/ min. up to 900 °C and is held for about 7 minutes to yield the volatiles matter. Oxygen is then introduced to the thermo-balance system to replace the nitrogen leading to the burning of the fixed carbon. The residue in the sample then represent the ash content. This method is significantly faster than the previous one, taking around 30 minutes. Also, in this method the fixed carbon is determined directly whereas in BS 1016 it is determined by difference as explained above.

The Thermo-gravimetric proximate analysis was used for the UK Gedling coal only (type 5). Table (3.5) shows the result of (TG) analysis compared to BS 1016 analysis. The agreement between the results of both methods are seem to be reasonably good 5%, 0.5%, 1% and 5% within to difference in moisture, volatile matter, fixed carbon, and ash respectively.

3. 2. 3 The Ultimate Analysis

The ultimate analysis is fundamental for coal characterization, since it involves determining the coal content in weight of carbon, hydrogen, nitrogen, sulphur, and oxygen. To determine the carbon, hydrogen, and nitrogen (CHN) content in the present study the elemental analyzer, (Carlo-Erba Strumentazione Automatic Analyzer CHN-S-O Model 1106) was used. The elemental analyzer is fitted with two automatic samplers (Type A 550), and an electronic peak integrator (Type SP 4100 Computing integrator, Spectra Physics). Figure (3.14) shows analytical and block diagram for the elemental analyzer. A coal sample 0.5 to 1.0 mg. is sealed into light tin capsule and dropped into a quartz reactor at a preset time heated to 1030 ± 10 °C. The reactor, through which a constant flow of helium (the carrier gas) is maintained, contains known amounts of chromium oxide and slivered cobaltous cobaltic oxide as catalysts. As the sample is introduced into the reactor the helium is temporally enriched with pure oxygen. Primed by oxidation of the capsule, flash combustion of the sample occurs raising its temperature to around 1800 °C. Complete combustion of the sample is then achieved by passing the product gases through the catalysts in the reactor. In order to eliminate excess oxygen and reduce any nitrogen oxides in the product gases, these are then swept through copper powder at 650 ± 20 °C in the secondary furnace. The individual components of the product gases are then separated in the chromatographic column at 103 ± 2 °C and eluded as nitrogen, carbon dioxide, and water vapour in that order. These gases are then detected by a hot wire detector whose signals for individual gases are visualized on a potentiometric recorder Fig. (3.15). The area under the respective peaks are calculated by the electronic peak integrator and subsequently used as an indication

of the percentage content of nitrogen, carbon, and hydrogen.

As mentioned earlier the determination of the sulphur content of the coal is of great practical importance. For this purpose there exist several micro-determination methods to determine the sulphur content e.g (oxygen flask combustion and furnace methods). In the present study the furnace method was employed using the elemental analyzer mentioned above. In this method the sample is dropped slowly into the quartz reactor packed with tungstic anhydride and quartz turnings as catalysts arranged in two successive layers and heated to $980 \pm 10^\circ\text{C}$. Once the sample is in the reactor the carrier gas is temporarily enriched with pure oxygen, where flash combustion takes place. Quantitative conversion of sulphur compounds to SO_2 is then achieved by passing the combustion gases through the catalysts. After the water vapour is eliminated via the trap packed with magnesium perchlorate, Fig (3.14), the mixture is then introduced into the relevant chromatographic column at $90 \pm 2^\circ\text{C}$, where SO_2 is separated from other combustion gases. The sulphur percentage is thus calculated in a manner similar to that described above.

For the determination of oxygen content, the sample is sealed into a light silver capsule and dropped into quartz reactor at $1060 \pm 10^\circ\text{C}$. This reactor, through which a constant flow of helium is maintained, is packed with nickel plated carbon and quartz turnings. Quantitative conversion of pyrolysis gases to carbon monoxide is achieved on contact with the catalysts. The mixture of pyrolysed gases is then swept into a relevant trap where interfering gases are removed and the remaining gases are passed to the relevant chromatographic column to separate the carbon monoxide. The oxygen percentage is calculated with

reference to carbon monoxide in a manner similar to that described above in the (CHN) analysis.

The method just described for oxygen is however expensive due to the use of expensive catalysts and silver containers. It is also difficult to perform since the catalysts should be kept under rigidly controlled ambient conditions. An easier way for the determination of oxygen content is by differencing and this was done in the present study. In this method the sample weight is taken to represent 100%, subtracted from which are the carbon, nitrogen, hydrogen, and sulphur contents determined earlier, to yield the sum of oxygen and ash contents. The ash content being known from the proximate analysis, detailed earlier, the oxygen content thus becomes readily available.

The main problem in ultimate analysis of coal contents involves conversion of its contents to, and quantitative recovery to, the detectable gases. Quantitative conversion to the detectable gases can be achieved by adjusting the factors affecting the chemical equilibrium between the product gases and the detectable gases. These are mainly the reactor temperature, the oxygen concentration in the carrier gas, and the presence and effectiveness of oxidative catalysts. accordingly the reactor were cleaned every 100-200 (CHN) samples and 100 (S) samples, depending on the ash content. The catalysts were also replaced every 300 (CHN) samples and 1000 (S) samples.

The accuracy of the analytical results is obviously closely related to the accuracy of the sample weighing. Accurate weighing was performed using an electronic micro-balance with a digital read out range of (0.0000-10.000 mg), and 0.1 micro-gram sensitivity, (Model 4431 ultramicro-balance, Satorious

instruments Ltd).

For conditioning and calibrating the elemental analyzer, micro analytical standards were used. Samples of Cyclohexanone 2,4 Dinitrophenyl hydrazone (51.79% C, 5.07% H and 20.14% N) for the (CHN) process, and Sulphinlank (18.62% S) for the (S) process, were analysed as reference compounds. The calibration and check were carried-out every (25-35) samples in order to maintain a consistent and reasonable level of accuracy. Figure (3.16), shows a typical analysis for (CHN) of Sulphinlank (41.84% C, 4.68% H and 16.21% N) as check process, and indicates a good level of accuracy of about 2% in carbon, 2% in nitrogen, 3% in hydrogen .

Extensive ultimate analysis for different coal types were performed on as-received basis. Examples of the results are shown in Figs. (3.17 to 23), indicating that each of the coal types studied have, more or less, uniform composition, and good sampling. Table (3.6) and Fig.(3.24) summarize the average of the ultimate analyses of at least 30 samples for each coal type. The same analysis was also carried out by the NCB and BP Research centres for coal types 1 and 3 respectively , and the results are shown in Tables (3.7 and 8) in comparison with the present results. The three sets of results show good agreement with maximum differences in carbon, hydrogen, nitrogen and sulphur, of about 1.6%, 2%, 5% and 1.5% respectively.

3.2.4 Heating Value

There are several experimental methods for determining the heating or calorific value, e.g. Bomb calorimeter Mereys (1981) and Differential

Scanning Calorimetry (DSC) Fyans (1977). It can also be calculated from the coal ultimate analysis, an approach which was followed here. Several equations have been developed for the calculation of the heating value of fossil fuels Lloyd and Davenport (1980), which generally agree to within $\pm 3\%$ of the measured one.

The equation described by Jain and Sundararajan (1981) was selected on the basis of its close agreement with the heating values for coal measured with the bomb calorimeter (to within $\pm 1.5\%$). This equation reads

$$H.V = 1.096 (C/3 + H + S/8 - O/8) - 0.8817 \quad 3.1$$

where

H.V is the heating value in MJ/Kg.

C is the carbon %

H is the hydrogen %

S is the sulphur %

O is the oxygen %

Based on this equation the heating values are shown in Fig. (3.25), and Table (3.9). The heating value for coal type 3 was also measured by BP research centre and reported to be 28.38 MJ/Kg., which was less than 2% different from the value calculated for the same coal type .

3. 3 Sampling Technique

3. 3. 1 Sampling Probe

The major requirement in combustion exhaust gas sampling

systems is to prevent any further chemical reactions in the sample after being extracted from the flame Tine (1961). This is generally achieved by a steep drop in the sample temperature. A typical sampling system in a coal flame study generally consists of sampling probe, a sampling line and a disengager or water/particles trap. In pulverized coal air furnaces three probe types are mainly used, namely: water-cooled, water-quench and water- quench water-cooled sampling probes.

In the water-cooled or indirect quench probes shown in Fig. (3.26 a), sample cooling occurs by heat transfer to water in the jacket surrounding the suction passage. The main problem with water-cooled probes is their frequent blockage Hassan (1983) due to the accumulation of the solid particles within the suction passage. In water-quench probes shower-bath, developed by Lewis and Smoot (1981) for particle laden-gas samples, direct quenching of the sample takes place by injection of the cooling water through small holes near the tip of the probe as shown in Fig. (3.26 b). This probe suffers less from the blockage problem which is partly solved by the flow of the quenching water and its natural cleaning effect. Its major disadvantages, however, is the possible boiling and/or flashing of the quenching water Hassan (1983). In water-quench water-cooled probes this problem (boiling or flashing) is solved by using two separate paths for cooling water and quenching water as shown in Fig. (3.26 c). The shower-bath probes further offers more effective quenching of the samples Hassan (1983).

In the sampling system constructed for the present study char particles were extracted from the furnace using the water-quench water-cooled probe shown in Fig. (3.27). This probe was made entirely from stainless steel as a modified version of that used by Hirji (1986). This modifications were such

that:

- 1- Longer neck(50%) which allowed sampling nearer to the quarl as well as the burner and hence a better chance of obtaining combustion information near to the burner region.
- 2- 4 times larger suction area to reduce further the blockage problem, especially close to the quarl and near the furnace axis. This also lead to smaller particles segregation effect.
- 3- Although the suction area of this probe was 4 times larger than the old version the total cross-sectional area of the probe was only 24% larger, hence causing relatively smaller disturbances to the flow. This was achieved by increasing the diameter of the water tubes while keeping their number at a minimum.

Gas and solid particle samples were quenched by direct injection of swirling water jets through the small holes near the tip. Due to the highly turbulent water jets in the probe, a fast quenching of the sample was possible. Furthermore, because of the large heat capacity of the quench water and its initial lower temperature only a small rise in its temperature occurs as hot samples pass through the probe. The cooling water was introduced to the probe through two tubes 4 mm. in diameter each as shown in Fig. (3.27).

The use of probes of finite dimensions and the sample suction through the probe cause disturbance and distortion in the flow pattern both upstream and downstream of the probe. The flow field in the present study is heterogeneous and therefore the requirement of the isokinetic sampling becomes of some importance in order to obtain representative samples. However in swirling, recirculating and highly turbulent flows, isokinetic sampling is very difficult if not impossible Bilger (1977). Nevertheless in order to reduce the flow

disturbance in the vicinity of the probe inlet, an attempt was made to balance the static pressure of the incoming flow in the vicinity of the probe inlet, measured through the static pressure tap near the tip, with that at the same height at the furnace wall. Some control of the probe pressure was achieved by adjusting the quenching water flow rates. The quenching water was thus introduced to the probe at flow rates of approximately (300-500 cc/min).

The sampling probe was accurately located at the desired location to within ± 2 mm using the mechanical traversing mechanism shown in Fig. (3.28). The probe was successfully used for collecting char particles in the present work as well as gaseous samples by other researchers at Imperial college.

3. 3. 2 Sampling Line

The sample collected by the water-quench water-cooled probe described above is three-phase (gas, particle & water) and a special sampling line had to be devised to separate the solid phase and facilitate its analyses. A schematic of this sample collecting system is shown in Fig. (3.29). To extract the sample two water ejectors were fitted in parallel at the end of the sampling line to create the required suction in the line. These ejectors were supplied by water at 2.5 bar and the flow rate was adjusted in accordance with the measuring location and the furnace operating conditions as explained earlier.

Gases were removed from the sample by passing the latter through a 3 litre conical bottle used as the disengager, where water and particles were collected. Under the normal operating conditions of the furnace random fluctuations in the sample flow were expected and therefore sampling had to be

carried out over a sufficiently long period of time in order to obtain a representative sample. Hassan (1983) and Hirji (1986) suggested a sampling period of 5 minutes. for exhaust gas species measurements. However, tests were carried out here to study the effect of the sampling time by sampling over two periods namely, 7 and 13 minutes. The relatively longer periods were mainly to allow for the collection of a sample of sufficient weight for subsequent processing and analysis. The results of these tests are shown in Table (3.10) and clearly indicate that a 7 minutes sampling period was adequate to collect the required amount of sample.

The char particles were separated from the solid/liquid sample collected in the disengager in the following steps:

- 1- The disengager was first emptied in a labeled Pyrex beaker and left for nearly 2 hours for the char particles to settle.
- 2- The quench water was next drained and the remaining solid sample put in an oven at 105-110 °C to dry untill the remaining water was completely evaporated and a constant weight of the char sample was reached.

The dry samples were henceforth treated in a manner similar to that detailed in Section (3.2) including sample preparation, ultimate analysis, proximate analysis and heating value calculations. Comparison between the ultimate analysis of samples collected by the present method for solid sample separation and by the filtering method employed by Hassan (1983) was carried out. The results are shown in Table (3.11) and indicate good agreement (to within 0.4% in the total char burn-out). The advantages of the present method are easy to perform and capable of trapping most of the char particles. It also allows collection of sufficient sample at a relatively low cost. Its main disadvantage is

that its operation time is longer.

3. 3. 3 Tracer Technique

Tracer techniques are concerned with the monitoring of the variation of certain component of coal during different stages of combustion and in the present study they have been used to calculate combustion efficiency as well as the release percentage for different components. Several coal components may be considered as particle tracers, for example: iron, aluminum, or ash. Due to the difficulty and the high cost of determining iron and aluminum traces in char samples ash was chosen here as the tracer. Badzioch and Hawksley (1970), Nsakala et al. (1977), Scaroni et al. (1981) and Phelan and Bortz. (1984) also used ash as a tracer. Kobayashi (1976) and Padia (1976) have pointed that some of the ash components are volatile at combustion heating rates and temperatures. Quann and Sarofim (1982) further reported that the error due to ash evaporation increases rapidly at temperatures above 2000 K. This was also confirmed earlier by Harding (1980) who also showed that the ash is somewhat soluble in the quenching water. It is very difficult to separate the effect of evaporation and solubility on ash loss. Hassan (1983) estimated that the measured value of ash content in the char sample may be less than the actual value by some 5-10%. An investigation of the use of ash as a tracer was made by Jamaluddin (1985) who showed that the technique is not recommended for gas temperature above 2000 K and particle temperature above 2200 K. At gas temperatures around 1673 K ash gave an underestimated value of nearly 5% of the true value.

The maximum temperature in the furnace of the present

investigation was reported by Hirji (1986) to be around 1673 K. Because of the simple nature of the char analyses and independence of its results of the sample collection efficiency, the use of the ash as a tracer was considered a reasonable choice.

The ash fraction in the solid sample (char particles) was used to determine the extent of the particle burn out (burn off) using the results of the char particle proximate and ultimate analyses from the following relationship Harding (1980);

$$\psi = (1 - (\omega_k / \omega_x)) / (1 - \omega_k) \quad 3.2$$

where ψ is the char burn out and ω is the ash weight fraction, and the subscripts k and x refer to ash content in the input coal and char sample respectively. Dividing by the weight fraction of combustible material in the input coal ($1 - \omega_k$) normalizes the range of the burn out between 0 and 100%. The above calculations were carried out assuming no ash loss because of the difficulty of accurately determining the ash loss due to both evaporation ash solubility in the quenching water. The error resulting from this assumption on the char burn out calculations was found to be negligibly small at the most ($\approx 0.5\%$) as compared with that based on the 10% ash loss assumption of Hassan (1983).

The component release percentage (C, H, N) was calculated using the results of the char particles ultimate analysis from the following equation Michel and Payne (1980) and Skinner (1980).

$$\% \text{Released } (\beta) = 1 - ((\omega_{ix} / \omega_{ik}) (\omega_{\alpha k} / \omega_{\alpha x})) \quad 3.3$$

Where ω_i is weight percentage of the species of interest, ω_{α} is the ash weight percentage, and k and x stand for different content in the input coal and sampled char respectively. This equation was also used for calculating the heat release and volatile release.

Coal Name	Coal Number
UK Grimethorpe (normally ground)	Type 1
UK Grimethorpe (microfine)	Type 2
South African (A)	Type 3
South African (B)	Type 4
UK Gedling (normally ground)	Type 5
UK Gedling (microfine)	Type 6
Low Volatile Char (BLVG)	Type 7

Table (3.1): Different Coal Names and their Numbers.

Particle Size	Coal Type 1	Coal Type 2	Coal Type 3	Coal Type 4	Coal Type 5	Coal Type 6	Coal Type 7
710	100	100	100	100	100	100	99
425	100	100	100	100	100	100	94
200	97	100	98	98	100	100	82
100	90	100	85	88	89	100	70
75	85	99	78	81	80	97	56
50	75	95	64	71	68	88	40
40	68	89	56	64	60	80	29
25	45	60	40	50	40	68	8
15	28	37	26	29	23	48	5
10	17	21	15	16	15	33	3
7	9	11	8	8	10	20	2
5	3	5	4	4	6	10	1
3	-	0.5	0.5	0.5	0.5	0.5	-
Mean Size	42	20	50	43	45	11	73

Table (3.2): Particle Cumulative Weight % Under-Size for Different Coal Types.

Content Coal Type	Moistue %	Volatile Matter %	Fixed Carbon %	Ash %
Coal Type 1	3.2	30.8	58.2	7.8
Coal Type 2	6.6	31.7	53.0	8.7
Coal Type 3	3.0	25.3	58.8	12.9
Coal Type 4	6.7	19.3	32.0	42.0
Coal Type 5	6.3	35.8	53.7	4.2
Coal Type 6	2.4	34.4	51.8	11.4
Coal Type 7	9.4	2.8	67.1	20.7

Table (3.3): Proximate Analysis for Different Coal Types.

Content	BP research center	Present analysis
Moistrue	3.0 %	2.8 %
Volatile Matter	25.3 %	26.4 %
Ash	12.9 %	12.8 %
Fixed Carbon	58.8 %	58.0 %

Table (3.4): Comparison between Different Proximate Analysis for Coal Type 3.

Content	BS 1106	TG1
Moisture	6.3	6.2
Volatile Matter	35.8	35.4
Fixed Carbon	53.7	54.2
Ash	4.2	4.2

**Table (3.5): Comparison between BS and TG1
Proximate Analysis for Coal Type 5.**

Content Coal Type	Carbon %	Hydrogen %	Nitrogen %	Sulphur %	Oxygen %*
Coal Type 1	73.00	4.96	1.76	1.14	11.34
Coal Type 2	69.76	4.85	1.55	1.38	13.76
Coal Type 3	70.50	3.97	1.63	0.41	10.59
Coal Type 4	40.88	2.56	1.04	0.40	13.12
Coal Type 5	72.60	5.05	1.29	1.55	15.31
Coal Type 6	69.93	4.91	1.43	1.24	11.09
Coal Type 7	71.78	0.83	0.39	1.30	5.30
* - by difference					

Table (3.6): Ultimate Analysis for Different Coal Types.

Element	NCB research centre	Present analysis
Carbon	72.78 %	71.65 %
Hydrogen	4.92 %	4.84 %
Nitrogen	1.60 %	1.67 %
Sulphur	1.16 %	1.14 %

**Table (3.7): Comparison between Different Ultimate Analyses
for Coal Type 1.**

Element	BP research centre	Present analysis
Carbon	71.6 %	70.5 %
Hydrogen	3.96 %	3.97 %
Nitrogen	1.7 %	1.63%
Sulphur	0.41 %	0.41%

**Table (3.8): Comparison between Different Ultimate Analyses
for Coal Type 3.**

Coal Type Heating Value (kJ/kg)	Coal type 1	Coal type 2	Coal type 3	Coal type 4	Coal type 5	Coal type 6	Coal type 7
Gross Heating Value	29.26	28.21	27.83	15.12	29.29	28.70	25.80

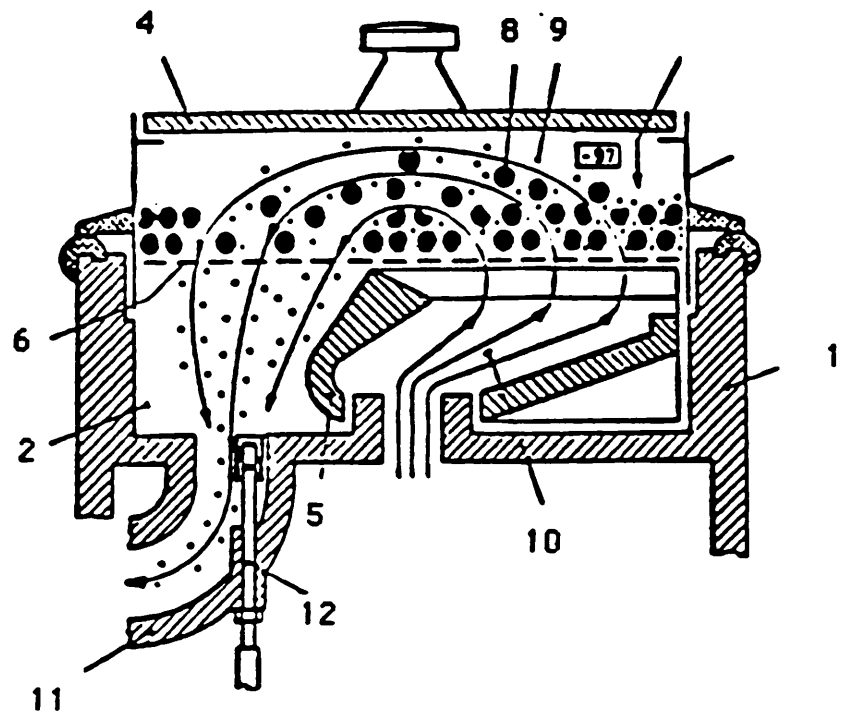
Table (3.9): The Calculated Heating Values for Different Coal Types.

Experiment (A) Time 13 min				Experiment (B) Time 7 min			
N %	C %	H %	%	N %	C %	H %	%
0.42	21.26	0.39	97.6	0.32	20.21	0.25	97.8

Table(3.10): Effect of the Particle Collecting Time on Char Burn-Out.

Experiment (A) Filtering				Experiment (C) present study			
N %	C %	H %	%	N %	C %	H %	%
0.42	21.26	0.21	97.6	0.65	19.9	0.38	97.8

Table(3.11): Comparison between Two Char Separation Methods.



- 1- Housing
- 2- Dish
- 3- Sieve Drum
- 4- Lid
- 5- Slit-Nozzle
- 6- Gauge
- 7- Layer of Coal
- 8- Coarse Coal
- 9- Fine Coal
- 10- Air Jet
- 11- Discharging Socket
- 12- Pressure Gauge Socket

Fig. (3.1): Schematic of Air Jet Sieve.

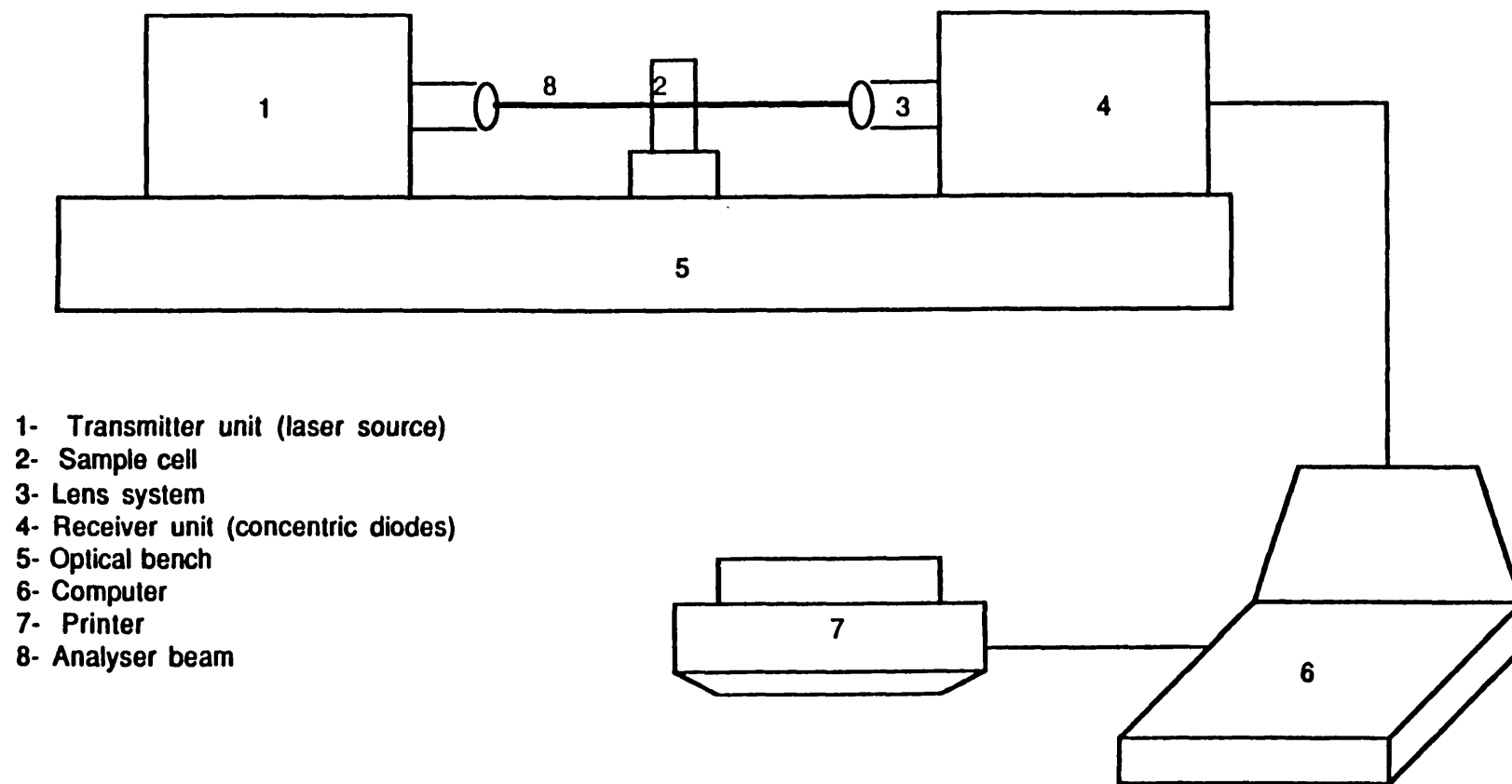


Fig. (3.2): Schematic of the Laser Analyser (Malvern 3600).

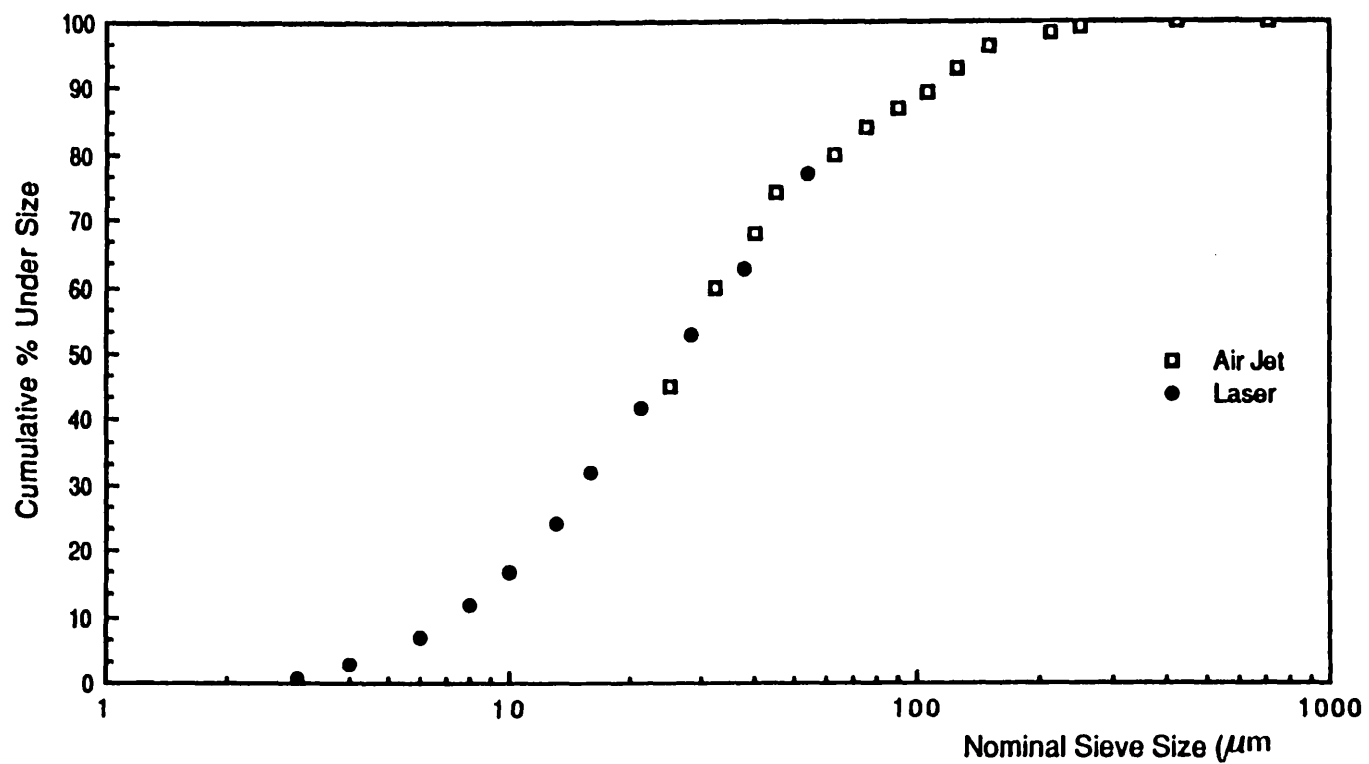


Fig. (3.3): Cumulative under Size Distribution for Coal Type 1.

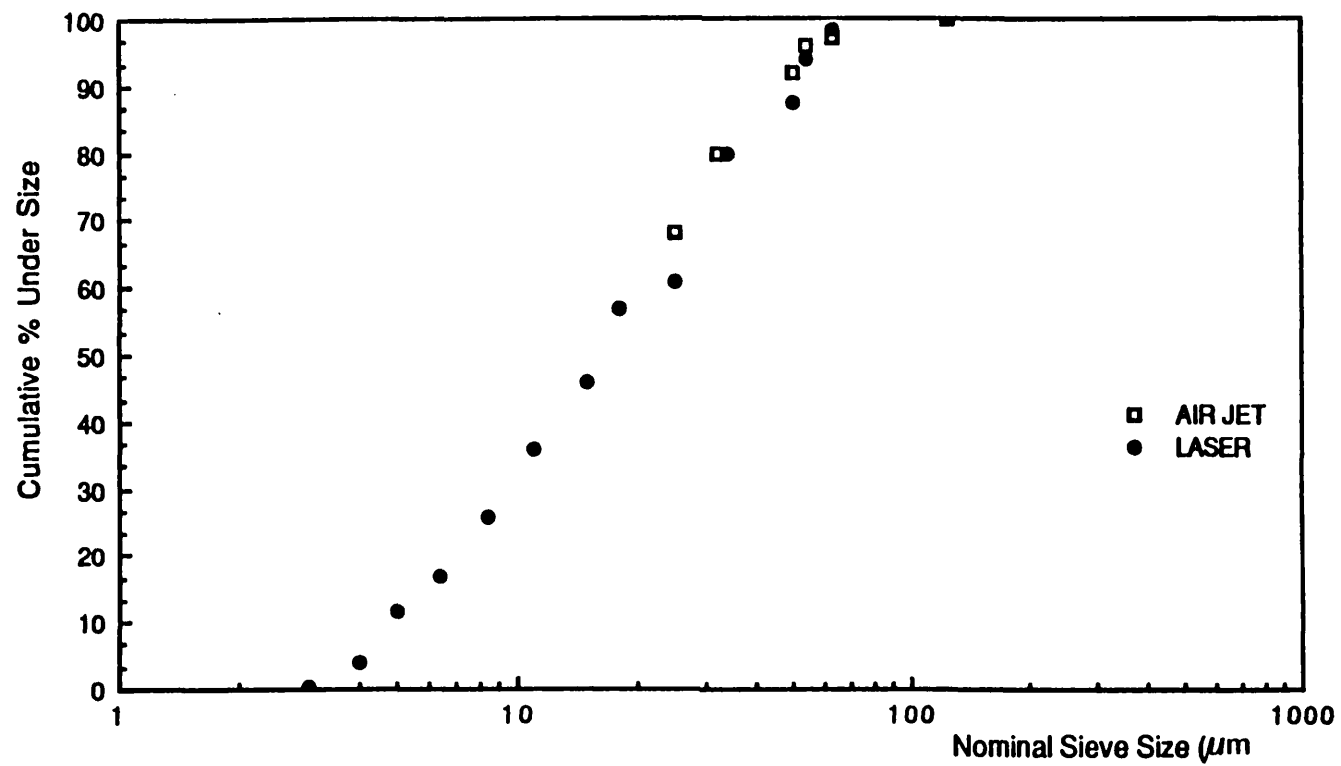


Fig. (3.4): Cumulative under Size Distribution for Coal Type 2.

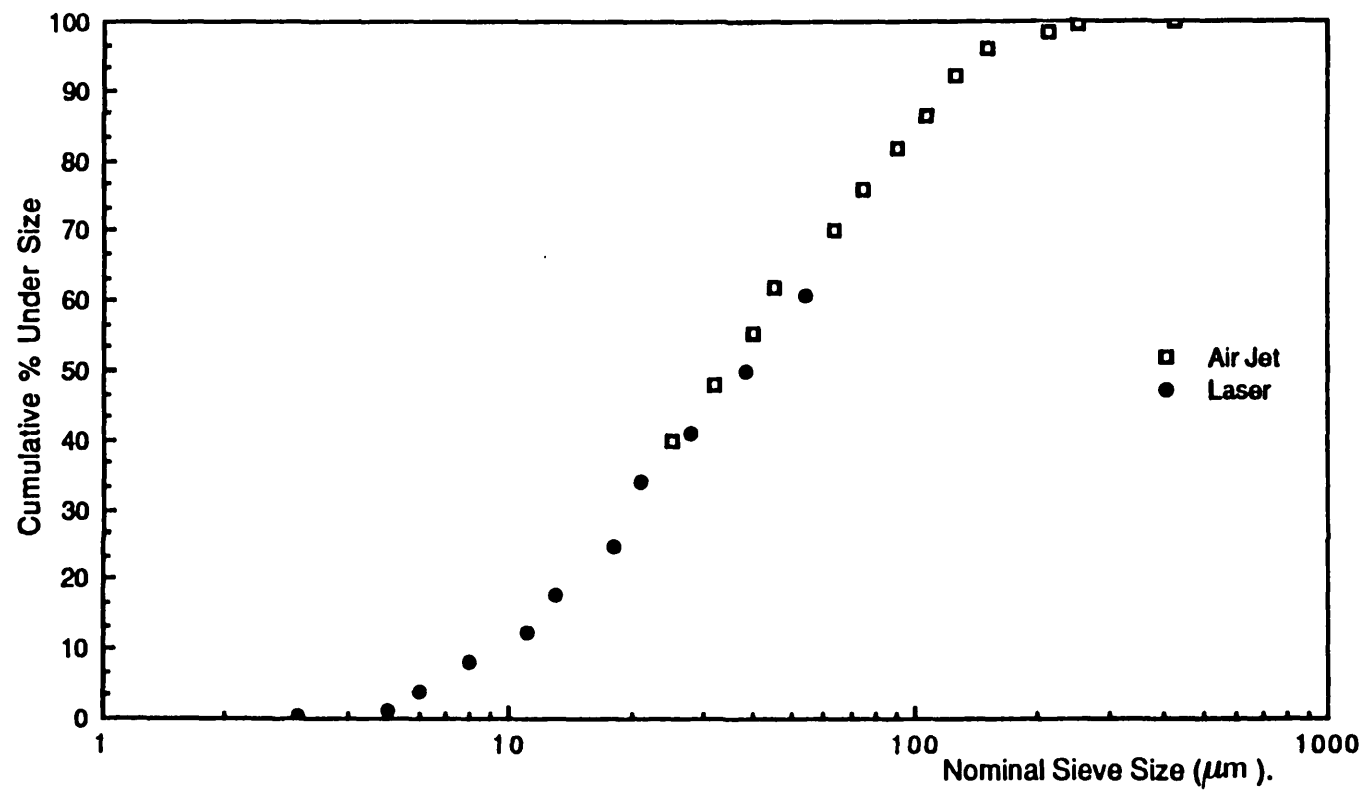


Fig. (3.5): Cumulative under Size Distribution for Coal Type 3.

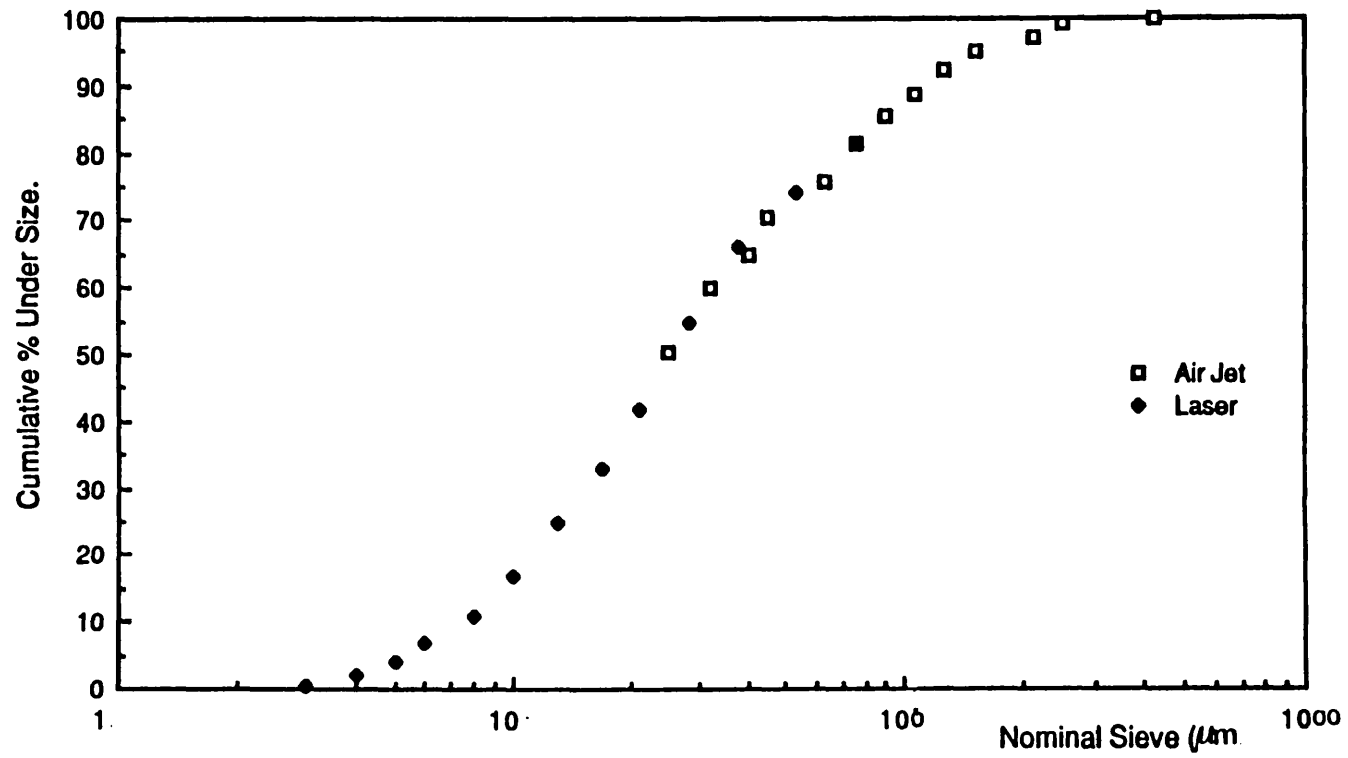


Fig. (3.6): Cumulative under Size Distribution for Coal Type 4.

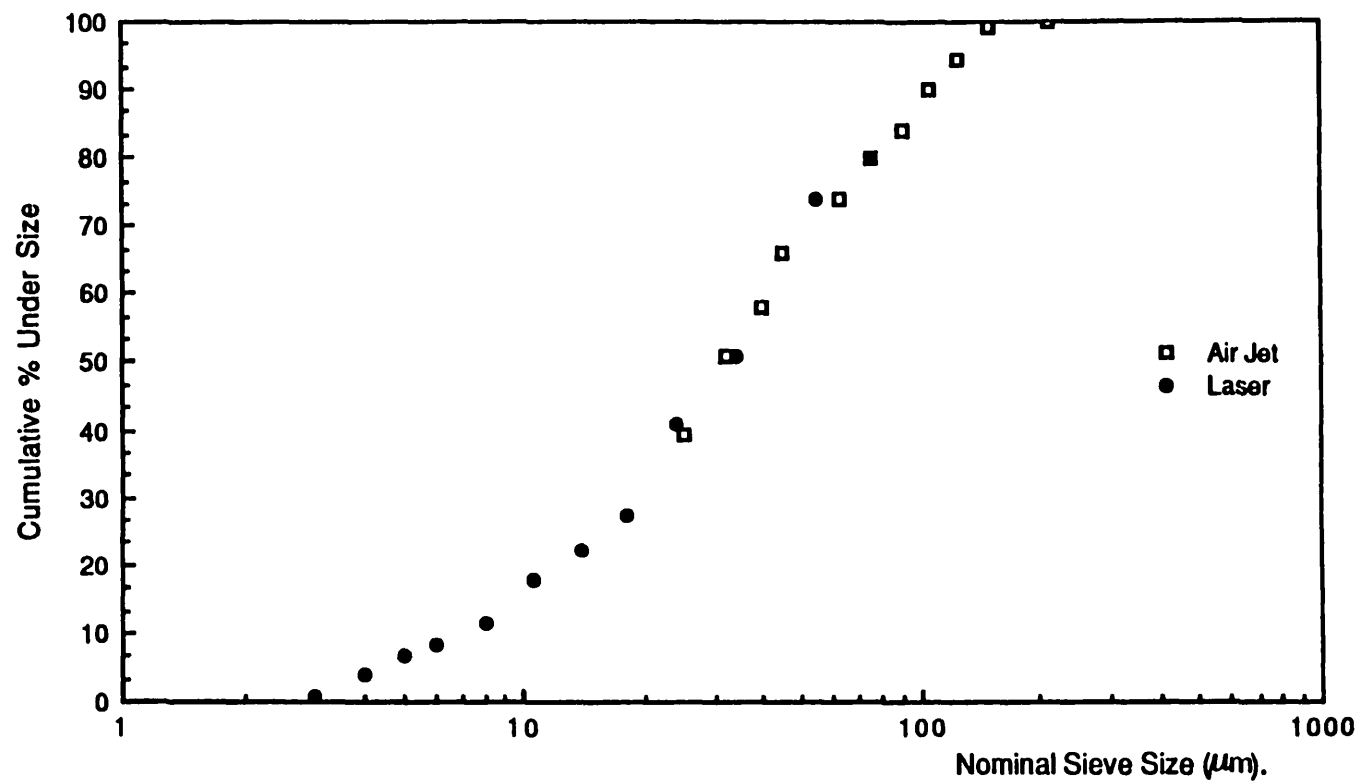


Fig. (3.7): Cumulative under Size Distribution for Coal Type 5.

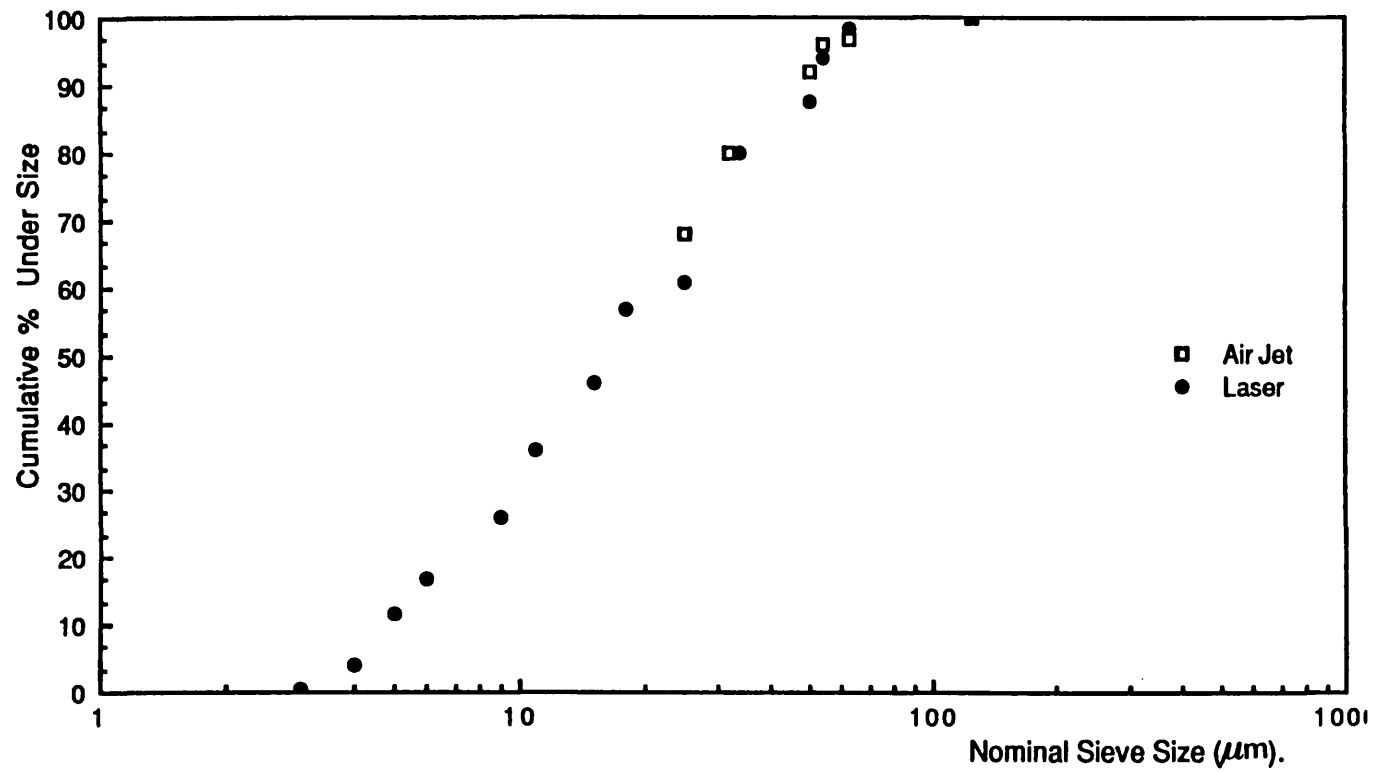


Fig. (3.8): Cumulative under Size Distribution for Coal Type 6.

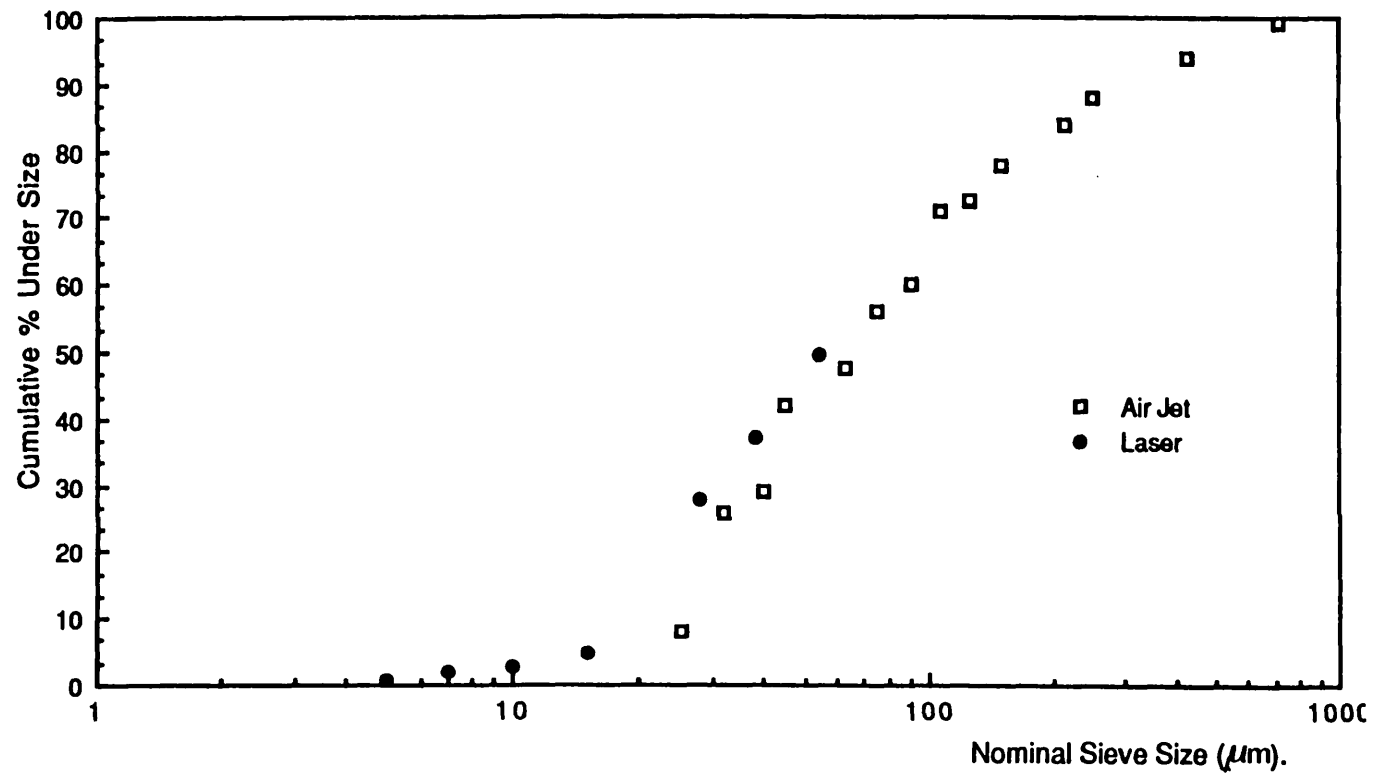


Fig. (3.9): Cumulative under Size Distribution for Coal Type 7.

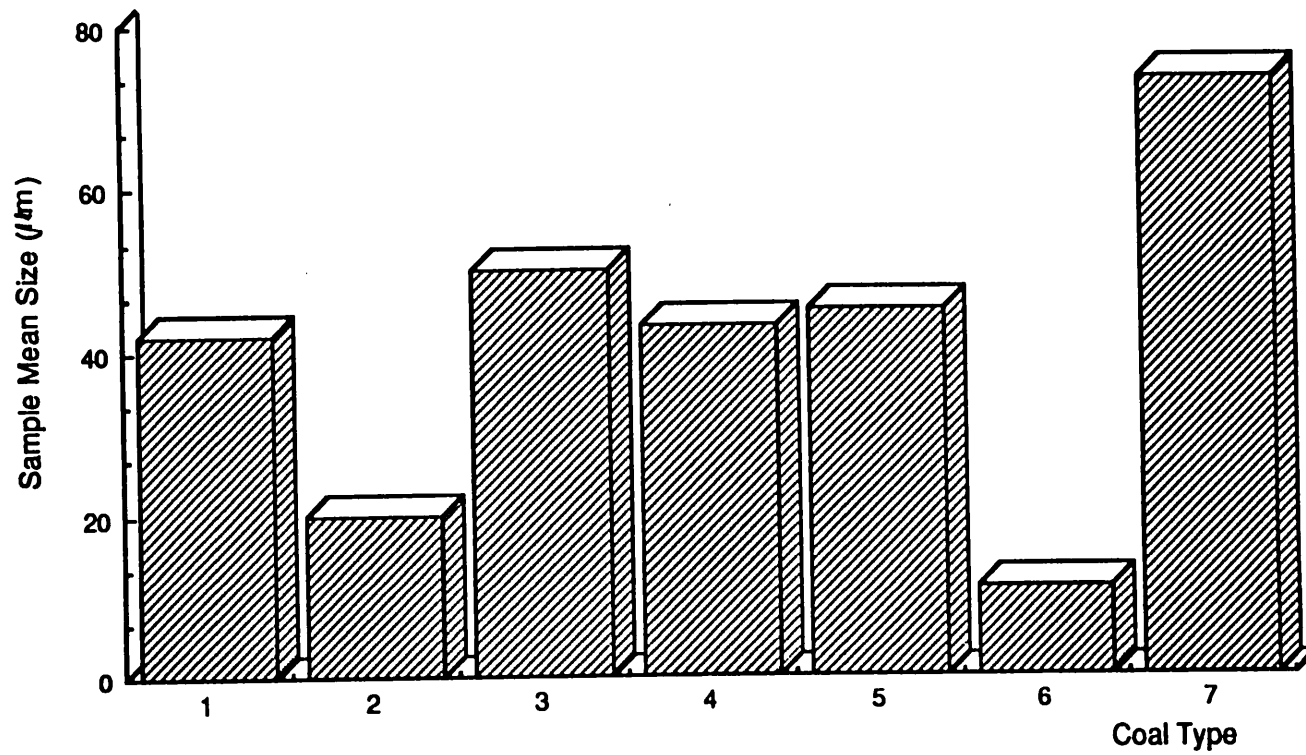


Fig. (3.10): Mean Sizes for Different Coal Types.

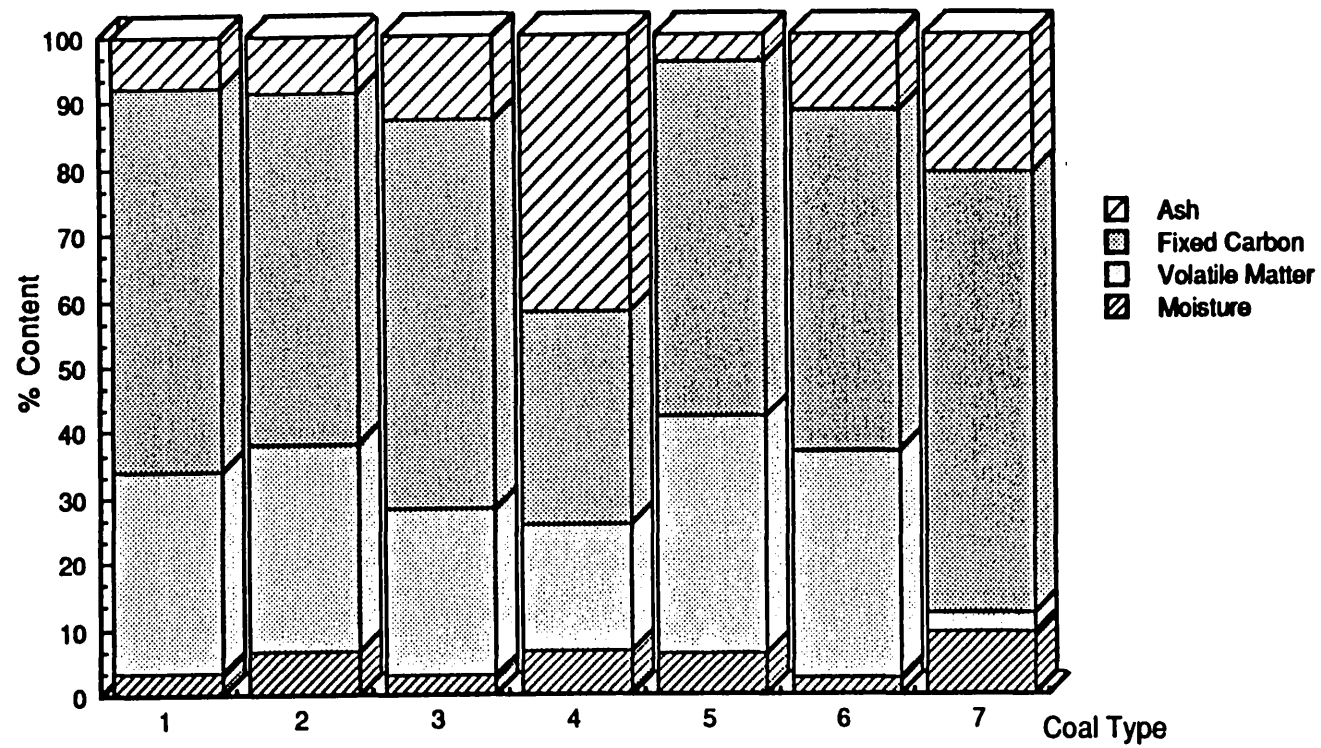


Fig. (3.11): Proximate Analysis for Different Coal Types.

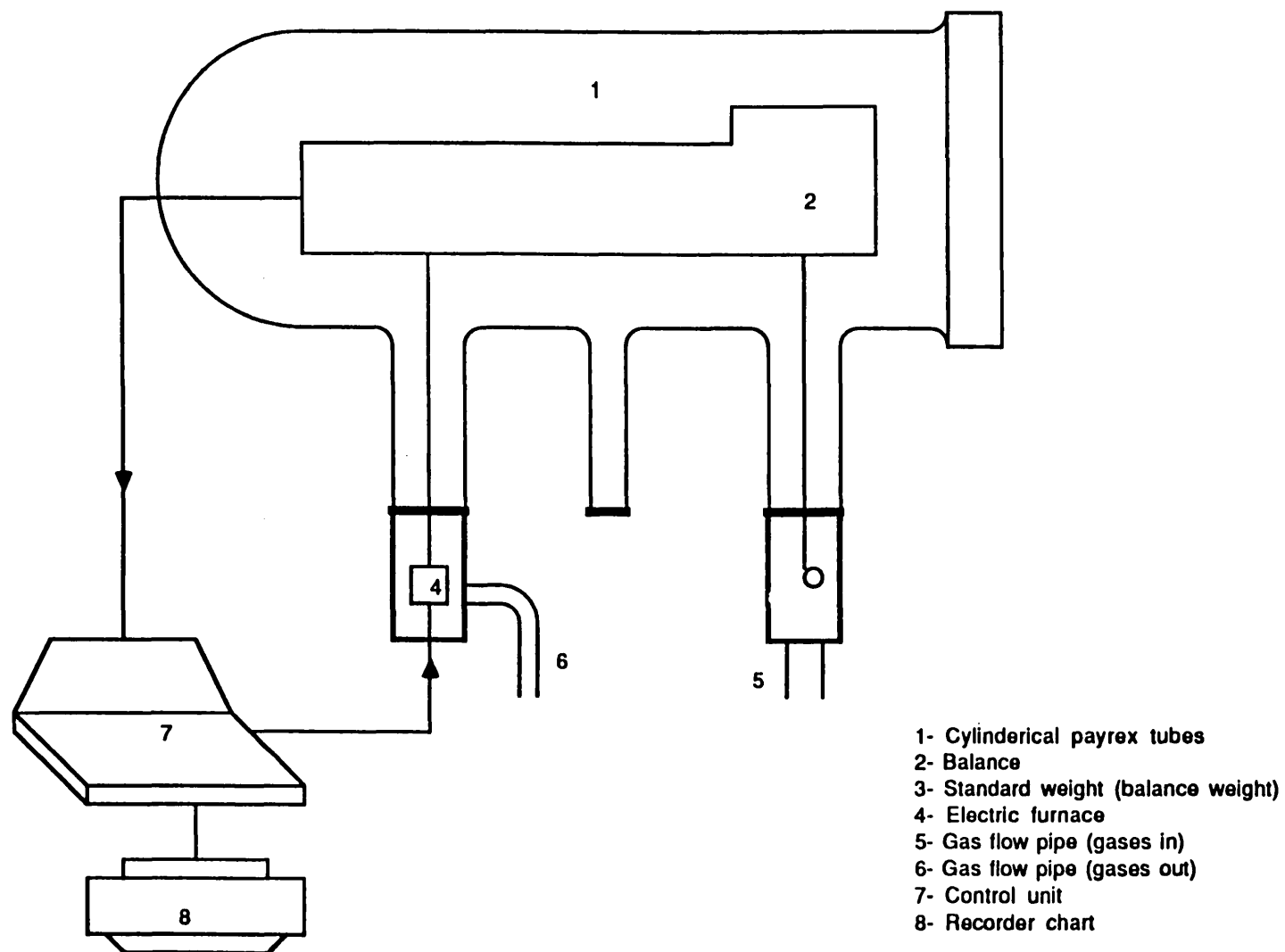


Fig. (3.12): Schematic of the Thermo-Balance (T.G1).

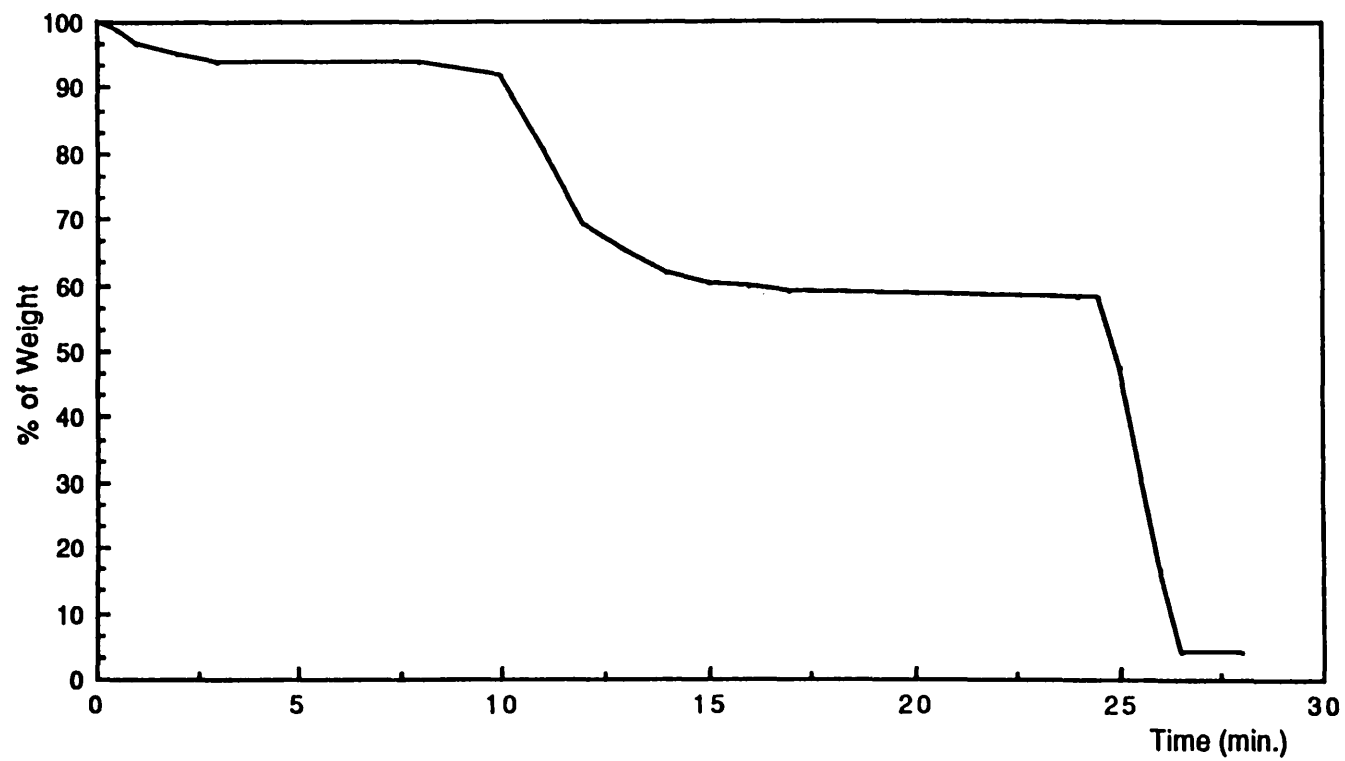
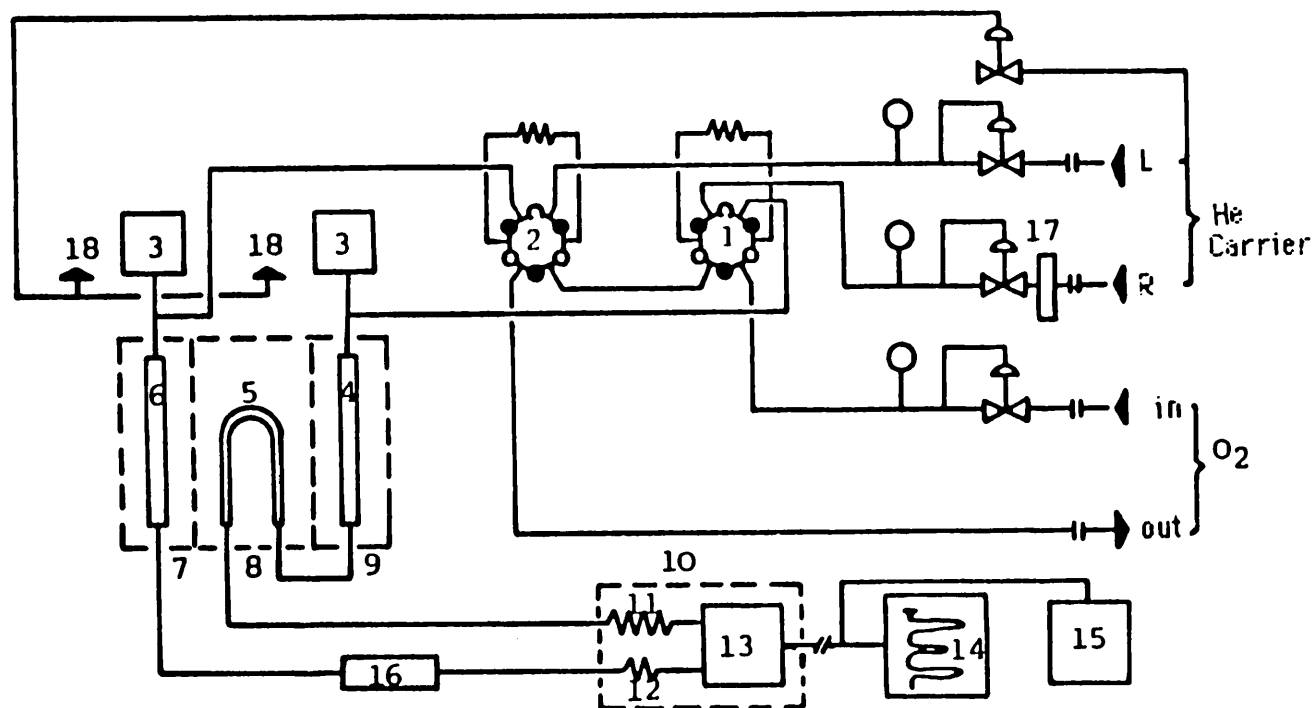


Fig. (3.13): Chart for Proximate Analysis Obtained from TG1.



- 1- Oxygen injection valve (CHN)
- 2- Oxygen injection valve (S)
- 3- Samplers
- 4- Combustion reactor (CHN)
- 5- Reduction reactor.(CHN)
- 6- Pyrolysis/combustion reactor (O/S)
- 7- Pyrolysis/combustion Furnace (O/S)
- 8- Reduction furnace (CHN)
- 9- Combustion furnace (CHN)
- 10- Thermostated oven
- 11- Chromatographic column (CHN)
- 12- Chromatographic column (O/S)
- 13- Detector
- 14- Recorder
- 15- Integrator
- 16- Trap (O/S)
- 17- Doping System
- 18- Purge

Fig. (3.14): Block Diagram of the Element Analyze (Carlo-Erba 1106).

INJECT TIME 01:38:17

{ 05H5101111

1.15 1.00110

2.98

3.72

7.27

11.00ER0

C3

01:38:17

FILE 1 METHOD 0. RUN 8 INDEX 8

PEAK#	AREA%	RT	AREA	BC
1	0.28	1.15	4411	01
2	11.838	2.98	186359	01
3	66.186	3.72	1041953	01
4	21.696	7.27	341558	01

TOTAL 100. 1574281

Fig. (3.15): A Typical Chart for (CHN): Ultimate Analysis
(Carlo-Erba 1106).

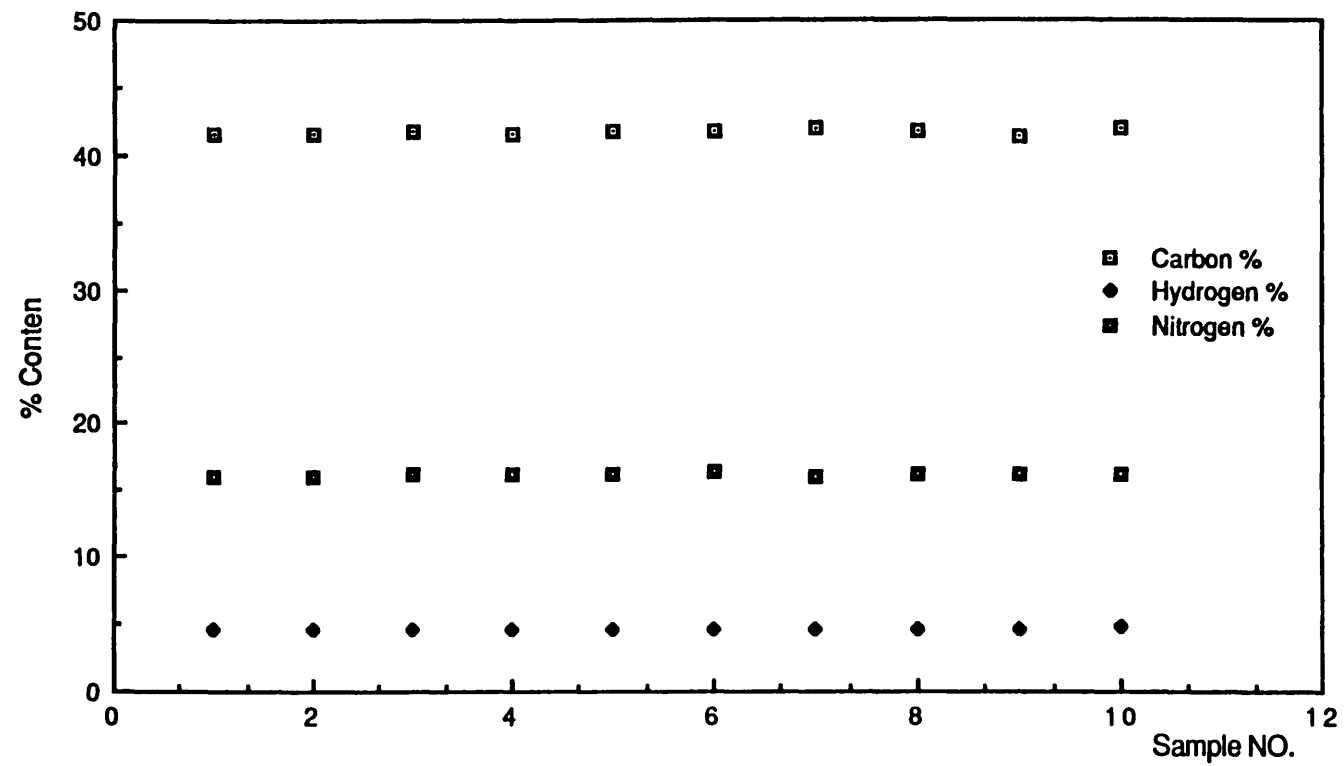


Fig. (3.16): Ultimate Analysis for Standard Sampling.

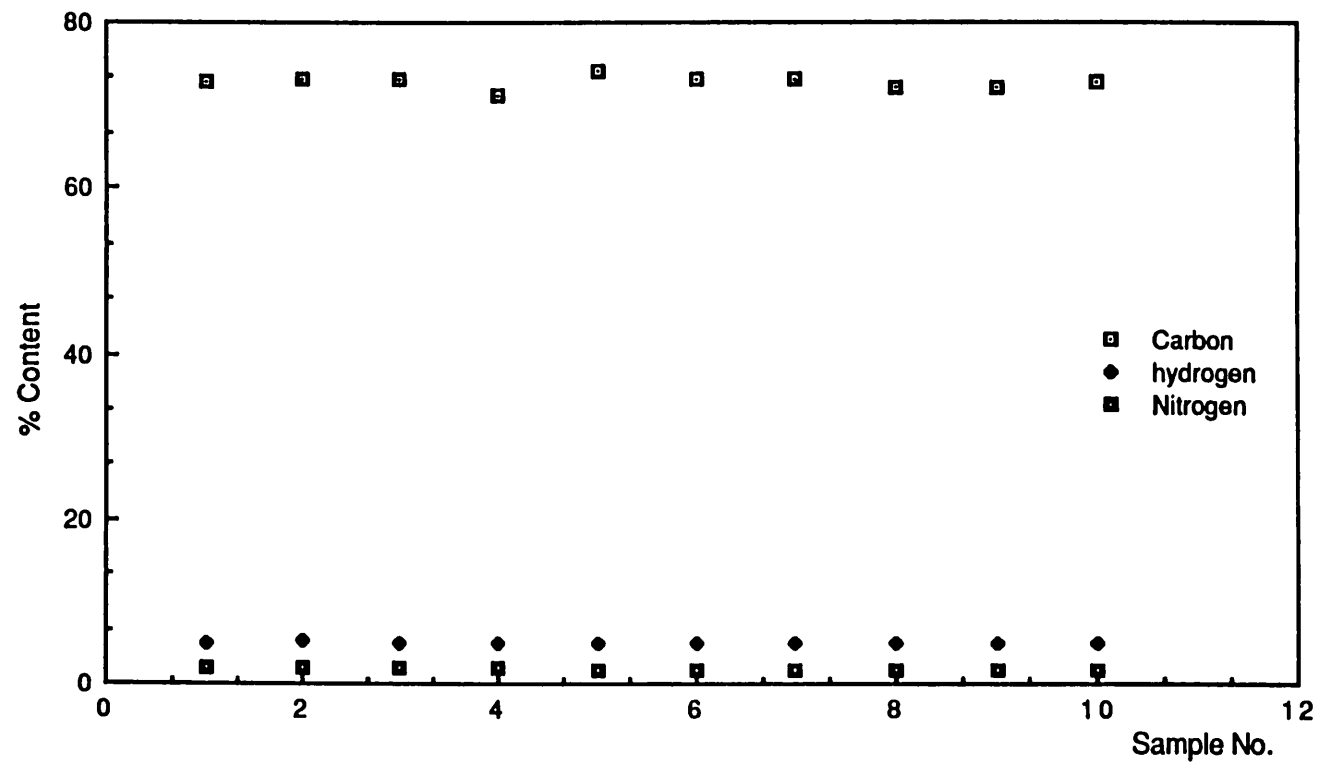


Fig. (3.17): Ultimate Analysis for Coal Type 1.

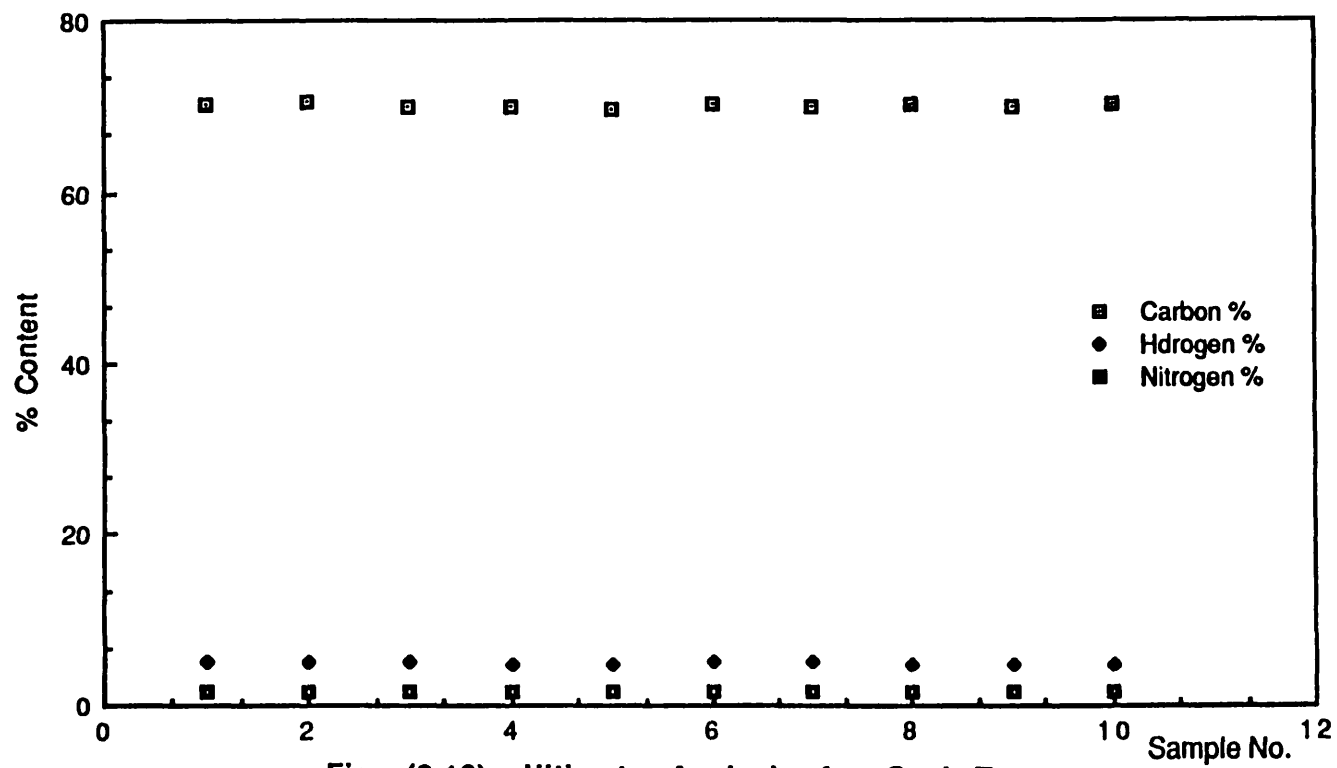


Fig. (3.18): Ultimate Analysis for Coal Type 2.

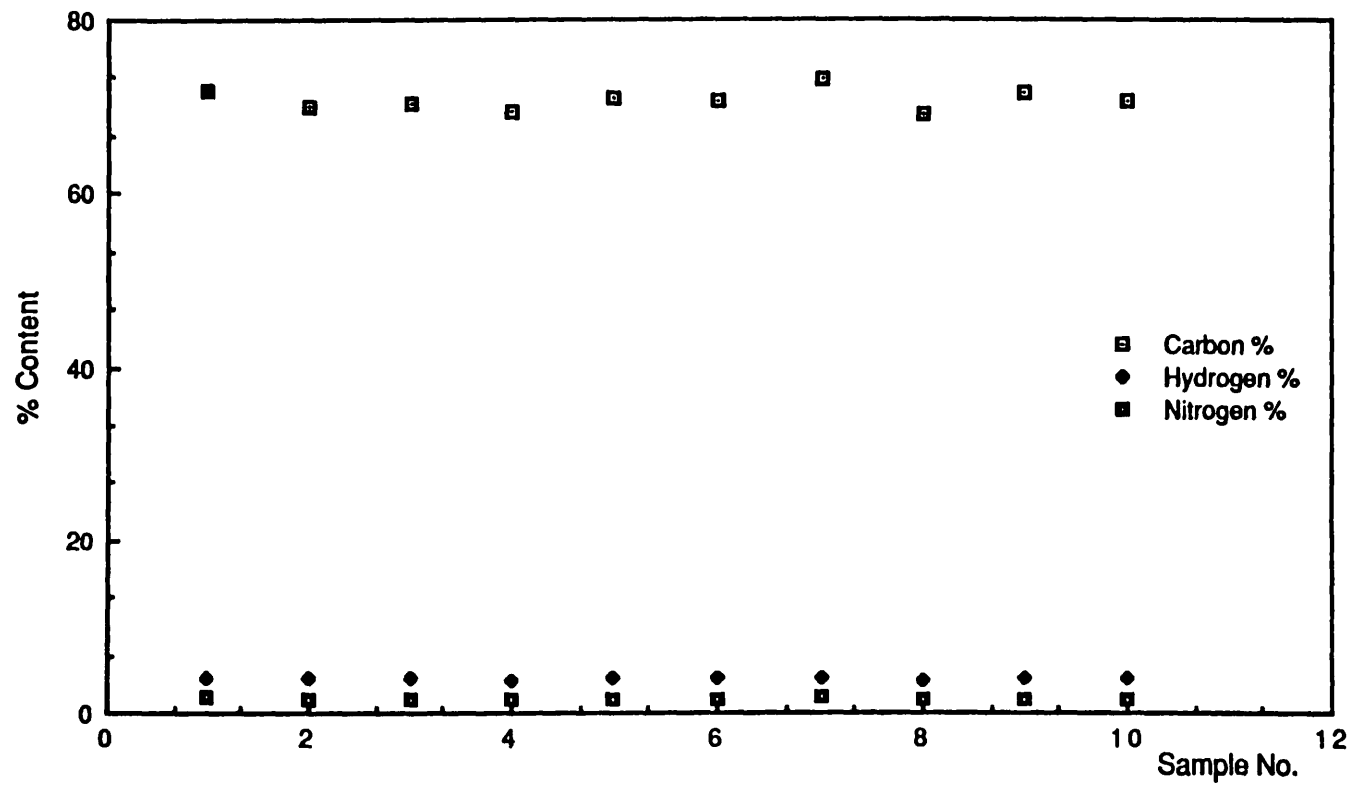


Fig. (3.19): Ultimate Analysis for Coal Type 3.

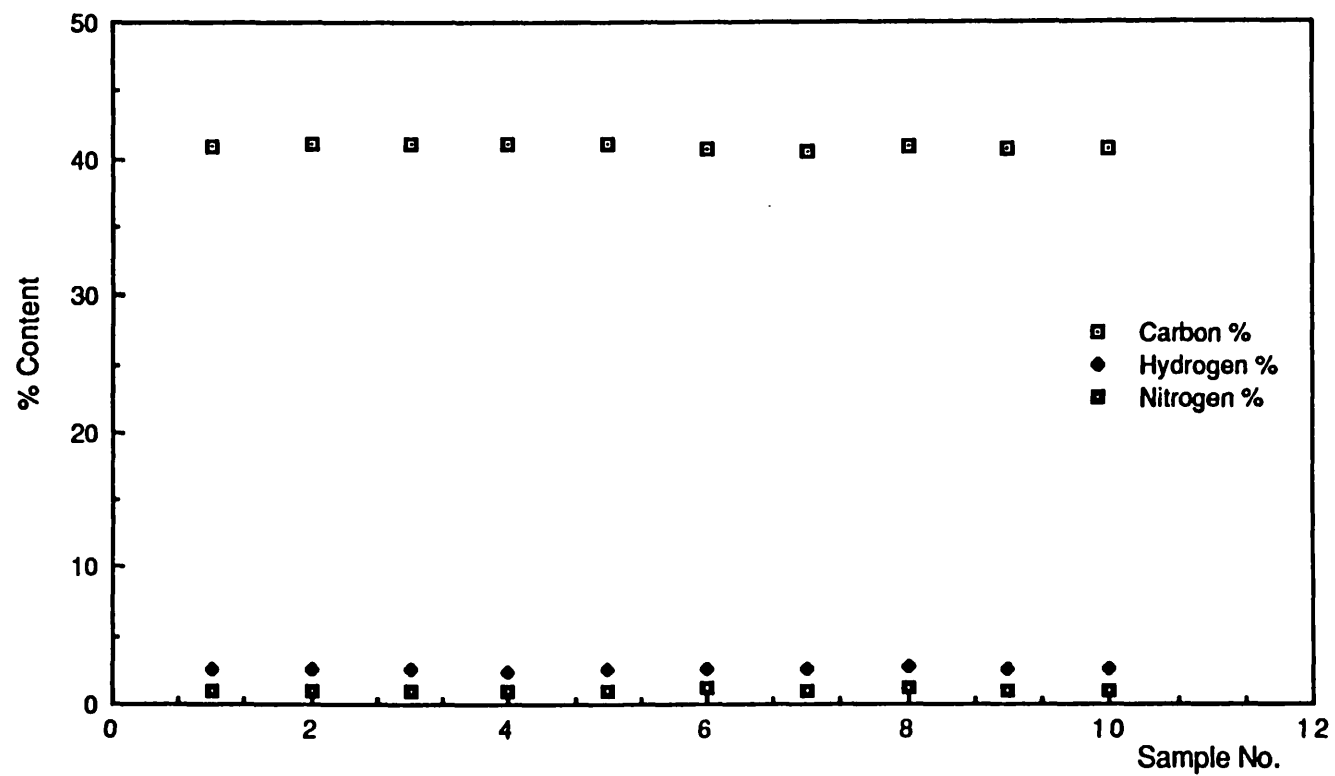


Fig. (3.20): Ultimate Analysis for Coal Type 4.

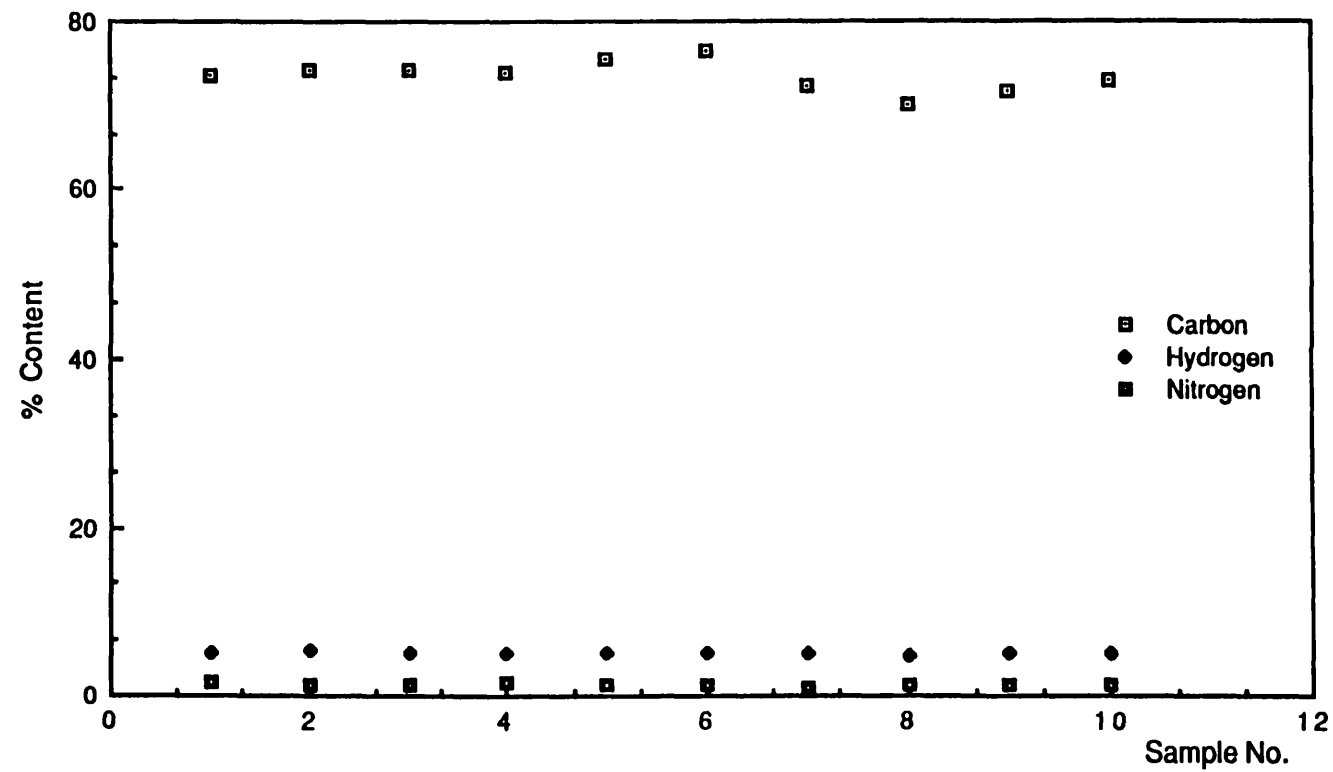


Fig. (3.21): Ultimate Analysis for Coal Type 5.

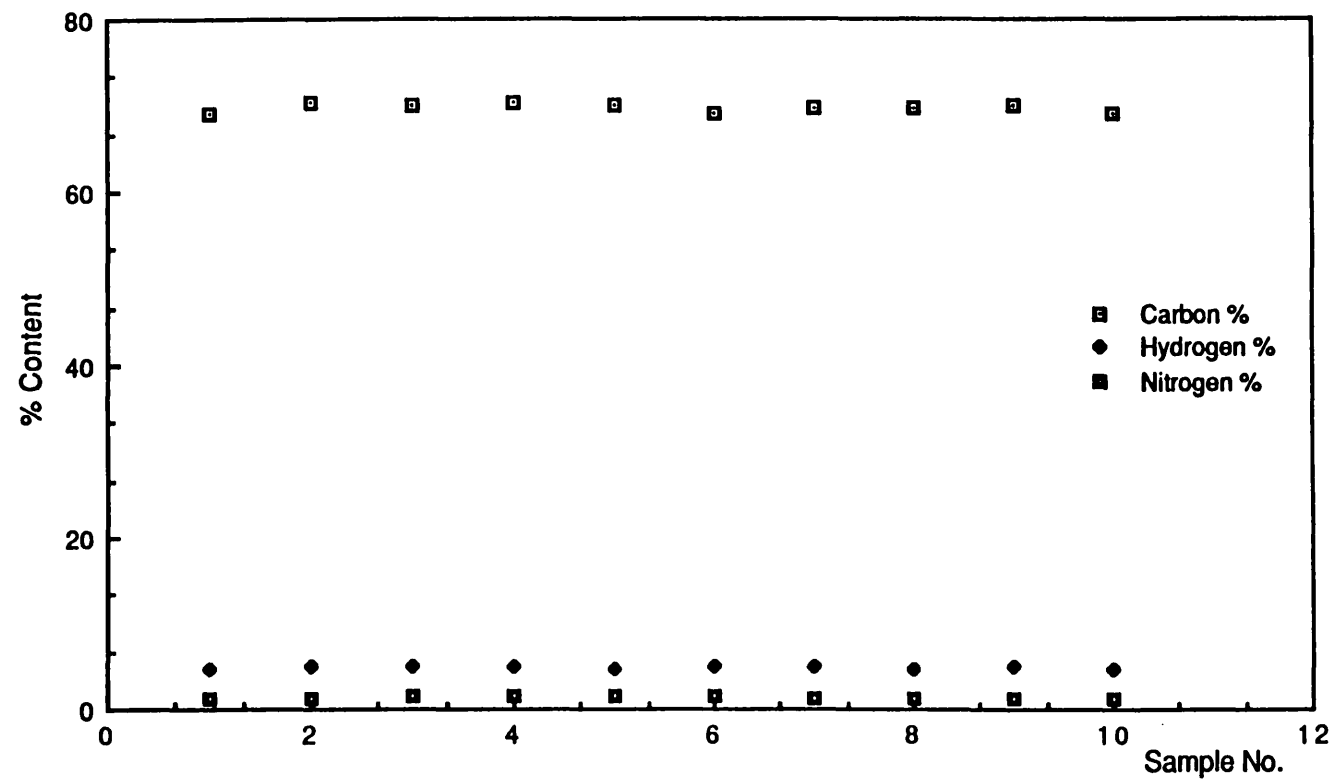


Fig. (3.22): Ultimate Analysis for Coal Type 6.

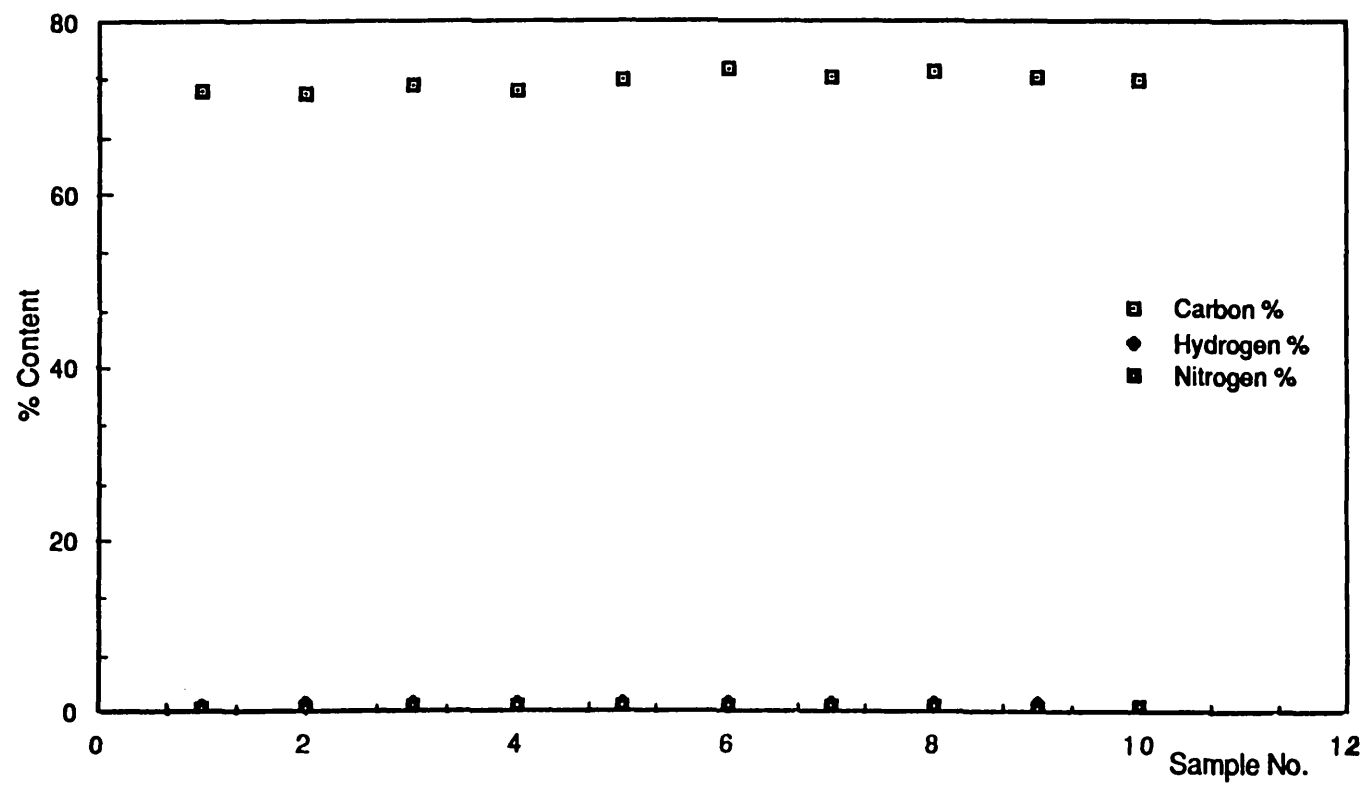


Fig. (3.23): Ultimate Analysis for Coal Type 7.

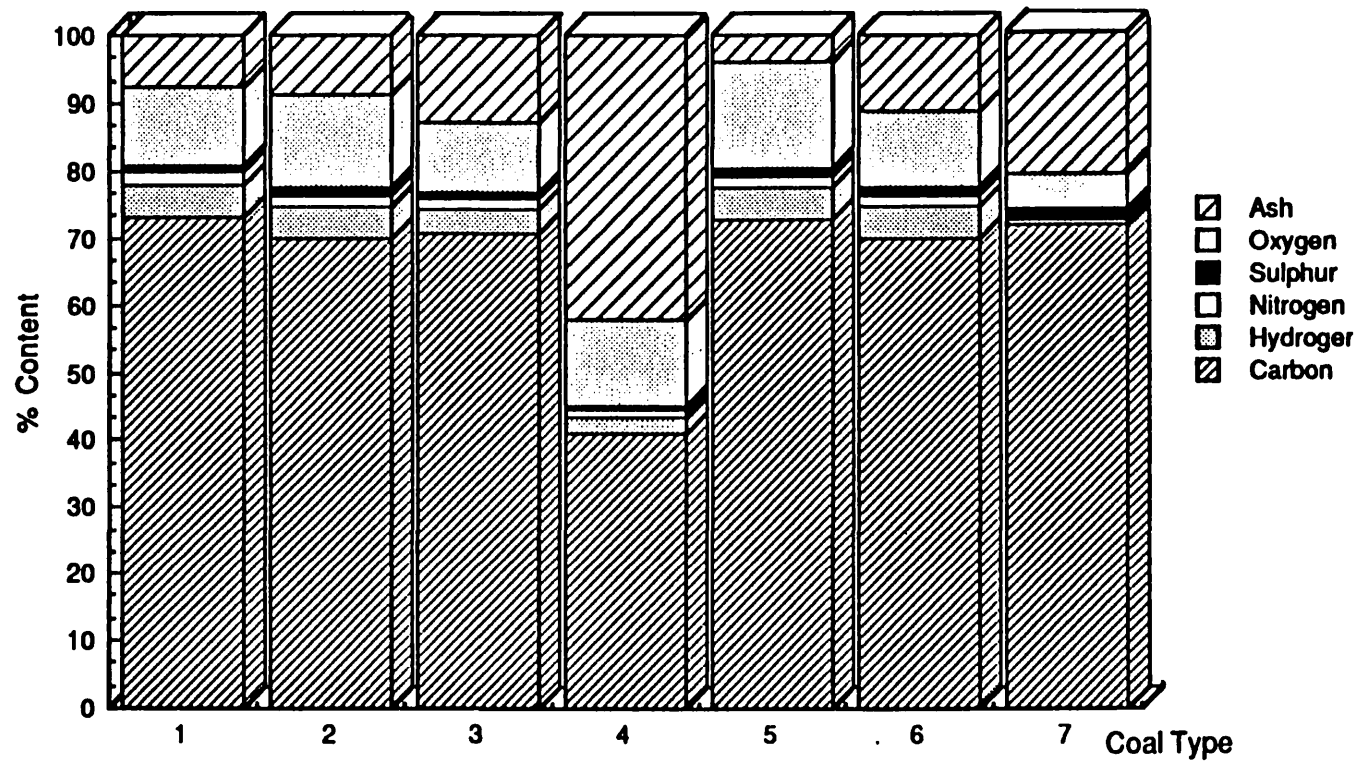


Fig. (3.24): Ultimate Analysis for Different Coal Types.

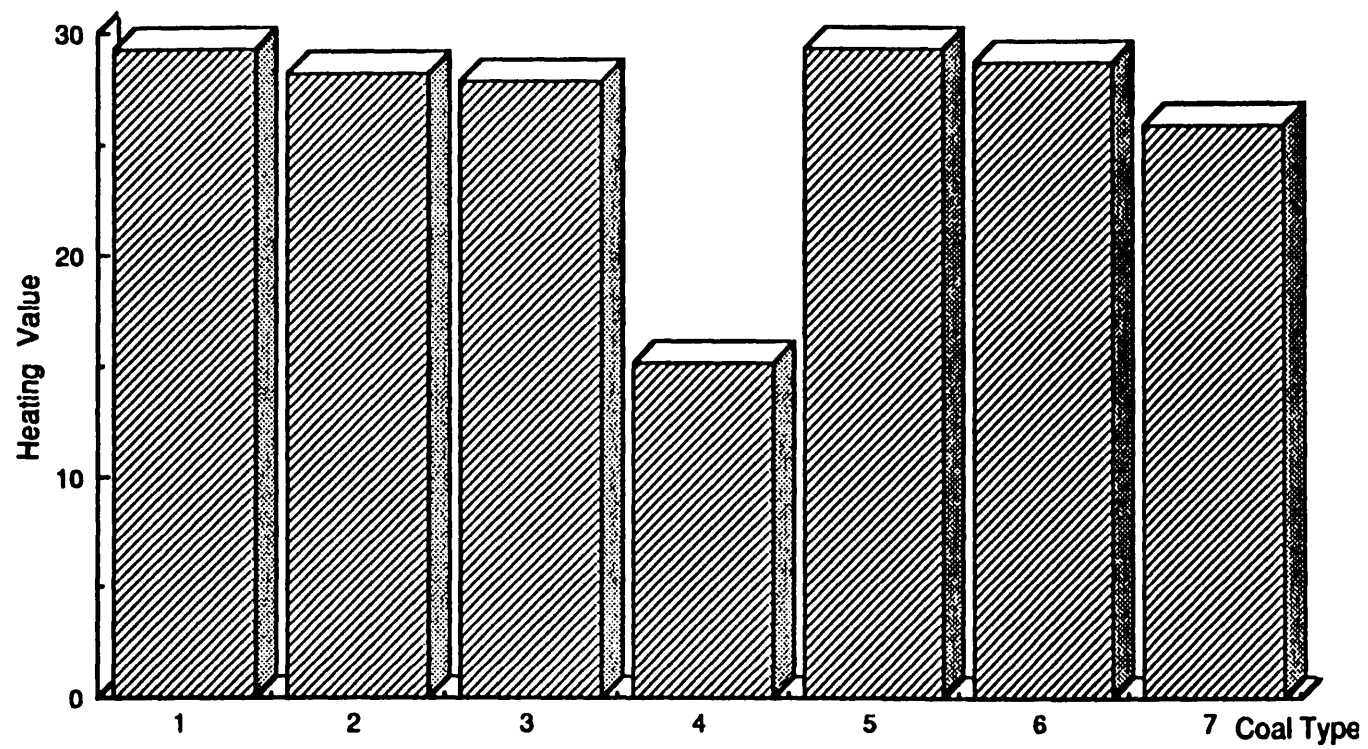
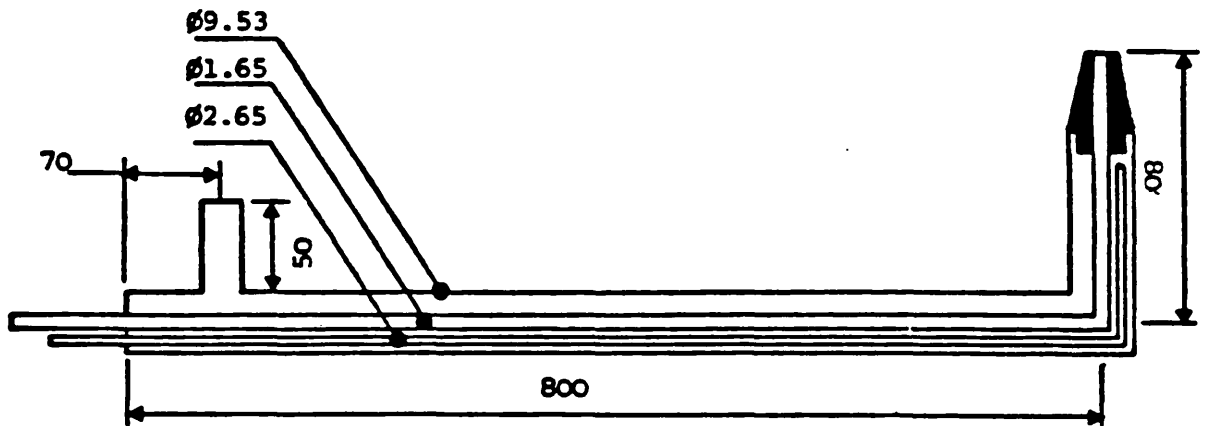
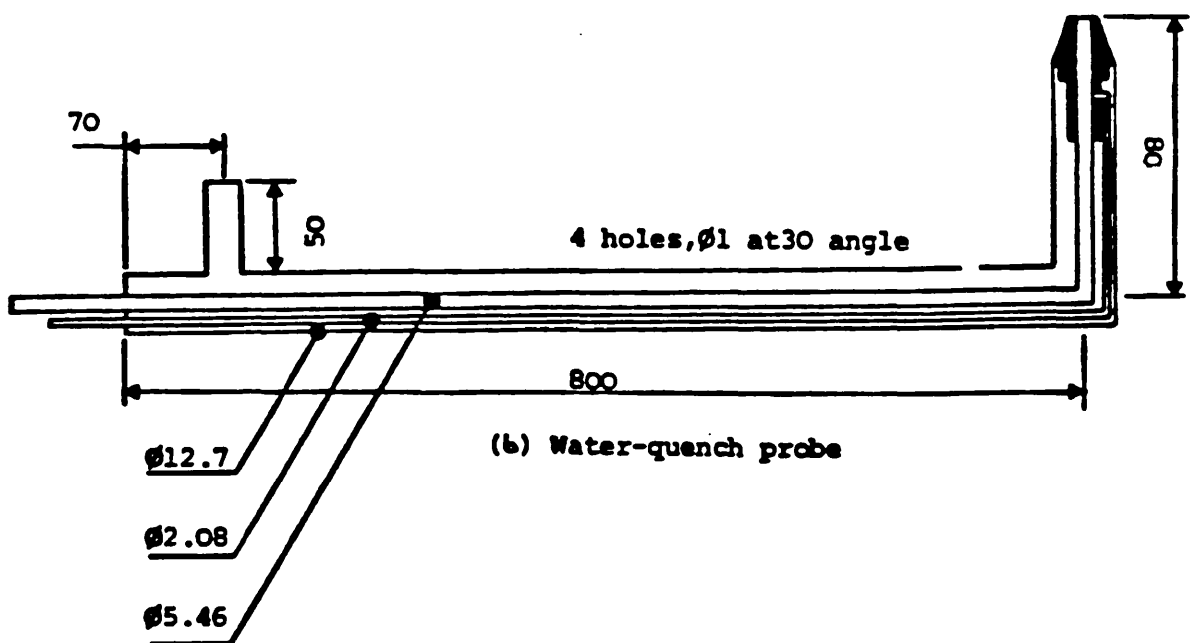


Fig. (3.25): Heating Value for Different Coal Types.

Dimensions in mm

(a) Water-cooled probe



(b) Water-quench probe

Fig. (3.26): Sampling Probes.

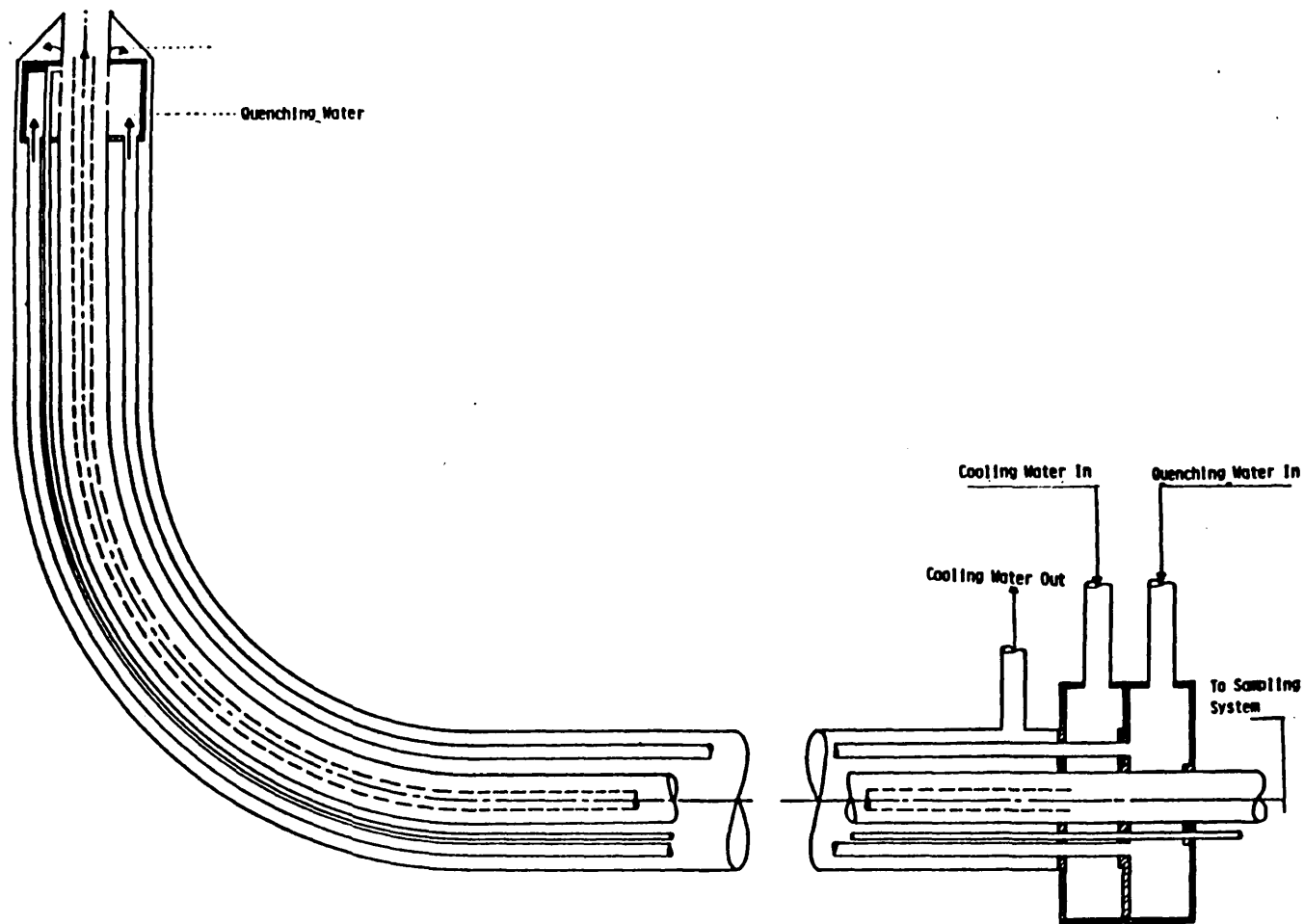


Fig. (3.27): Schematic for Water-Quench/Water-Cooled Probe.

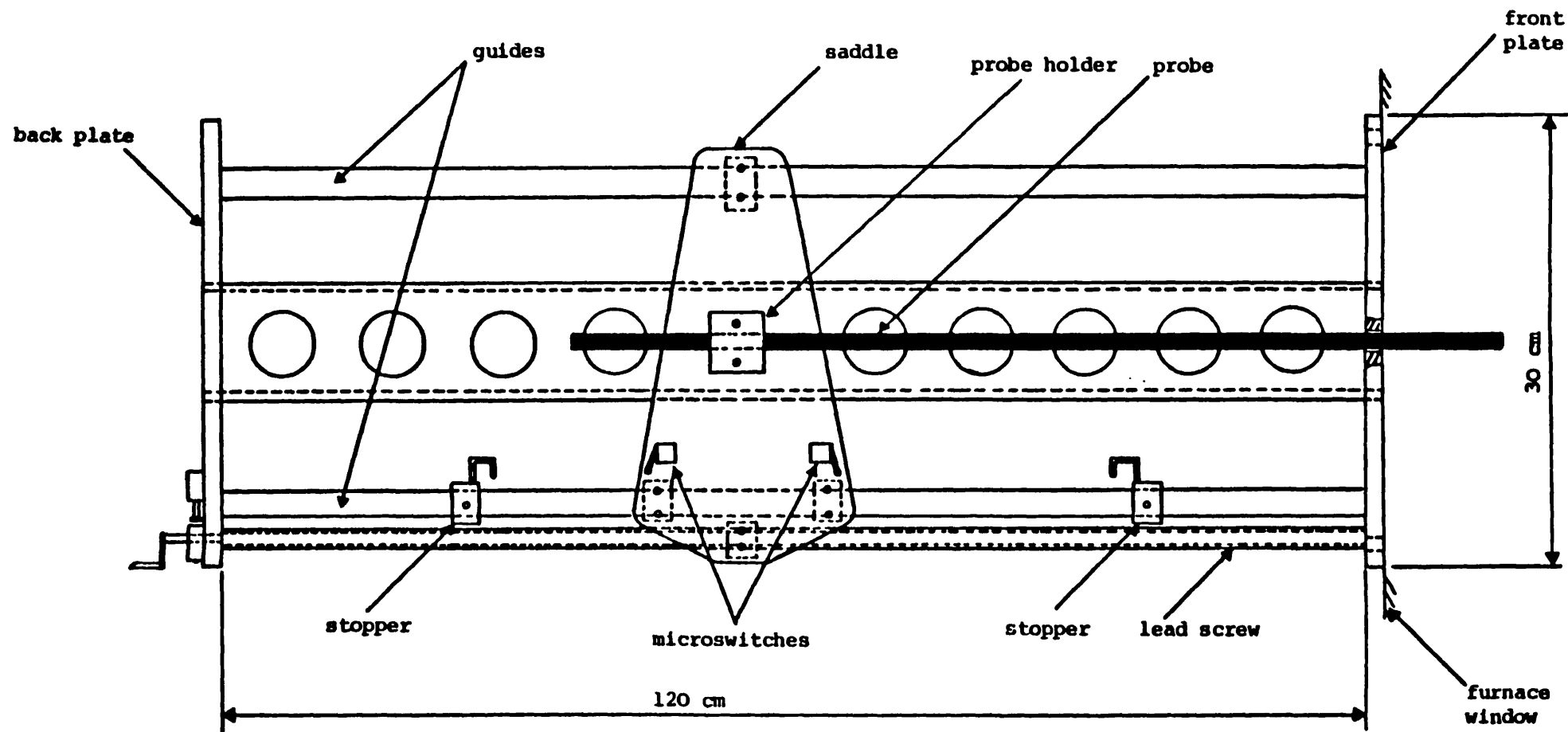


Fig. (3.28): Schematic Diagram of the Traversing Mechanism.

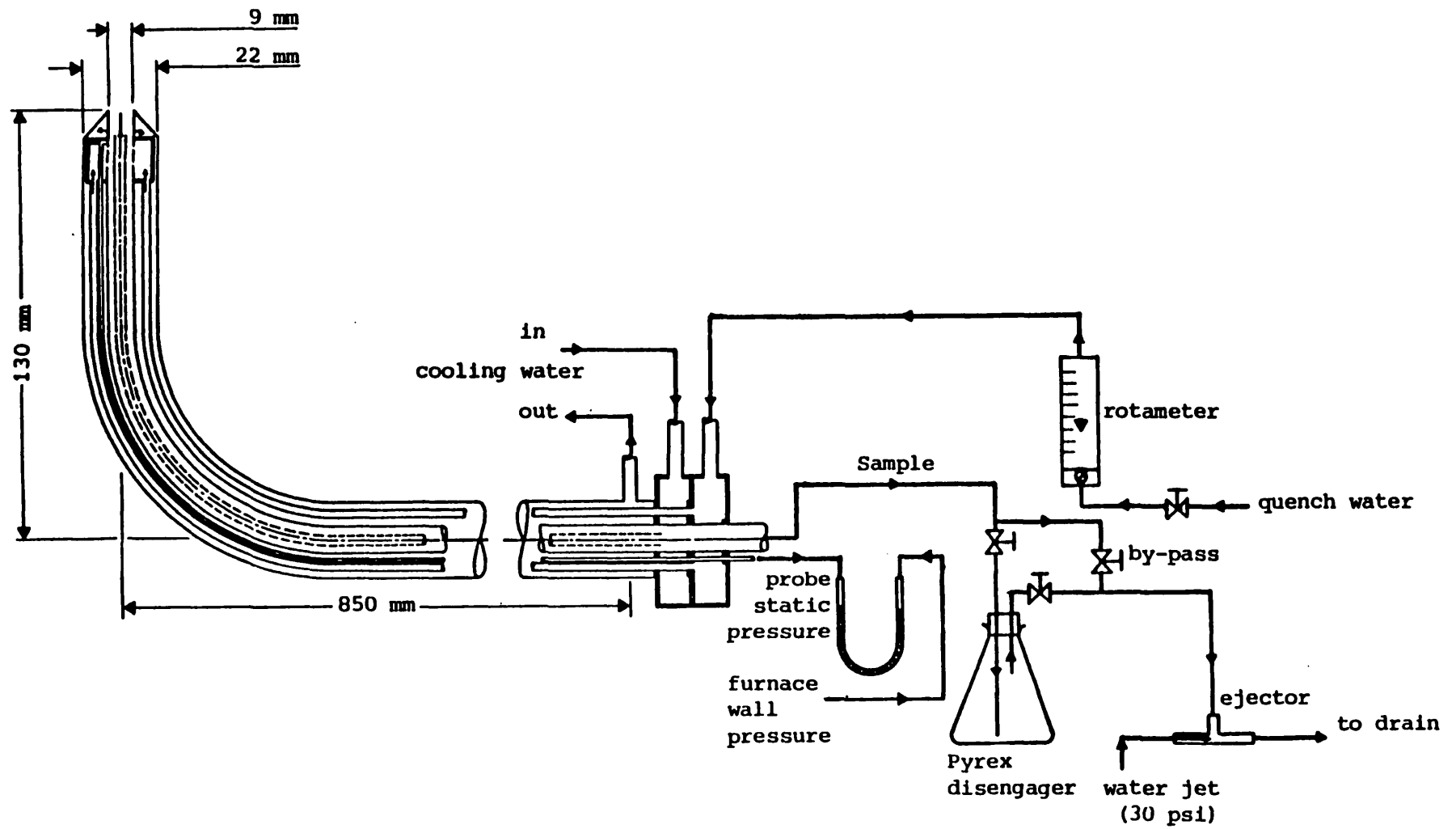


Fig. (3.29): Schematic Diagram of Char Particles Sampling System.

Chapter 4

RESULTS AND DISCUSSION

4-1 Introduction

The performance of inflame measurements on large pulverized coal flames is a difficult and a time consuming task. Experimentors have usually resorted to measuring just the exit conditions of large boilers. Others have conducted measurements in small scale furnaces or drop tube furnaces to study the combustion behaviour of single or a few particles or diluted particle suspensions, see chapter (1). Data from large scale furnaces which utilise a burner configuration similar to that of the present study have emerged in the main from IFRF and from Smoot's group at Brigham Young University, Utah, USA. Most of these studies are reviewed in chapter (1).

Several sets of inflame char burn-out data are presented in this chapter. The data will enhance further the physical understanding of the process of the combustion of pulverized coal and are valuable for the validation of computer prediction codes. The validity of the measurements together with main measurements problems are out-lined in section 4.2. The behaviour of coal particles during combustion is presented in section 4.3. In section 4.4 axial char burn-out data are presented and discussed for four excess air ratios, four levels of the swirl number, and three momenta ratios as well as the radial data for two swirl numbers. Flame stability limits are presented and discussed in section 4.5. A summary of the chapter is presented in section 4.6.

4.2 Measurements Validity

The measurements described in this chapter required periods of long duration of furnace firing, typically ten hours a day over a number of weeks. It follows that much care had to be taken as to the material uniformity of the fuel, the consistency of fuel and air flow rates, the preheat temperature and the geometry and condition of the burner and the furnace. In order to verify the consistency of the measured data from one day to another, the gas species concentration near the furnace exit was always measured and the flame stability limits were observed prior^{to} taking measurements. A prior measurement of particle burn-out at furnace exit, for each set, typically 98%, permitted the calculation of the theoretical gas species concentration. The disparity between the two in the oxygen concentration was not permitted to exceed $\pm 10\%$ of its theoretical value.

The main measurements difficulties (gas concentration and char burn-out) in the present study were:

- (i) Instrumental error
- (ii) Maintenance of input flow conditions: calibration, coal analyses, preheat temperature, and inlet flow profiles.
- (iii) The burner geometry: misalignment, position of the primary tube, asymmetrical surface of slagged quartz.
- (iv) Mechanical condition of the swirl generator.
- (v) Ash fouled walls.

To prevent the above problems the following steps had been followed:

- (1) The instruments were checked against standard samples as well as other

laboratories analysis.

- (2) The air flow rates were re-calibrated after two sets of data collected.
- (3) The coal analyses were re-examined after each set of data collected.
- (4) The swirl generator was visually checked for damage or blockage.
- (5) The burner was aligned after each set of data collected.
- (6) During the experiments the burner quarl was kept free of slag.

For a single set of data, using ash as a tracer, a material balance ($m_{in}=m_{out}$) was calculated. The outflow (m_{out}) was found to be less than inflow (m_{in}) by about 5%. Because this calculation involves a number of assumptions and includes experimental errors from the measurements of all the involved quantities, when applied to this experimental system, a general operating rule was developed; namely if the oxygen concentration at the furnace exit was within $\pm 10\%$ of its theoretical value, a material balance was deemed to be unnecessary. A heat balance also was calculated, for the same single set of data, from measurements of cooling water flow rates and the temperature rise as well as the exhaust gas flow rate and temperature. Typically 5% of the heat input was not accounted for.

4.3 Coal Particles Behaviour in the Combustor

Devolatilization converts coal into volatile products and solid residue. The devolatilization is, therefore, a result of complicated sequence of phenomena, involving a wide spectrum of chemical reactions coupled with the transport of the released volatiles species through the coal structure. Knowledge of the kinetics of devolatilization is required for understanding the combustion of

coal particles in flames. Volatiles evolution is known to influence the combustion of solid particles, and the predominance of volatiles generation on flame stability is established.

4.3.1 Coal Ignition Mode

It has traditionally been assumed that complete devolatilization of a coal particle occurs before the combustion of the residual char begins, and that the volatiles are assumed to burn rapidly compared with the burning time of the char, Field et al (1967). However, on the basis of combustion studies in a plug-flow reactor, Howard and Essenhigh (1965, 1966, 1967), suggested that for particles larger than 65 μm diameter (critical diameter) some combustion at the particle surface takes place before devolatilization becomes appreciable. This is followed by the release of volatiles which emerge at such a rate that they prevent oxygen from reaching the particle surface. Particle combustion is then inhibited until the rapid devolatilization ends. For particles smaller than this diameter, or for low devolatilization rates, both heterogeneous and gas-phase volatiles combustion proceed simultaneously. Suuberg et al (1978) estimated the critical diameter to be about 40 μm .

The theoretical analyses of Bandyopadhyay and Bhaduri (1972) and Annamalai and Durbetaki (1977) are in general agreement with the hypothesis of Howard and Essenhigh (1967) but indicate that the ignition behaviour will also depend on the volatiles content and on the ambient oxygen concentration. The hypothesis of heterogeneous ignition has further been tried experimentally in a jet stirred reactor with a heating rate of 10^6 $^{\circ}\text{C}/\text{sec}$ by Goldberg and Essenhigh (1978). Their results show that there can be mass loss by both pyrolysis and

heterogeneous reaction, with the balance between the two determined by the fuel/air ratio. Under fuel rich conditions heterogeneous reaction is completely suppressed. As the mixture becomes leaner an increasing fraction of mass loss is by heterogeneous reaction. However, they suggested that the mechanism of ignition is the same as that of Howard and Essenhigh (1967) who experimented at a lower heating rate of 10^4 °C/sec.

Seeker et al (1978) postulate from their experimental observations that for smaller particles (mean diameter less than 10 μm) ignition is due to heterogeneous combustion, whilst for larger particles ignition is due to homogeneous reactions. McLean et al (1981) show through time resolved shadow-graphs of burning coal particles (mass mean diameter 65 μm), that these particles are shielded from oxygen by the envelope of the released volatiles so that combustion is initiated by ignition of the volatiles. Similar observations are also made by Hertzberg et al (1982) and by Timothy et al (1982).

More recent experiments in a small drop-tube furnace performed by Chen et al (1984) and Tognotti et al (1985) exhibit ignition temperatures of coal and char particles as low as 700 K. Their results are in agreement with the theory based on heterogeneous ignition. Computer predictions of coal particles devolatilization by Musarra et al (1986) use the assumption that ignition of particles smaller than 20 μm is due to heterogeneous combustion whereas for larger particles homogeneous volatile combustion are more important. The results of single particle ignition experiments are probably not directly applicable to the ignition of dust clouds due to the "cooperative" mechanism. Cassel and Liebman (1959) observe a decrease in the ignition temperature with increasing dust concentration, the decrease being more pronounced for finer particles.

The present investigation aims to obtain devolatilization and combustion information from a large scale laboratory furnace for pulverized bituminous coal (UK Gedling coal) with a particle size of 80% by weight under 75 μm , this fineness of grind is believed to be directly applicable to practical pulverized coal flames.

4.3.2 Results and Discussion

Coal particles reaction is an essential aspect in all coal combustion processes. These reactions have direct impact on the formation of fly-ash particles, nitrogen and sulphur-containing species, and other pollutants. Coal reactions are generally divided into two distinct components Gray et al (1974) namely: devolatilization and char oxidation. When coal is heated, the coal moisture evolves early as the temperature rises. With increasing temperature tars and hydrocarbons are emitted. Given sufficient available oxygen these products react with oxygen in the vicinity of the residual particles. The residual mass, enriched in carbon and depleted in oxygen and hydrogen, and still containing some nitrogen, sulphur, and most of mineral matter (ash), is referred to as the char. The nature of the char is dependent on the original coal type and size and also on the conditions of pyrolysis and char formation.

Plate (4.1) shows microphotographs of the raw Gedling pulverized coal and a char sample at the exit of the furnace. The large pores or blow-holes appearing in the char sample are initiated by the jetting out of the volatiles. The residual char particles oxidize or burn heterogeneously with oxygen diffusing from the surrounding to and into the particle. This heterogeneous process is often much slower than the devolatilization process. Its rate varies with coal type,

temperature, pressure, char characteristics and oxygen concentration. Devolatilization and char oxidation may take place simultaneously, especially at very high heating rates. The discussion that follows attempts to give insight into the characteristics and the nature of these reaction processes for the Gedling coal fired in a combustor that closely simulates practical environment.

The relation between weight loss (dry basis) and time, obtained from the TG thermogravimetric balance (proximate analysis, see chapter 3), for various locations on the centreline of the flame are plotted in Fig. (4.1). Each curve is characterised by a devolatilization region followed by a combustion region with rapid weight loss when oxidation occurs. The percentages of volatile matter, fixed carbon and ash of the solid char samples, as measured by proximate analysis along the flame axis for the running conditions of Table (4.1), are presented in Fig. (4.2). It appears that a small amount of the volatile matter is carried in the unburned residue leaving the furnace. This volatile residue survives over a substantial length of the flame and therefore appears to be relatively stable component of the original volatile matter. These data furnish a general picture of the combustion mechanisms in the coal flame under investigation.

As discussed at the beginning of this section the size of the particles can play a significant role in the coal ignition mode. It can be argued that different schemes of the ignition mechanisms happened in the present case due to the size distribution range of the incoming fuel. It appears that smallest particles, less than 10 μm , rise in temperature and ignite so rapidly that a distinctive preliminary devolatilization phase cannot be anticipated. On the other hand, ignition of the largest particles, greater than 60 μm , will be delayed with respect to devolatilization time scale. A size analysis of the coal shows a distribution of up

to 15% of particles less than 10 μm , therefore a similar percentage may ignite in a heterogeneous ignition mode.

When pulverized coal particles are rapidly heated, either in the presence or absence of an oxidizing gas, they undergo radical changes in chemical and physical properties Tsai and Scaroni (1987). It is also well known that the volatiles weight loss for rapid decomposition is always greater than the volatiles weight loss from the proximate analysis. It is usually characterised by the so called ' Q factor ' which is ratio of the actual volatile yield to that of a proximate content. The immediate loss of fixed carbon revealed by Fig. (4.2) is believed to be due to the following: (i) the change of the chemical and physical properties of the coal particles, (ii) the 'Q' factor and (iii) simultaneous devolatilization and char combustion. Figs. (4.2 a and b) show that in the first few throat diameters up to $X/D_s = 1.34$ volatiles and fixed carbon are consumed at a similar rate shown by a similar slope of the two curves.

Further downstream, the rate of volatile loss becomes more rapid since volatile matter, in addition to being lost by pure evolution into the gaseous state, may also be burned in the solid state along with fixed carbon, see Howard and Essenhigh (1967). Furthermore, the flame temperature reaches a substantial value, as measured by Godoy et al (1988 and 1989), augmenting the rate of evolution of the volatiles considerably . After this period of rapid devolatilization which lasts until about $X/D_s=12$, although about 10% volatile matter still remains in the particles, the rate of loss of the volatile matter becomes so slow, that about 3% of the original volatile matter is carried-out from the combustion chamber in the unburned solid residue leaving the furnace.

Suuberg (1977) has studied the effect of particle thermal history on the product compositions and formation kinetics in rapid pyrolysis for lignite and bituminous coals in a helium atmosphere. They identified four phases for rapid devolatilization: (i) low temperature surface moisture removal, (ii) evolution of pyrolytical water (300- 400 °C), (iii) softening of the particles accompanied by tar evolution (400-900 °C), and (iv) evolution of CO and H₂ (above 900 °C). Figure (4.3) illustrates the results as a plot of $(H/C)_x / (H/C)_k$ ratio against char burn-out, from the ultimate analyses of the coal and char particles. The ratio in the char falls slowly at first, and then with increasing rapidity. This trend is explained by initial loss of hydrocarbons (heavy oil, tars, etc.) with later loss of hydrogen as gas Essenhigh (1977). From Figs (4.3 and 4), it can be said that stages (i) and (ii) and part of the stage (iii) occur mainly between the burner exit and about our first measuring location at $X/D_s=1.34$. The rest of stage (iii) and stage (iv) occur mainly between the latter location and the next at $X/D_s=12$.

The yield of volatiles from a given coal depends on the temperature/time heating history; that is, on factors such as the rate of temperature rise, the final temperature attained and the duration of the decomposition at that temperature, as well as the composition of the volatiles. Some constituents of the volatiles matter as initially released are reactive with one another and with the char that remains, and the ultimate yield and composition of the volatiles will depend in part on the speed at which they are removed from the solid residue and diluted by mixing in the gas phase. The yield and composition of volatiles in slow decomposition differ from those produced by the rapid decomposition which occurs in pulverized coal flames where the decomposition products are rapidly removed from contact with the particles and diluted with the

gas in which the particles are suspended, rendering chemical interactions less likely to occur, Badzioch and Hawksley (1970).

To illustrate the way in which the constitution of the solid particles varies through the flame, the carbon (B_C) and hydrogen (B_H) concentration in the char particles on the axis, expressed in each case as a fraction of their initial values (in the feed coal), have been plotted in Fig. (4.5). The calculation of these values is based on the conservation of ash in the coal. Let ω_x , ω_{Cx} , ω_{Hx} stand for the concentrations of ash, carbon and hydrogen respectively in the char particles and ω_k , ω_{Ck} , ω_{Hk} represent the corresponding values in the feed coal, then

$$\bar{B}_C = (\omega_k / \omega_x) (\omega_{Cx} / \omega_{Ck}) \quad 4.1$$

and $B_H = (\omega_k / \omega_x) (\omega_{Hx} / \omega_{Hk}) \quad 4.2$

The values $(1 - B_C)$ and $(1 - B_H)$ represent respectively the proportion of the carbon and hydrogen gasified whether by devolatilization or by direct combustion of the solid residue. Comparison of the values of $(1 - B_H)$ with the values of the volatile release rate, Fig. (4.2), shows only slight differences. The same conclusion has been drawn by Loison and Kissel (1962).

The volatile matter is released rapidly but not instantaneously, as it can be seen in Fig. (4.5), because time is required for both heating and pyrolysis of the particles to take place. Rapid combustion of the volatile matter is controlled

by the availability of oxygen within the flame boundaries, Badzioch and Hawksley (1970). Combustion can only proceed as more oxygen reaches the interior of the flame as a result of the mixing of the primary- and secondary-air streams.

Figure (4.5) shows that in the present study the mass initially evolved from the coal particles initially is enriched in hydrogen, whereas that evolved later from the particle is enriched in carbon constituents. Indeed, each of these elements has its own unique history for evolution from the particle. This history is different for different coal types and possibly for different operating conditions (i.e type of oxidizer, heating rate, etc); Smoot and Smith (1985).

Figure (4.6) shows the data obtained from the ultimate analyses on the relative rates of release of different basic elements (C, H, N) plotted against the coal burn-out at various points throughout the combustor under different test conditions. Results of Fig. (4.6) indicate that the extent of element release is largely a function of the extent to which the coal has been burned. From these data it is apparent that carbon Fig. (4.6 a) is released at about the same rate as total coal mass release (most data lies on the 45° line), while hydrogen, Fig. (4.6 b), is liberated more rapidly. Fuel nitrogen, Fig. (4.6 c) is liberated at a slightly slower rate than that of the coal burn-out .

The relation between weight loss and the change in the volatile matter, on a dry ash-free basis, can be established as follows:

The change in the volatile matter ΔVM , as a percentage of the feed coal, is calculated from

$$\Delta VM = VM_k - VM_r \quad 4.3$$

$$VM_r = (100 - \omega_k / (100 - \omega_k)) (VM_x / \omega_x) \quad 4.4$$

where VM is the proximate volatile matter content, and the subscripts x and k stand for the sample and the feed coal respectively. VM_r is the volatile matter content of the char expressed as a percentage of the weight of the feed coal. ω_k and ω_x are the proximate ash contents, on dry basis of the feed coal and the char respectively.

Figure (4.7) presents the variation of the mass ratio of volatile matter/fixed carbon of the char sample (VM_x/FC_x), as a percentage of their feed coal value (VM_k/FC_k), with the degree of the char burnout, expressed by the fraction of the original fixed carbon remaining in the solid char sample (FC_x/FC_k). A horizontal line in Fig.(4.7) illustrates consumption of the fixed carbon and volatile evolution at the same rate, while a vertical line signifies evolution of volatiles without consumption of fixed carbon. The figure which should be read from right to left to correspond with the passage of particles from the burner through to the furnace exit., shows that during the early few diameters in the chamber (up to $X/D_s=1.34$) the ratio $((VM_x/FC_x) / (VM_k/FC_k))$ remains nearly constant. The appearance of an almost constant $((VM_x/FC_x) / (VM_k/FC_k))$ ratio may be due to the following possibilities that:

(a) As discussed above both consumption of the fixed carbon and volatile release

are occurring at the same rate.

(b) The char samples collected in this zone is a mixture of fresh and burned fuel. This mixture contains two type of particles namely: (i) the recirculating burned particles coming from downstream which are expected to have higher amount of finer particles. Finer particles tend to follow the gas stream more than bigger particles (smaller relaxation time). Because of the nature of heterogeneous combustion during the ignition of these finer particles, which may be burning more fixed carbon, their char samples are expected to have a higher value of (VM_x/FC_x) . (ii) The char particles collected from the incoming stream may have higher percentage of bigger particles than those obtained from the size distribution analysis, again because of the fact that bigger particles tend to follow their own streams due to their inertia, while the smaller particles tend to follow the gas stream, Godoy et al (1989), as explained above. The ignition mode for bigger particles is dominated by volatile evolution, so their char particles are expected to show a smaller value of (VM_x/FC_x) . The finer particles collected from the incoming stream may also be dominated by heterogeneous combustion.

Further downstream the temperature of the particles becomes so high that the principal devolatilization reaction when it is finally set in, is very fast, and the loss of volatile matter by gaseous evolution is much faster than the loss by heterogeneous combustion. As a consequence, VM_x/FC_x drops rather rapidly. The final flattening of the function signals the termination of consumption of volatile matter and continuing of heterogeneous combustion.

Ideally the weight loss, W , should be determined directly by weighing the feed coal and the char produced. However, this has not been possible

because the char particles cannot be recovered quantitatively. The weight loss, therefore, has been calculated indirectly by using the ash associated with coal as a tracer on the assumption that its mass remains constant throughout the combustor. The yield of char (YCH) expressed as a percentage of the feed coal is given by:

$$YCH = (100 \omega_k / (100 - \omega_k)) \times ((100 - \omega_x) / \omega_x) \quad 4.5$$

Thus the weight loss, W, expressed as a percentage of the feed coal

$$W = 100 - YCH \quad 4.6$$

Figure (4.8), shows the variation of the weight loss (W) and the change in the volatile matter (VM). To the extent that it may be presumed that all of the initial weight loss is due to devolatilization alone then the curve must pass through the origin. In the absence of heterogeneous reaction it will be linear with the slope giving the 'Q' factor, Essenhigh (1977). It will also be linear if the weight loss due to heterogeneous reaction and devolatilization happen to be linearly related. The apparent linearity of the present relation may be due to a combination of these two possibilities. The slope of the curve gives an apparent 'Q' factor equals to 2.4 for the present coal and furnace.

The percentage of the heat release along the flame axis is shown in Fig.(4.9) . The heat release has been calculated as follows:

$$W_x = \omega_k / \omega_x \quad 4.7$$

$$Ht_x = Hv_x \times W_x \quad 4.8$$

$$\text{and ,} \quad Ht_k = Hv_k \quad 4.9$$

$$\text{then} \quad \text{Heat release \%} = (1 - (Ht_x / Ht_k)) \times 100 \quad 4.10$$

where W_x is the weight fraction (kg/kg of coal), Ht is the total heat (MJ), and Hv is the heating value (MJ/kg) and the subscripts x and k stands for the sample and the feed coal respectively. The heating value can be calculated from the coal ultimate analysis, this approach is adopted in the present study. Several equations have been developed for the calculation of the heating value of fossil fuels Lloyd and Davenport (1980). The equation described by Jain and Sundararajan (1981) is selected on the basis of its close agreement with the bomb calorimeter. This equation reads

$$Hv = 1.096 (C/3 + H + S/8 - O/8) - 0.8817 \quad 4.11$$

where C , H , S and O are the respective mass fraction of carbon, hydrogen, sulphur and oxygen: these values are determined from the ultimate analysis of the char sample. Based on this equation the calculated heating value of the Gedling coal (as received) is 29.29 MJ/kg with an expected error less than 2%, see (chapter3). Figure (4.9) shows that the heat released from the coal flame can also be used as an indication of flame efficiency as well as the char burnout. These heat release calculations are meant to assist the calculation and modelling of the different modes of heat transfer in the coal combustors.

4.4 Char burn-out Measurements

4.4.1 Axial profiles

This section presents the results of an experimental study on the combustion performance of pulverized United Kingdom Gedling high volatile bituminous coal fired in a laboratory cylindrical furnace. The tests are carried-out in order to determine the effect of the excess air level, the swirl number, and the momentum ratio on char burn-out. Test run conditions are summarized in Table (4.2).

1. Discussion of the experimental results

As explained earlier when coal particles enter the flame, the initial processes which occur are the thermally induced decomposition or pyrolysis of the coal resulting in the release of combustible gaseous species. Under conditions present in pulverized coal flames, pyrolysis is essentially completed in 10 to 50 ms, Morgan and Dekker (1987), and during this period some oxidation of the combustible solid residue occurs. The rate of combustion of the volatile matter is believed to be controlled by its rate of mixing with the combustion air. Char combustion occurs both within and downstream the flame envelope. Thus the minimum requirement for a quantitative description of coal combustion includes the rate of char combustion as an important indicator to the furnace combustion efficiency. This information is needed under the different operating parameters present in the actual (industrial) coal firing furnaces, i.e. the excess air ratio, the swirl number, the momentum ratio.

The effect of various values of the excess air ratio, λ (defined as the mass of air supplied/the mass of air required for stoichiometric coal combustion) on the on-axis char burn-out is presented in Fig. (4.10), for flames B1, B2, B3 and B4. Increasing the excess air ratio accelerates the combustion process through enhancement of volatile combustion, since the combustion of coal particles is strongly controlled by the availability of oxygen in the heart of the flame, see Rees et al (1981), leading to the enhancement of the heterogeneous oxidation in the early part of the flame. It should be emphasized that in the early stages of combustion up to 1.34 throat diameters, when the excess air level exceeds about 20% of the stoichiometric air required ($\lambda > 1.2$), the higher primary stream velocity is seen to reduce the burn-out in the primary flame zone (less residence time near the burner zone). Figure (4.11) illustrates measurements of the char burn-out at the furnace exit for various excess air ratios. Increasing the input excess air for constant swirl number ($S_s = 1.03$) and momentum ratio ($R_m = 0.24$) increases the char burn-out to reach a maximum constant value of nearly 99%. This value persists until the excess air level exceeds the value of 1.18, beyond which the reduction of flame temperature, due to the dilution effect of the excess air, slightly reduces the exit char burn-out.

Figure (4.12) shows the effect of secondary air swirl (S_s) on the percentage of the char burn-out measured on the centre line of the furnace for four flames namely : D1, D2, D3 and D4 . Measured burn-out values are expectedly a strong function of swirl number especially in the primary flame zone, up to $X/D_s = 12$, where the release of volatile matter and volatiles combustion dominate the combustion process. Char burn-out is higher for $S_s = 1.27$ and 1.45 up to

$X/D_s=4$, this may be again due to the coal particles velocities being reversed (reverse axial flow) increasing their residence time in the central fuel rich zone and leading to augmented of particles reaction. The longer residence time of the particles in this region the greater the char burn-out. Further downstream, the influence of swirl number on the char burnout is comparatively small. It is to be stressed that the mixing intensity (controlled by the swirl level) between coal/primary air stream and secondary combustion air, in the presence of sufficient excess air, as well as the recirculated hot combustion products, controls the early time/thermal/chemical history of the coal particles in the flame. Consequently it determines the extent of char combustion and controls the development of the fuel rich primary flame zone.

Figure (4.13) illustrates the effect of swirl on the percentage of char burn-out at the furnace exit for swirl numbers ranging between 0.78 and 1.45, a modest range which all the same encompasses the bulk of industrial practice. The figure shows that on increasing the swirl number, whilst maintaining the momentum ratio and excess air constant, the char burn-out increases to reach a maximum of 98.8% at S_g of about 1.05 and then decreases again. The rise in the char burn-out may be explained with reference to the fact that with increasing the swirl the forward stagnation point moves further upstream towards the burner resulting in a shorter penetration of the primary stream into the inner recirculation zone; Schmid et al (1987). This in turn increases the particles residence time in this central fuel rich zone resulting in more devolatilization and char combustion. Increasing further the swirl number above 1.05 increases the tendency for the primary stream to be radially deflected away from the central internal recirculation zone towards the fuel lean secondary

air stream reducing the char burn-out.

The effect of the variations in the momentum ratio, R_m (the ratio of the primary stream, coal and air, to secondary air axial momentum rates), on the on-axis char burn-out is illustrated in Fig. (4.14) for flames C3, C4, C5 while Fig. (4.15) shows the effect of R_m on the char burnout at the exit of the furnace. The increase of the momentum ratio results in a decrease in the burn-out over most of the furnace axis Fig. (4.14). As R_m increases, the flow penetration of the internal recirculation zone extends further downstream, which means less residence time near the critical burner zone, hence causing a decline in the char burn-out. This type of flow persists and gradually transforms into a flow with no inner recirculation zone for the highest values of R_m .

The burn-out at the furnace exit Fig. (4.15), however, shows that the change R_m in the studied range of 0.16 to 0.28, has a negligible overall effect. This insensitivity of furnace exit char burn-out to momentum ratio is believed to be due to two opposite effects. On the one hand, the mixing between the primary and secondary streams declines with increasing R_m in the critical near burner region due to the deeper penetration of the primary flow in the recirculating bubble. This means that as the momentum ratio increases the residence time of the particles in the near burner zone decreases, hence lower char burn-out. On the other hand, the requirements that all other input conditions be held constant results in an increase of the ratio of the primary air to coal mass flow rates with increasing R_m , thus providing more oxygen to the char particles, hence an increase in char burn-out, see Hazanov et al (1985). Both effects seem to cancel each

other resulting in the shown trend in Fig. (4.15).

4.4.2 Radial Profiles Measurement Of Char Burnout

The percentage of the char burnout along the axis for the two flames S6L (D_1) and S7L (D_2) Table (4.3) are illustrated in Fig. (4.12) . As explained in section (4.3) most of the burn-out trends for both swirl conditions show that the reaction volume occupies only the upper region of the furnace up to $X/D_s = 12$, where intense coal pyrolysis and combustion take place manifested itself in the steep burn-out gradients. Further downstream, profiles are flat and are distinguished only by fairly minor differences in the burn-out. The increase in swirl number leads to a more compact reaction zone and a more rapid burn-out .

The effect of the degree of swirl on the combustion efficiency of a combustor as expressed by the burn-out percentage can be explained, Beer and Chigier (1969), from the close relation between swirl, mixing and recirculation in the furnace. As a result of imparting swirl to the secondary stream, the flame jet angle increases and two ring vortices are set up; one inside the jet boundaries usually referred to as the inner recirculation zone and the other between the jet boundaries and the walls of the furnace known as the outer recirculation zone. As the degree of swirl increases, the strength of the inner recirculation zone increases and hence the rate of entrainment of recirculated hot gases into the jet increases. This, in turn, results in more intensive mixing near the burner nozzle and a decrease in the volume of the upstream well-stirred section of the reactor relative to the plug flow section downstream, and hence a shorter flame, Beer and Lee (1965).

Figure. (4.16) illustrates the radial profiles of char burn-out for the S6L and S7L flames at three different axial stations. In the early stages of the flame up to $X/D_s = 12$, two regions may be identified: (i) a central core containing the reaction zone ($0 < r < 100$ mm) where most of the chemical reaction takes place as indicated by the steep gradient of the char burnout, and (ii) a wall recirculation outer zone ($r > 100$ mm) where the char burn-out is uniformly distributed as a result of the back mixing in this zone. Further downstream, $X/D_s > 10$ Fig. (4.16 c), the profiles of char burn-out are flatter approaching plug-flow behaviour as the flow reaches the furnace exit.

A comparison of the results for the two swirls employed in the present study showed that the central reaction zone width at $X/D_s = 1.34$ for swirl $S_s = 1.03$ is slightly more compact than that for $S_s = 0.78$. Also lower burn-out is observed in the outer region, this is probably due to the stronger swirl causing the particles to be flung outward towards the wall.

Figures (4.16 b and c) at $X/D_s = 6.73$ and 12.05 showed that a much lower burn-out was measured over the whole furnace cross section compared to that observed for $S_s = 0.78$ except very near to the centre. This is probably due to a greater spread of the particles for swirl $S_s = 1.03$, as explained earlier, hence a decrease of the oxygen to coal ratio in the outer region while this ratio would be increased in the center. It is clearly obvious that increasing the oxygen to coal ratio leads to higher burn-out in the near burner region because of the faster rate of coal combustion in the presence of excess hot oxygen. The higher burn-out of this swirl at the centre line is also due to the high amount of the recirculating

burned particles from downstream.

In fact, the combustion of coal can be divided into two stages, (i) ignition and volatiles evolution and (ii) combustion of volatiles and the combustion of residue. After the evolution of the volatiles, the residue is surrounded by a cloud of volatile matter, Hubbard (1960). This volatile matter burns and fresh supplies of oxygen must diffuse through the products of combustion before combustion of the residue can begin. If there is air in excess, the volatiles burn as soon as they are evolved and so combustion of the residue begins sooner. Conversely if there is insufficient air then the cracking volatiles and soot formation may occur, hence significantly delaying the combustion of the residue. The concave shape of the profiles for $S_s = 1.03$ between ($0 < r < 100$ mm) shows this effect, as the swirl increases coal particles are flung further away from the vertical axis, Godoy et al (1989), and therefore the oxygen to coal ratio decreases in this region.

Figure (4.16 d) shows the effect of distance inside the furnace on the char burn-out for $S_s = 0.78$. It also shows at $X/D_s = 22.77$ an almost constant value (flatter profile) of the char burn-out due to the further mixing of the particles of high burn-out values from the outer region with particles having lower burn-out values from the central region as compared with $X/D_s = 17.41$.

4- 5 Flame Stability

Coal is most often burned in industry combustors in pulverized

form using burners generally similar to those for oil and gas. The last two fuels are however much more conveniently burned than coal, the sole attraction of which is, in times of stable energy pricing, its low cost. One of the several disadvantages of coal firing is the restricted range of burner operating conditions for which stable flames can be achieved relative to oil or gas firing. The loss of the burner flames on turn down constitutes an unacceptable dust explosion risk. It is common practice in power station combustors to support pulverized coal flames during periods of low burner load (off-peak periods) by firing oil, or less frequently, gas to overcome the stability difficulty. However, when the price differential between oil and coal is large, this practice is expensive and, therefore, an urgent demand to reduce the amount of oil burnt in pulverized coal boilers arises. Ideally pulverized coal burners which can maintain stable flames at lower loads, as low as 5-10% of the boiler maximum rating, are required, Sarjeant (1981). This fact is behind the revival of interest in the pulverized coal stability research during the last few years.

In an early study Beer and Chigier (1969) stressed the importance of the secondary air swirl on enhancing pulverized coal flame but found that imparting swirl to the primary air stream had little effect. Wolanski and Wojcicki (1974) concluded that the rate of release of volatiles is the most dominant parameter controlling flame stability. Wroblewska et al (1976) used isothermal flow data to predict the performance of a full-scale coal burner and estimated an optimum value of the recirculating mass flow rate for flame stability of low calorific-value coals. Burner stability data provide extremities of flame conditions and as such are useful for the evaluation of computer prediction procedures. Such published stability data for pulverized coal flames are scarce .

4.5.1 Experimental Facility and Test Conditions

The present study reports an extensive set of burner stability trials for the United Kingdom Gedling bituminous coal using two different types of quarl: refractory and water-cooled, Fig. (4.17). The influence of swirl number, excess air, momentum ratio and burner load on flame stability were studied. The study also contains comparative char burn-out measurements. The work was motivated by the fact that the frequent slagging and the deslagging of the refractory quarl represent a practical difficulty. Moreover, the built-up of the slag deposits on the quarl, commonly known as the 'eye brow', renders the near-burner flow pattern asymmetric, alters the flame stability performance, and affects the pollutant emission and heat transfer modes. The use of the water-cooled quarl virtually eliminates the quarl slagging, see Plate (2 a and b); which shows both the refractory and water-cooled quarl after being subjected to similar operating conditions and firing periods. The quenching of the molten fly-ash impinging on the cooled surface of the water-cooled quarl prevents the tendency of these particles to adhere to it.

The coal analyses, and its size distribution are given in chapter 3, while the furnace run conditions are specified in Table (4.4). Before commencing the tests, the furnace was run until steady-state conditions were reached. Preheating of the inlet streams must enhance stability, and clearly sufficient preheating of the secondary air, although neither practical nor economically feasible, would lead to universal stability. In the present tests the inlet temperatures of the primary and secondary streams were fixed at values typical of industrial practice. The primary and secondary air temperature were respectively maintained at 80 °C and 330 °C. The experimental variables were the:

secondary air swirl, S_s , ratio of primary stream (coal and air) to secondary air axial momenta, R_m , excess air ratio (λ), and fuel firing rate. The stability trials were conducted by progressively reducing secondary air swirl S_s , all other conditions maintained constant, until flame lift off occurred. Lift-off was observed visually and also detected by an infrared flame monitor (Digiscan).

4.5.2 Criteria for Flame Stability

A stable flame is here defined as that initiates at or within the burner quarl. It is distinguished from a lifted flame which may stabilize several burner diameters downstream provided that the criteria for ignition are met, otherwise blow-off results. The principal factors influencing the stability of pulverized coal turbulent diffusion flame may be summarized as follows:

1. Coal properties

The single most significant coal property influencing flame stability is its volatiles content. The ease with which the volatiles are released when the coal is heated and the reactivity of the char are chemical properties which are also important, but they are ones which are known with precision for only a very few coals. The higher the volatiles content, the larger the proportion of the gaseous phase combustion which proceeds at a much faster rate compared with that of solid char particles. High volatiles content, along with low moisture and ash contents are desirable for flame stability, Wall (1984).

2. Coal conditions

The coal condition is mainly characterized by its fineness of grind. The stability of pulverized coal must in general be expected to improve with the fineness of grind. Finer particles will follow the gas flow more rapidly, absorb heat faster, and their surface oxygen reception rate will be greater, Vulis (1961).

3. The near burner aerodynamics of the flow (N. B. A)

In pulverized coal flames, the aerodynamic field of the flow near the burner will influence the mixing rate of fuel and oxygen, the rate of heating and the eventual combustion of volatiles and char. For flow through a swirl burners, an inner recirculation zone (IRZ) exists which plays an important role in flame stabilization by promoting the heat transfer from the hot recirculating combustion products to the incoming stream of coal and air and further, by reducing the axial velocity of the primary stream in the quarl, Gupta et al (1984). This is believed to maximize within the primary reaction zone the residence time, the particle heating rates, and availability of oxygen. Turbulent diffusion is also enhanced near the boundary of the inner recirculation zone (IRZ) due to the large velocity gradients existing there, Syred and Beer (1972). The strength and configuration of the inner recirculation zone (IRZ) depends on the swirl number on the geometry of the burner, and to a lesser extent the furnace geometry.

4. The particle time-temperature history near the burner

The incoming particles will be heated by radiation from the flame,

quarl and walls and by mixing with the hot recirculated combustion products. Beer (1964) estimated that near the burner region, up to 70% of the heat received by the particles is due to recirculation, therefore, the rate and extent of particle heating will depend on the aerodynamics of the burner-furnace system and on the input flow conditions. The heating rate will increase for finer particles and/or by increasing the preheating of the combustion air. The rate of particle heating, the final temperature attained and the residence time of particles at that temperature have a dominant influence on the rate of coal devolatilization as described by many authors see for example; Anthony et al (1975), Solomon and Colket (1978), Jost et al (1984) and Jamaluddin et al (1986). The time scale for devolatilization and volatiles combustion is of the order of a few micro-seconds whereas the combustion of char requires several hundred milli-seconds; Smoot and Smith (1985). Because devolatilization begins at lower temperatures than those for the combustion of the char, Essenhigh (1977), it is essentially a near-burner phenomenon and as such has much influence on the process of flame stabilization.

4.5.3 Presentation of the Data

Burner swirl is the single most important variable influencing the near burner flow field. The swirl number S_s is essential in any correlation of burner stability data. Burner stability will be strongly influenced by the mixing of the primary and secondary streams. For fixed swirl the mixing rate will also be a function of the ratio of the primary to secondary momenta, R_m . Therefore in the present study, flame stability data are presented, for a fixed burner geometry, constant excess air ratio and heat input, high Reynolds number ($>10^4$), and for specified quarl type and conditions, in terms of the secondary air swirl, S_s , and the

ratio of the primary stream axial momentum to that of the secondary air stream, R_m .

4.5.4 Discussion of The Results

In the present study the flame of the appearance root for stable flames was always very luminous and its diameter for a constant R_m was larger at higher swirl numbers. As the momentum ratio was increased or the swirl decreased, the flame base was observed to decrease in diameter until eventually the flame lifted off. These flames can be classified Schmid et al (1987) as a stable flame type II, a stable flame type I and a lifted flame type I, as in Fig. (4.18).

The type II flame, is a short intense, stable and characterized by a strong internal recirculation zone (IRZ) near the burner, it occurs for high swirl number combined with low primary to secondary momentum ratios. In this case the core of the primary stream jet partially penetrates the inner recirculation zone but is quickly entrained completely by the reverse flow prevailing in the region. Lower swirl coupled with higher momentum ratio reduces the internal recirculation zone and allows part of the primary flow to penetrate through the inner recirculation zone with a substantial portion still entrained by the reverse flow. This results in stable flame type I. These two stable flame types ignite in the immediate vicinity of the burner exit. The penetration of the IRZ by the primary jet for the type I flow may however be sufficient to cause the flame to lift. This happens because the particles residence time in the IRZ are too restricted to allow sufficient volatiles release there with the result that the flame initiates several burner diameters downstream. Lifted flames are unacceptable in

industrial furnaces and boilers because of the susceptibility to flame blow-off at any small disturbance in the operating conditions.

The flame stability data for both quarls, refractory and water-cooled, are presented in Figs. (4.19 and 20). The effect of different coal feed rates and two excess air levels are shown in the form of plots of swirl number, (S_s), versus the momentum ratio (R_m) defined, as stated earlier, as the ratio of the primary stream momentum (coal plus transport air) to the secondary axial momentum. For the primary stream there exists, for a given coal loading, a minimum air velocity below which the pulverized coal cannot be transported uniformly. This limiting value was taken for the lower value of R_m for a given coal throughput. The coal mass loading, $m_{c,p} = m_c/(m_c+m_p)$, as well as the primary and secondary velocities, V_p and V_s respectively, are provided as additional abscissa in the figure. The uncertainty of the experimental data is indicated by the cross-hatching on the curves.

The typical behaviour of the curves is characterized by a stable region bounded by a minimum limiting swirl and a maximum momentum ratio with the delineation being quite sharp in some cases. For each value of R_m within the stability region there exists a critical swirl number below which the flame is unstable. Lower values of the critical swirl numbers were generally attainable for smaller momentum ratios (R_m). It can be noticed that these critical swirl numbers are higher in the case of the water-cooled quarl. This can only be due to the significant heat loss experienced by incoming fluid and particles to the quarl walls.

The results in Fig. (4.19 a to d) and Fig. (4.20 a to d) also show that for the water-cooled quarl the maximum momentum ratio for stable flames decreases somewhat with increasing feed rate. This may be related to the fluid/particle residence time which is inversely proportional to the primary air velocity Rizvi (1985).

Two levels of excess air were used for the stability tests. A comparison of Figs. (4.19 and 20) show that minimum allowed swirl numbers are decreased by increasing the excess air from 15% to 25% for the whole range of operating conditions. For confined diffusion flames, the higher the amount of excess air, the shorter the time taken for fuel particles to find oxygen (the dust cloud concentrations or the fuel/air ratio drop as the air rate increases). Meanwhile, in the simplest terms, increasing the air flow rate simply blows the flame downstream. In addition, for a given swirl number and momentum ratio, there is a limiting excess air beyond which the flame temperature drops due to the presence of nitrogen and excess oxygen.

The contents of Figs. (4.19 and 20) are summarized in Figs. (4.21 a and b & 22 a and b) which portray the dependence of the limiting values of swirl number ($S_{s, \min}$) and the maximum momentum ratio ($R_{m, \max}$) on the coal feed rate and the excess air. The limiting value of $S_{s, \min}$ at low values of R_m may be linked with the magnitude of swirl required to produce an internal recirculation zone. The value of $S_{s, \min}$ in Figs. (4.21 a and b) for the studied range of coal feed rates are between 0.5 and 1.05 for the water-cooled quarl and 0.4 and 0.67 for the refractory quarl. It is known that the inner recirculation zone is established in similar combustors for swirl numbers of this magnitude, Beer and Chigier

(1972). The reason for the decline of $S_{s, \min}$ with increasing m_c is most probably due to the corresponding increase in heat release in which improves flame stability.

Figure (4.22 a) shows that maximum possible momentum ratios ($R_{m, \max}$) decreases as the coal feed rate increases for the water-cooled quarl. The better stability at lower loads is probably due to the longer fluid/ particle residence time in the inner burner region due to the smaller inlet velocities. It should also be noted that increasing the excess air adversely affects stability. Since higher magnitudes of velocity were utilised than for the case of 15% excess air, shorter fluid /particle residence time occurred, hence the observed trend.

The behaviour of $R_{m, \max}$ for the refractory quarl Fig. (4.22 b) is less easily interpreted. At low loads its values are small, presumably due to the relatively high heat loss. In this region increasing the excess air adversely affected stability. Since most of the extra air is accommodated by the secondary stream this is most probably because of the attenuated mixing/ reaction quenching resulting from the augmented primary to secondary momentum ratio. For the higher loads (> 16 Kg/hr) these trends are reversed. The marked improvement in the $R_{m, \max}$ stability limit with increasing burner load is most likely due to the high temperature of the external recirculation zone which will increase with increasing burner load (heat input) since some stability enhancement may also occur from the entrainment of these hotter gases into the near burner flow.

Figures (4.23 and 24) summarizes the comparison between the present stability data for the water-cooled and those for the refractory quarl. Fig.

(4.23) demonstrates the need for a higher swirl number in order to obtain a stable flame for the water-cooled quarl at the same feed rate for the refractory quarl. It further shows that at a certain feed rate (24 Kg/hr) where a stable flame could be obtained for the refractory quarl it is virtually impossible to obtain a stabilized flame if the quarl is cooled. These observations are also reflected in Fig. (4.24) in such a manner that the refractory quarl would sustain a higher momentum ratio especially as the feed rate increases. These differences in stability margins are probably due to the reduction in the heat transfer to the incoming coal particles in the case of cooled quarl. This in turn leads to a lower volatile yield in the near burner region which plays a crucial role in flame stability.

Figure (4.25) compares the measured on axis char burn-out values for the two quarls. The furnace exit conditions are relatively uniform so the data at $X/D_s=43$ are indicative of the overall char burn-out performances. A reduction in burn-out due to the water-cooled quarl is apparent everywhere. The differences seem to be most significant in the upstream third of the furnace and may be attributed to the delayed devolatilization in the quarl region and the consequent delay in particles combustion.

4.6 Summary and Conclusions

The present thermogravimetric technique permits accurate analyses of the relatively small char samples which can conveniently be extracted from the furnace. The information which can be deduced from the analyses allows thermodynamic and chemical histories of the particles to be constructed. These histories not only enhance physical understanding, but they are also of

considerable assistance to validation exercises on mathematical models. The volatile matter is released rapidly but not instantaneously because time is required for both heating and pyrolysis of the particles to take place. The initial volatile content may consist of hydrocarbons (heavy oil, tars, etc.) with later loss of hydrogen^{and} carbon monoxide. The hydrogen release rate is faster than the char burn-out. The carbon consumption correlates well with coal weight loss while, hydrogen is liberated more rapidly. The coarser bound nitrogen evolves at slightly slower rate.

The 'Q' factors for Gedling coal burning in the present combustor is bounded by an upper value of 2.4. Since predictions are quite sensitive to the 'Q' factor the modellers would do well to note this rather high value for a bituminous coal obtained in the circumstances of a large scale combustor as opposed to drop tube furnace or smaller scale laboratory devices. Some 3% of the original volatile matter leaves the combustor in the unburned residue. Due to a typical particle size distribution, heterogeneous combustion and volatile release are able to occur simultaneously. It is not usual for modellers to allow for this.

The axial measurements of the char burn-out show that there exists an optimum value of the swirl number when the furnace exit burn-out i.e. combustion efficiency is a maximum for constant momentum ratio and excess air. The same conclusion can also be applied to the effect of the excess air level. The burn-out, however, is insensitive to momentum ratio values in the range of (0.16-0.28).

The radial data for both $S_g=0.78$ and $S_g=1.03$ indicate the existence

of the central flame core (IRZ), probably surrounded by an outer recirculation zone. An increase of the swirl resulted in the particles being flung further away from the axis in the early stages of the flame. further downstream, burn-out profiles were flat.

A water-cooled quarl offers the considerable advantage of much reduced slagging compared with that of the conventional refractory quarl. This advantage is offset by a reduced burner flame stability performance. The reduced performance is, since the burner quarl and furnace geometries of the present comparative studies are identical, entirely attributable to the greater heat losses experienced by the fluid and particles in the quarl region. These heat losses, which will be both convective and radiative, reduce the initial rate of volatiles release, a crucial factor to the stability of the flame, resulting in a cooler and less effective IRZ. The char burn-out performance is also suppressed. However, it is important to recognise that these negative effects of a water-cooled quarl are likely to be much reduced in full scale power generation equipment where the heat losses will represent a much smaller proportion of the heat input.

In general, the stability performance of a swirl burner is characterised by a critical value of swirl number below which, and a critical value of the ratio of primary to secondary momenta above which, a stable flame is unattainable. The critical value of swirl number is the smallest one which ensures a well established IRZ, while the critical momentum ratio is the greatest one which does not cause the primary jet to transgress the IRZ. For good stability the char particles trajectories should be reversed within a strong IRZ so that their IRZ residence times are maximised. It is clear then that the required critical swirl number will rise with increasing momentum ratio and this is experimentally

confirmed .

A major attribute of the present data is their value to validation studies of mathematical models intended to assist designers of full scale equipment for which comparable data do not exist.

coal mass flow rate (kg/hr)	12
primary air flow rate (kg/hr)	29
primary air temperature (°C)	80
secondary air flow rate (kg/hr)	106.5
secondary air temperature (°C)	330
swirl number	0.78
excess air	15%

Table (4.1): Run Conditions: Coal Particles Behaviour in the Combustor.

Flame index	m_c (kg/hr)	m_p (kg/hr)	m_s (kg/hr)	excess air %	λ	R_m	S_s
B1	12	27.6	102.0	10	1.10	0.24	1.03
B2	12	29.0	106.5	15	1.15	0.24	1.03
B3	12	30.5	110.9	20	1.20	0.24	1.03
B4	12	31.9	115.4	25	1.25	0.24	1.03
C3	16	35.7	145.0	15	1.15	0.20	1.03
C4	16	38.7	141.9	15	1.15	0.24	1.03
C5	16	41.4	139.2	15	1.15	0.28	1.03
D1	12	29.0	106.5	15	1.15	0.24	0.78
D2	12	29.0	106.5	15	1.15	0.24	1.03
D3	12	29.0	106.5	15	1.15	0.24	1.27
D4	12	29.0	106.5	15	1.15	0.24	1.45

Primary air temperature 80°C and the secondary air temperature 330°C at burner exit.

Table (4.2): Run Conditions: Inflammation Measurements, Axial Profiles.

Flame no.	S_s	excess air %	R_m	m_s	V_s	V_p/V_s	Re_s
S6L	0.78	15	0.24	103.39	32.5	0.60	13330
S7L	1.03	15	0.24	103.39	32.5	0.60	13330
S7H	1.03	25	0.186	114.96	36.2	0.54	14820

* For all the runs:

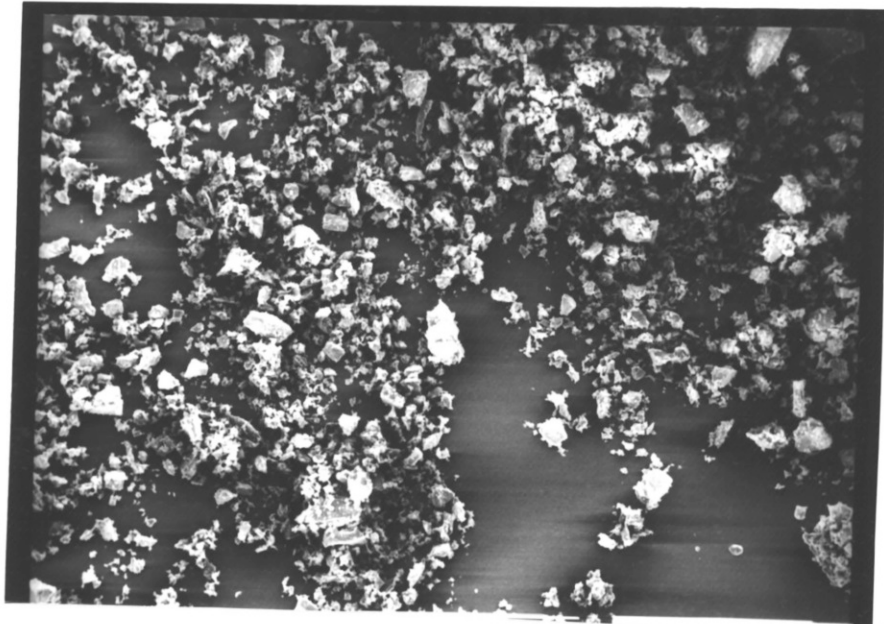
$$m_p = 27.47 \text{ kg/hr}, \quad V_p = 19.7 \text{ m/s}, \quad Re_p = 21250,$$

$$m_c = 12 \text{ kg/hr}, \quad m_{c,p} = 0.303$$

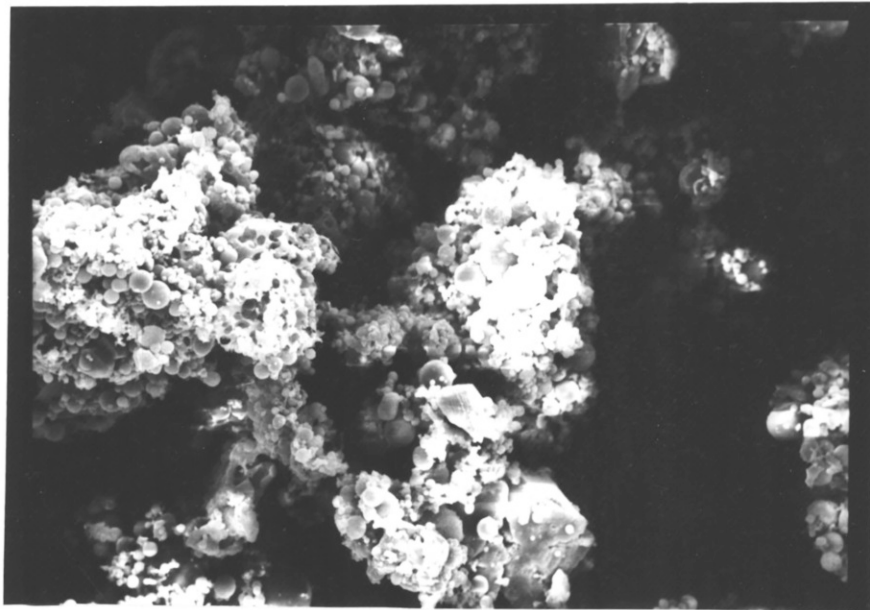
Table (4.3): Run Conditions: Inflamm Measurements, Radial Profiles.

Coal Feed Rate Kg/hr	8		12		16		20	
Excess air %	15	25	15	25	15	25	15	25
Gross Heat Input Kw	65		98		130		163	

Table (4.4): Run Conditions: Flame Stability.



a



b

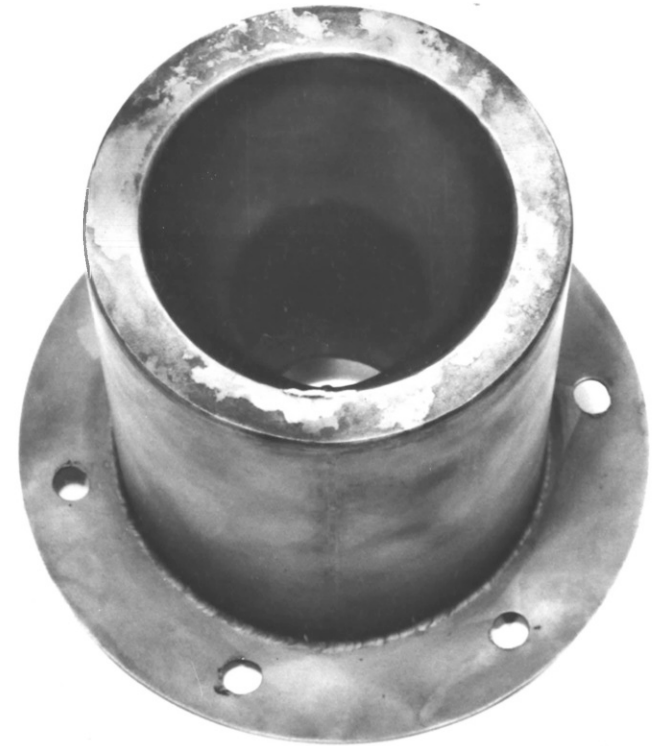
Panel (4.1) Selected Scanning Electron-microscope Photographs.

(a) Feed coal (x 500)

(b) Char from the exit section of the combustor. (x 3000)



(a) Refractory Quarl



(b) Water-Cooled Quarl

Panel (4.2) Photographs of Furnace Quarls.

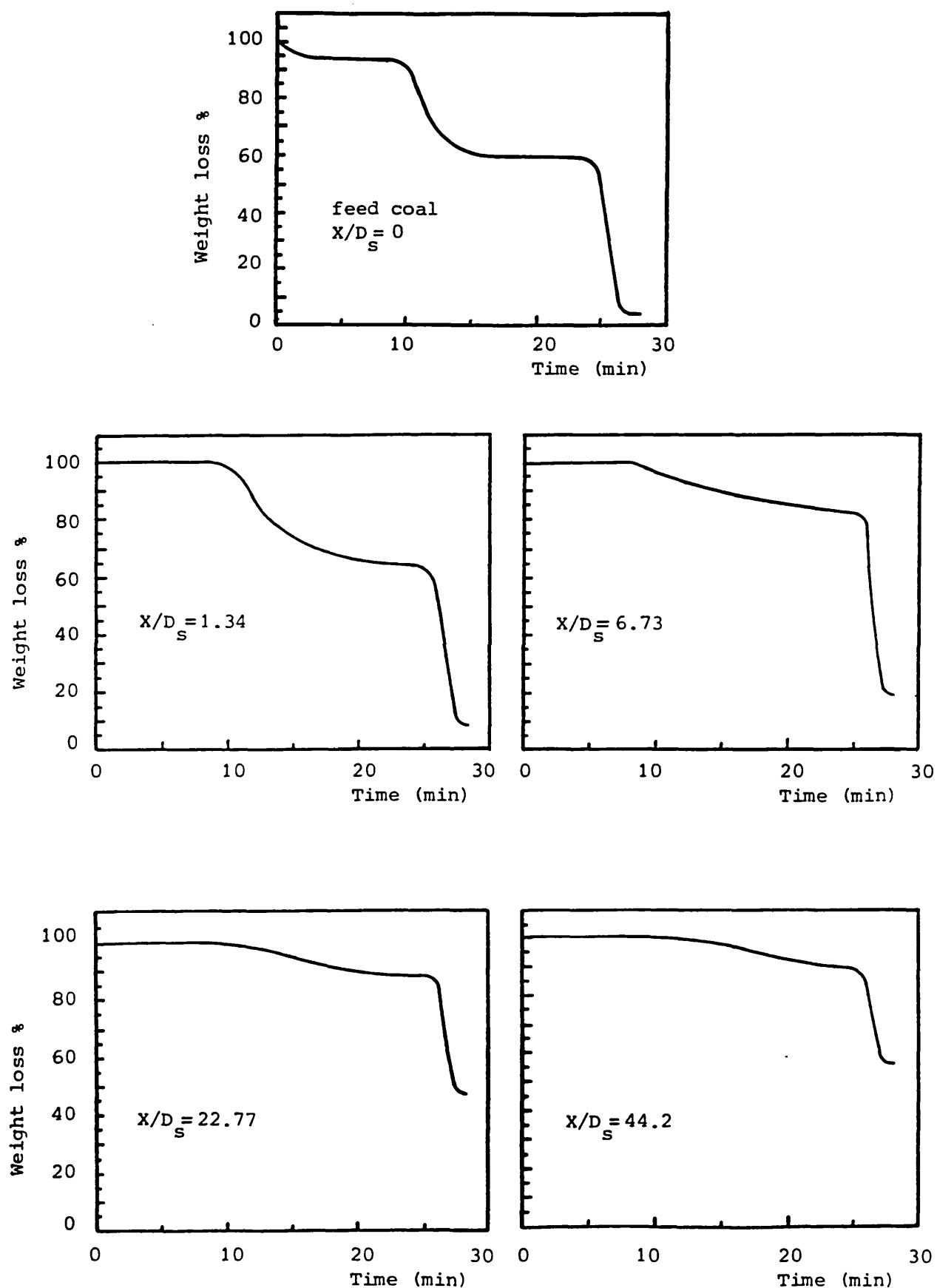


Fig. (4.1): Thermogravimetric Mass Loss versus Time Curves for Char Samples along the Flame Axis.

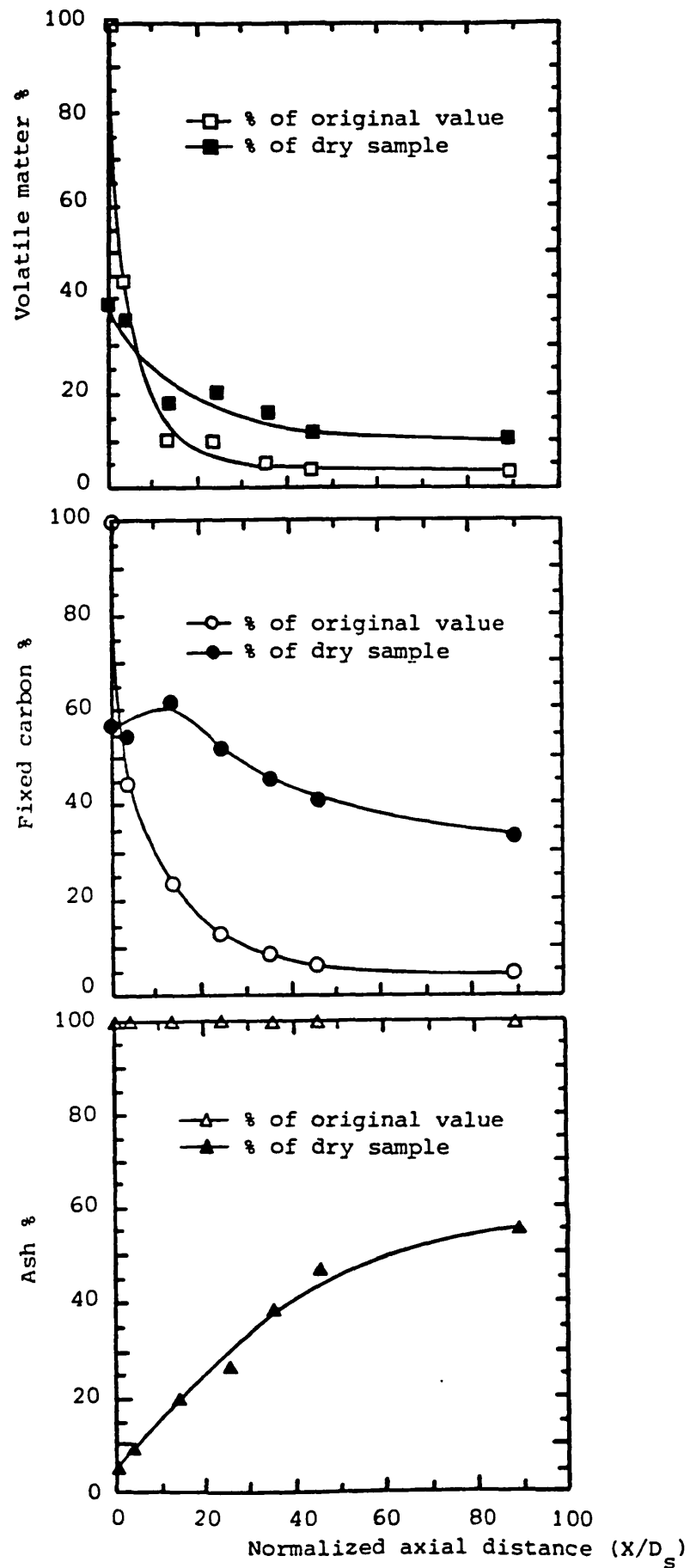


Fig. (4.2): The Profiles of Proximate Composition of Char samples (Dry-basis), along the Flame Axis.

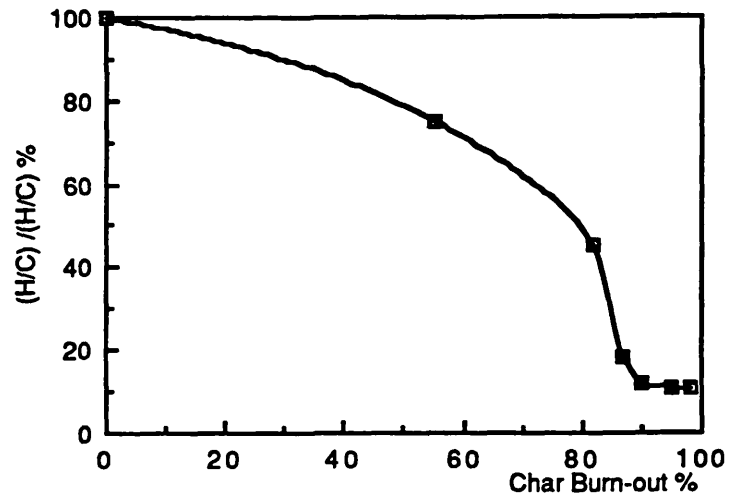


Fig. (4.3) Variation with Total Burn-out of Normalized Hydrogen/Carbon Ratio $((H/C)_x / (H/C)_k)$

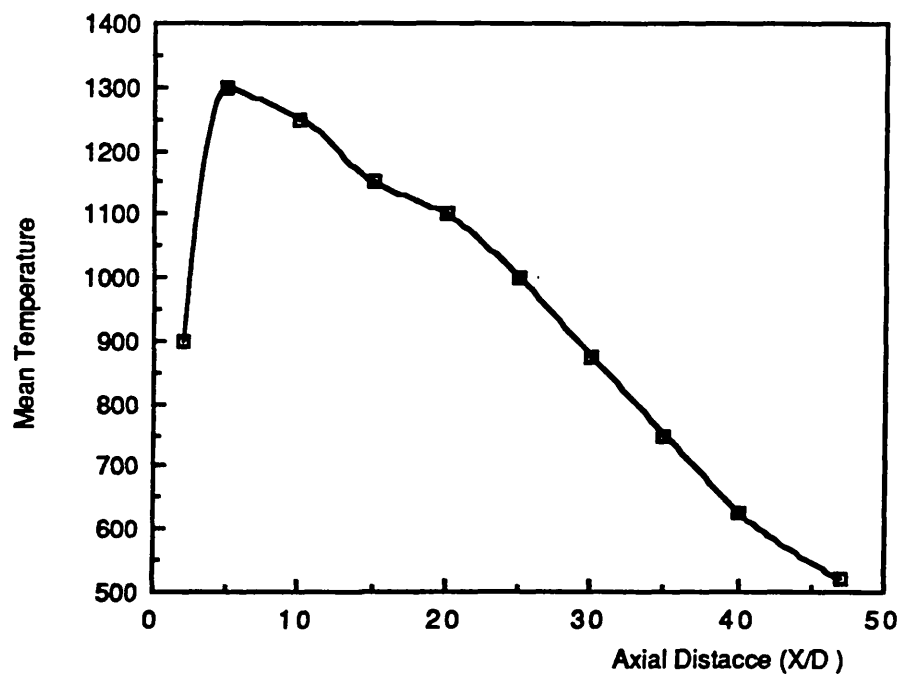


Fig. (4.4) Mean Temperature Axial Profile (after Godoy et al 1989)

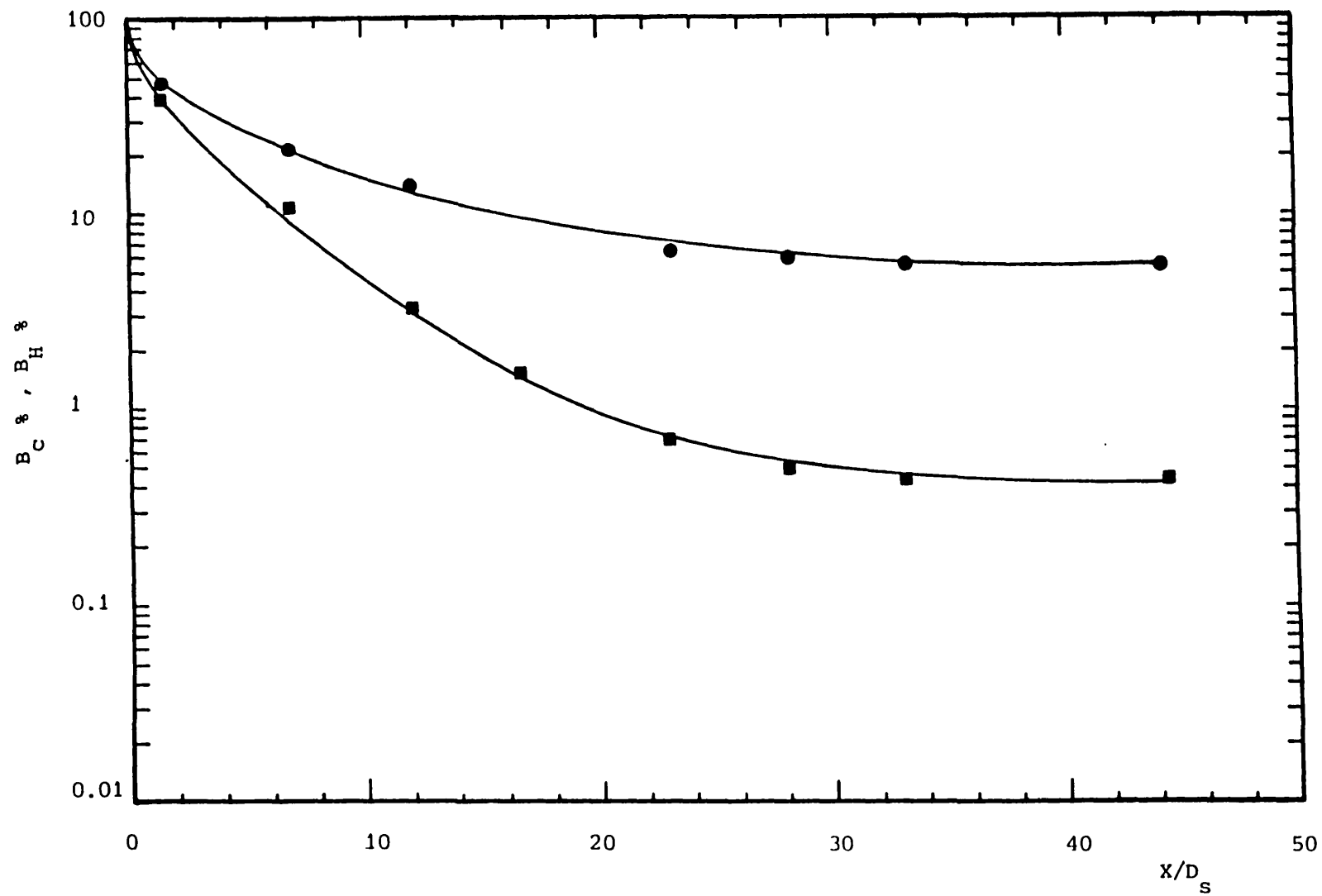


Fig. (4.5): Variation In Carbon and Hydrogen contents of Char Particles along the Axis of the Flame.

—●— B_C , —■— B_H

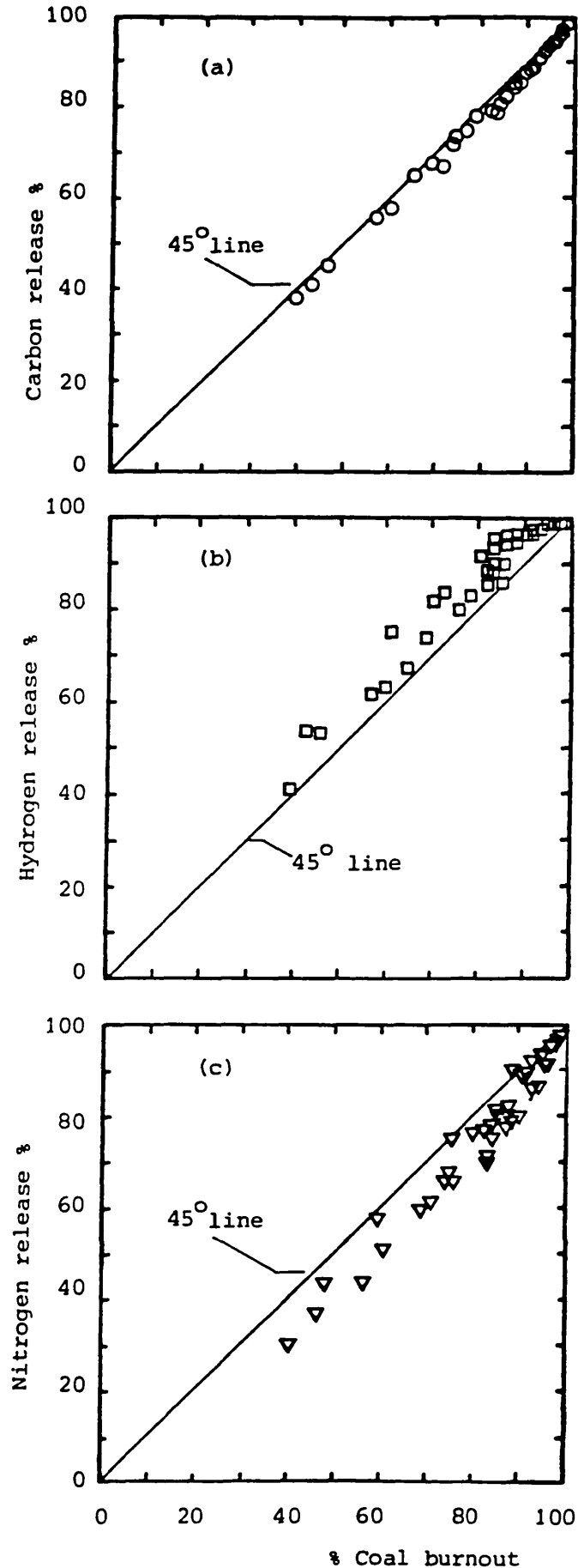


Fig. (4.6): Release of Various Elements from the Gedling Bituminous coal during combustion.

(a) carbon, (b) hydrogen, (c) nitrogen.

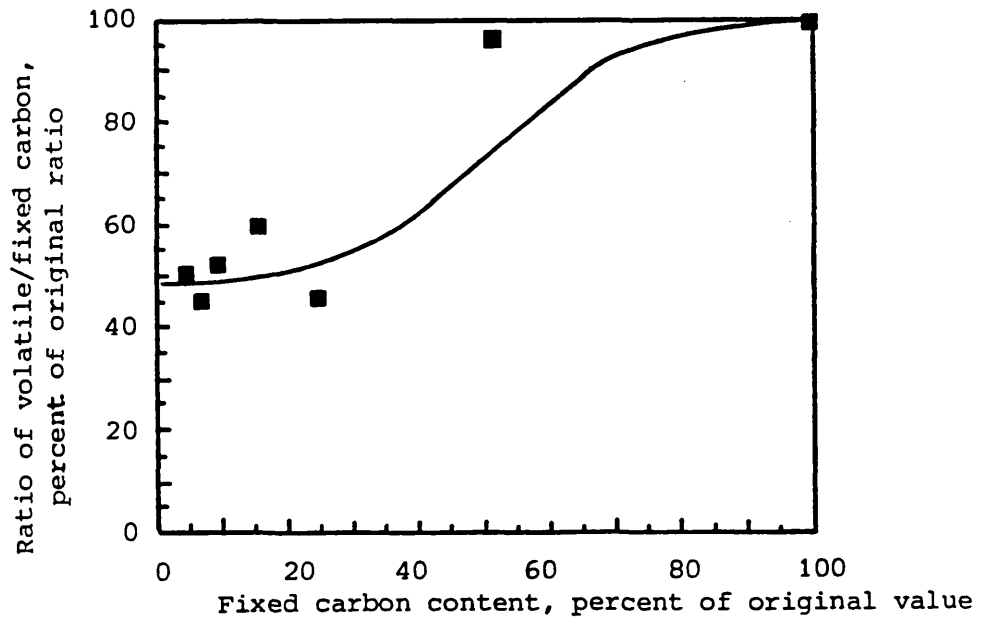


Fig. (4.7): Variation of Proximate Composition of the Char with Burn-out.

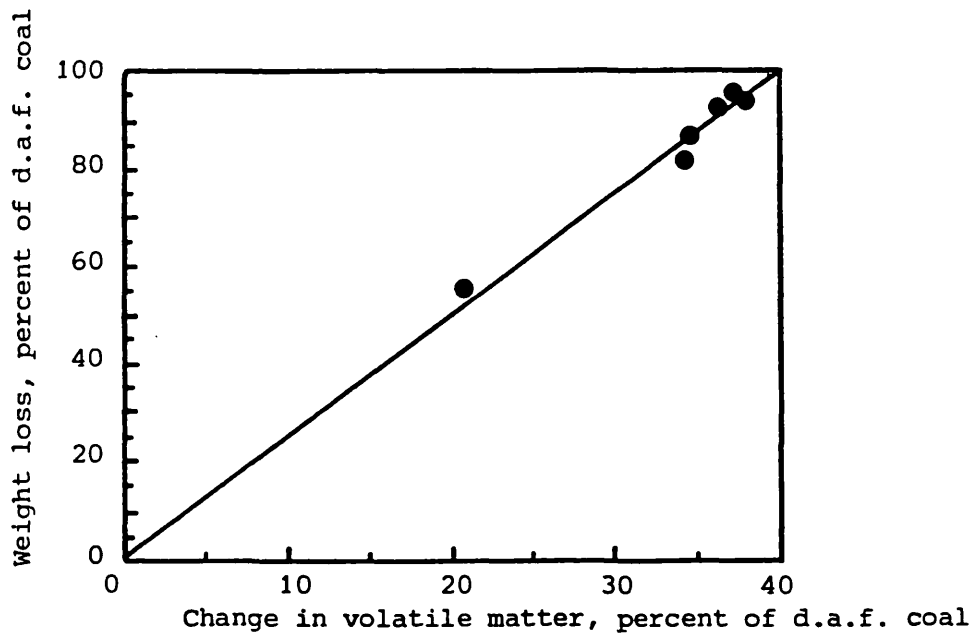


Fig. (4.8): Correlation between Weight Loss and Change In volatile matter.

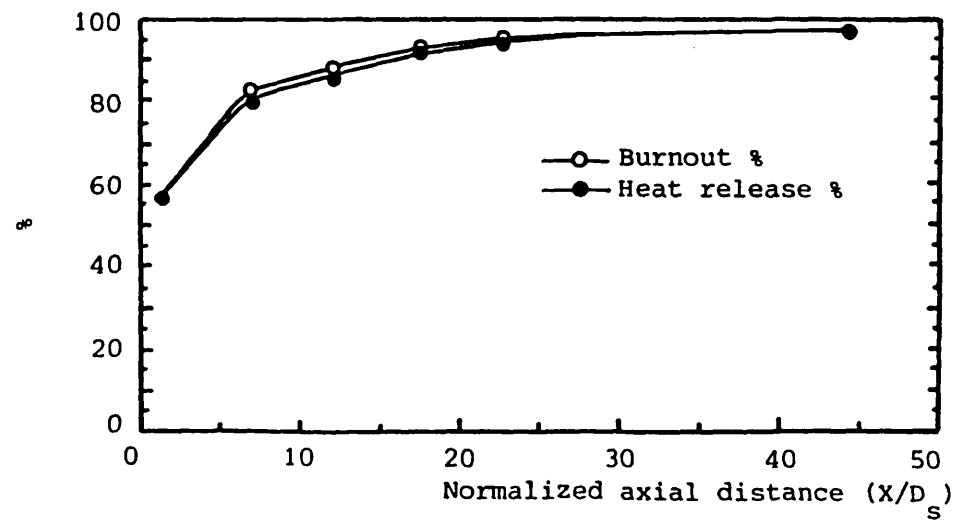


Fig. (4.9): On-axis Profiles of Burn-out and Heat Release.

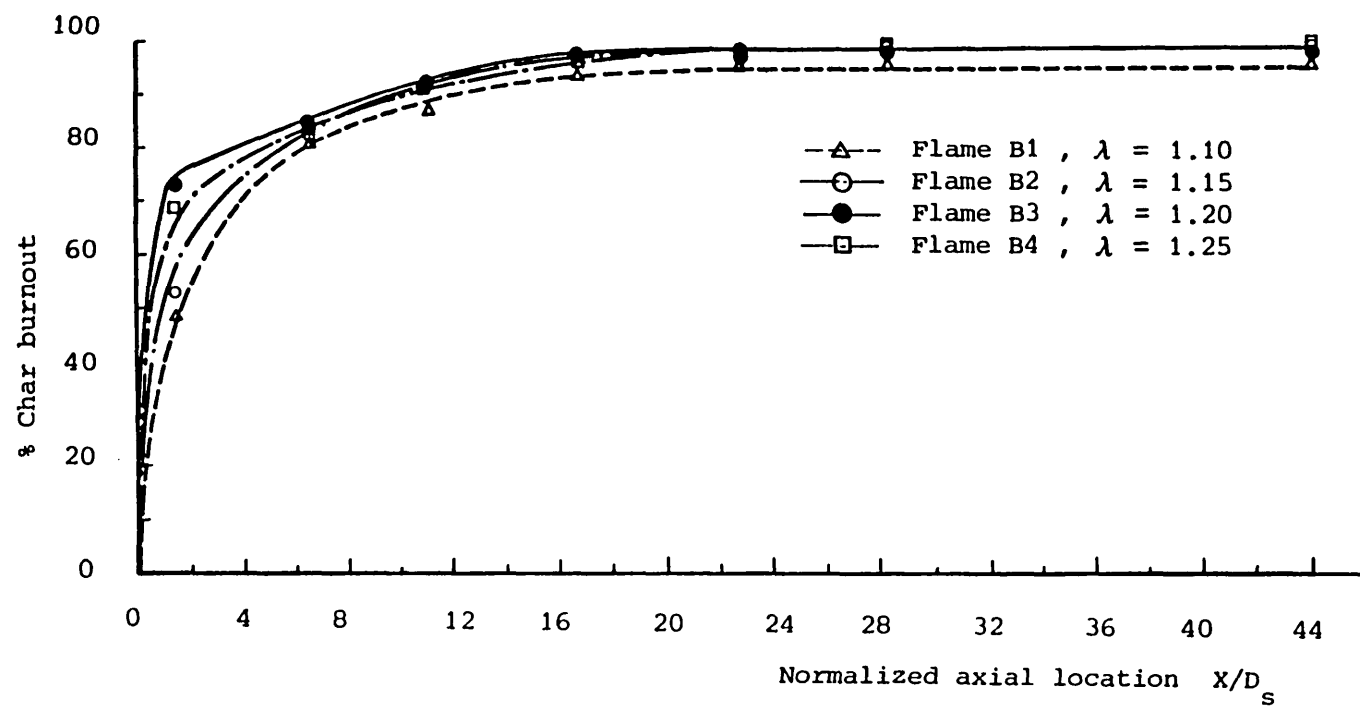


Fig. (4.10): Effect of Excess Air Ratio (λ): on the Axial Profiles of Char Burn-out.

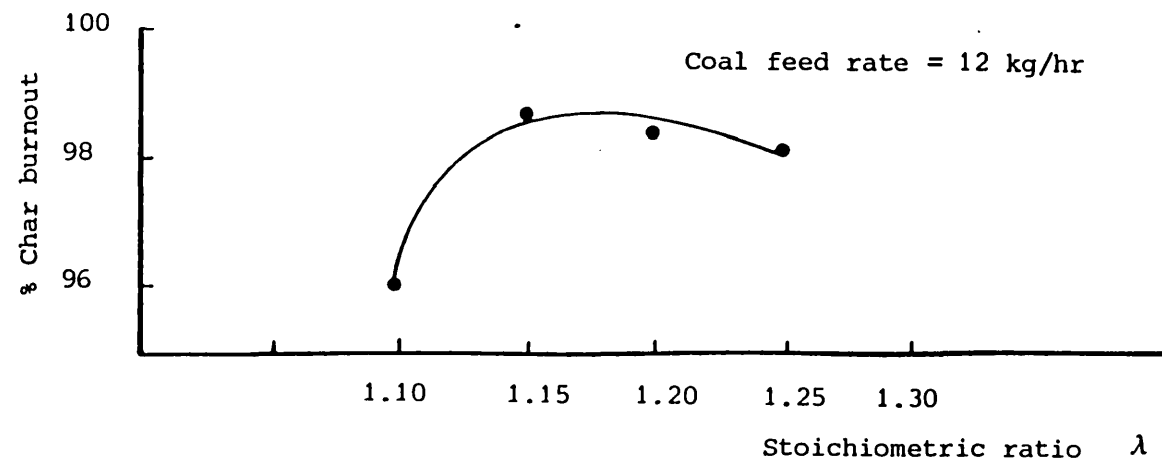


Fig. (4.11): Effect of Excess Air Ratio (λ): on the Char Burn-out at the Furnace Exit.

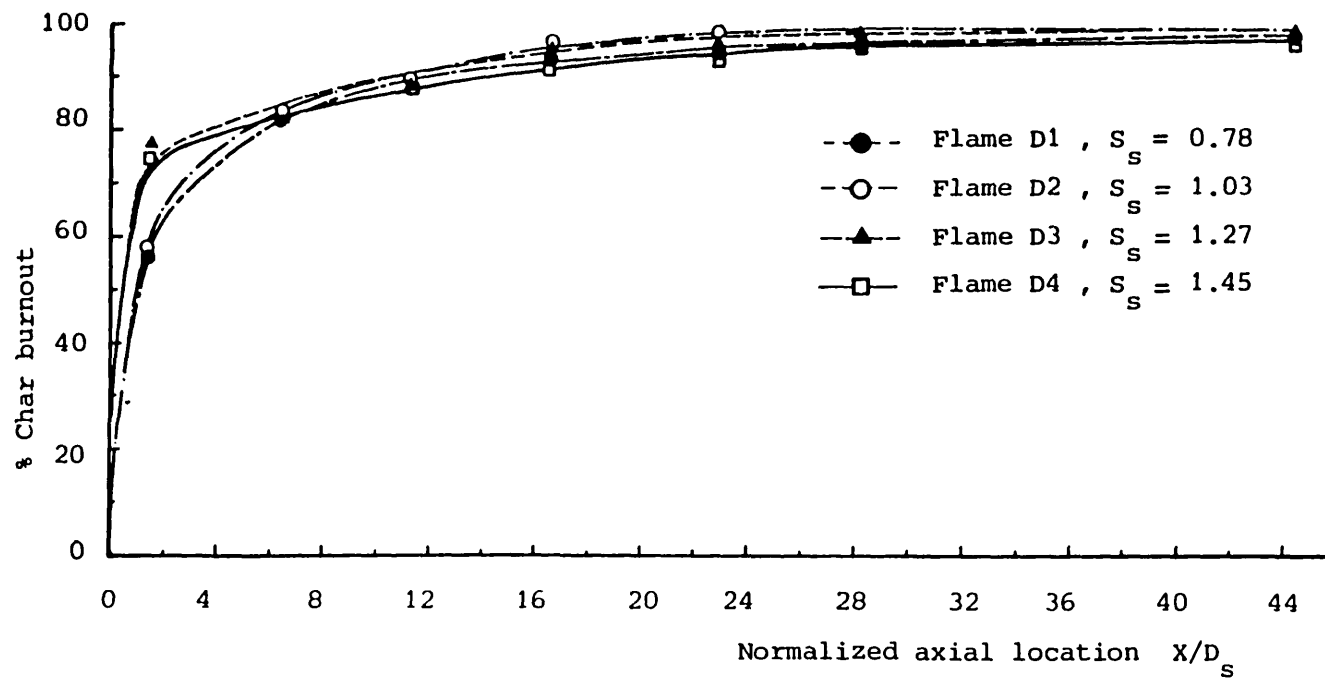


Fig. (4.12): Effect of Swirl Number (S_s): on the Axial Profiles of Char Burn-out.

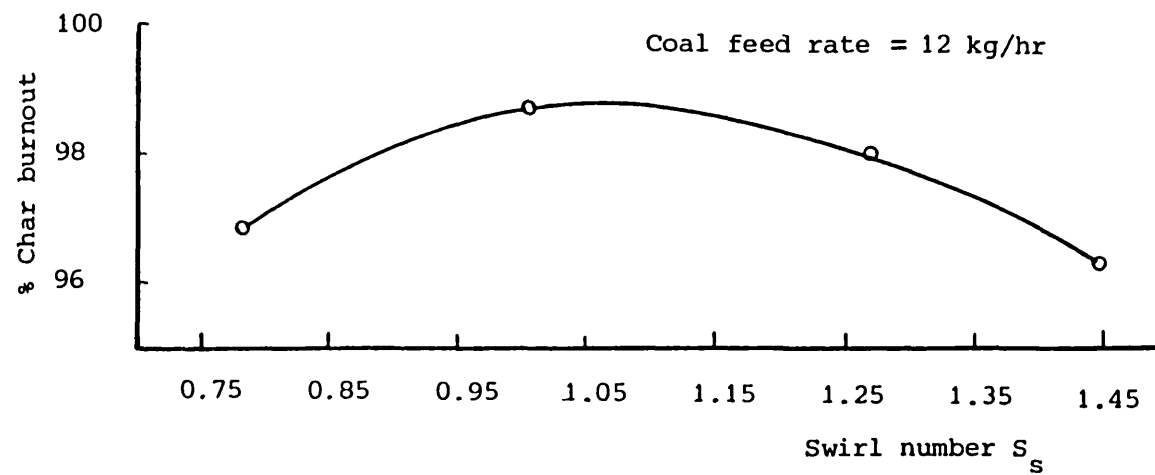


Fig. (4.13): Effect of Swirl Number (S_s): on the Char Burn-out at the Furnace Exit.

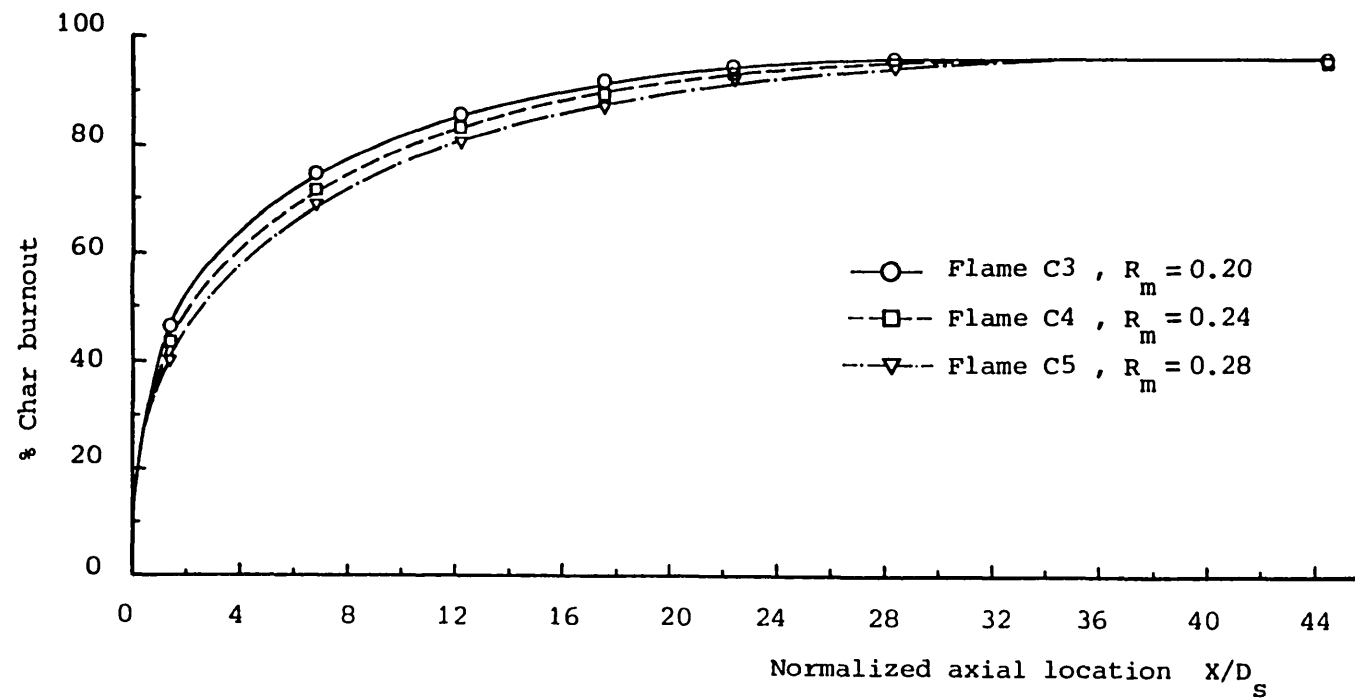


Fig. (4.14): Effect of Momentum Ratio (R_m): on the Axial Profiles of Char Burn-out.

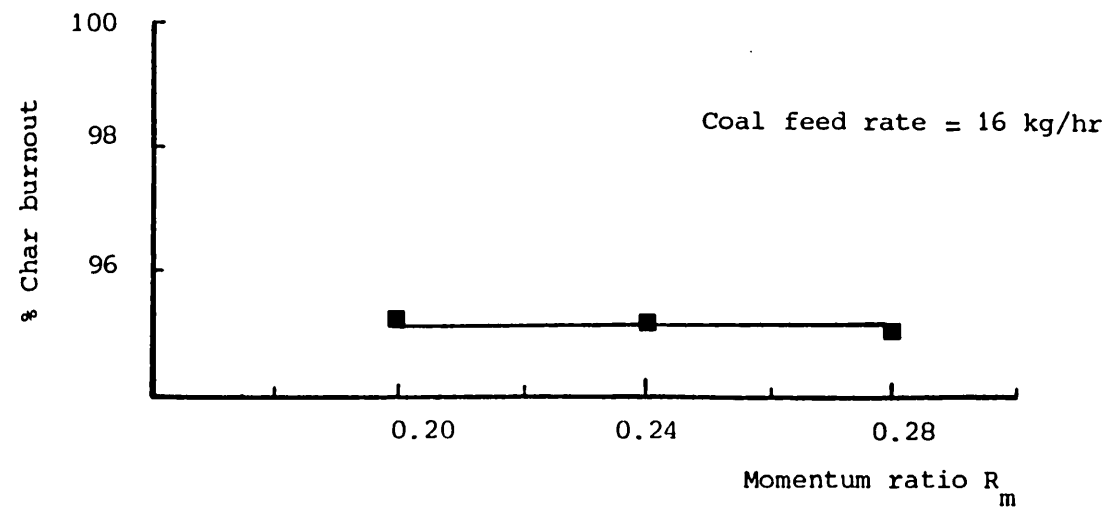


Fig. (4.15): Effect of Momentum Ratio (R_m): on the Char Burn-out at the Furnace Exit.

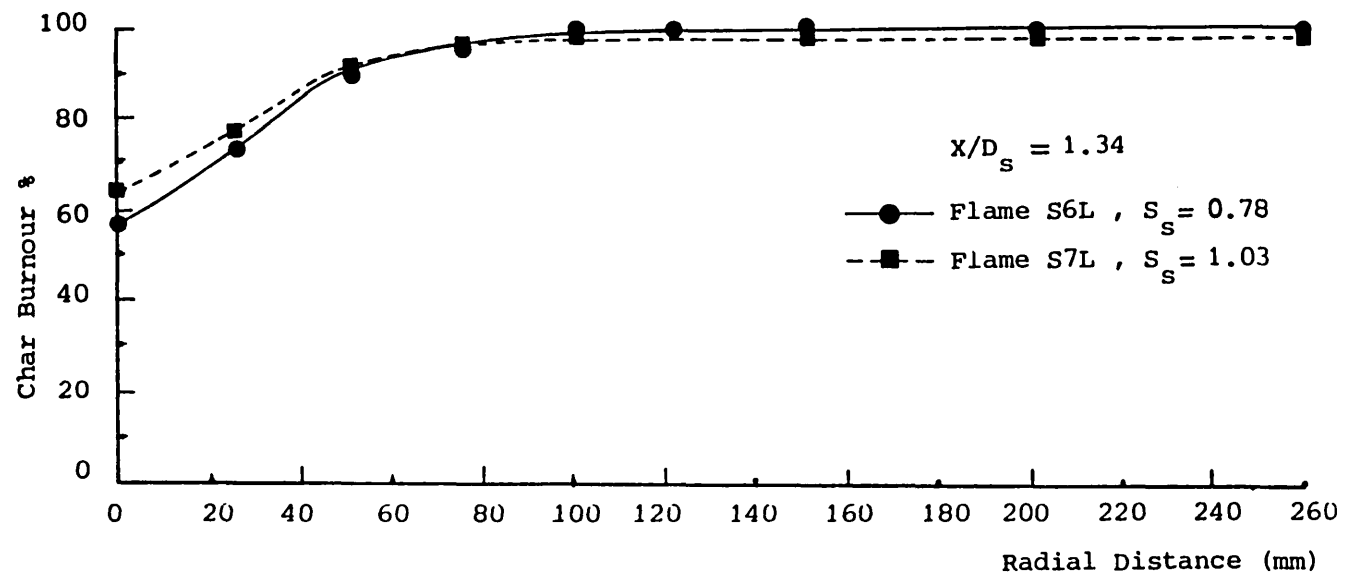
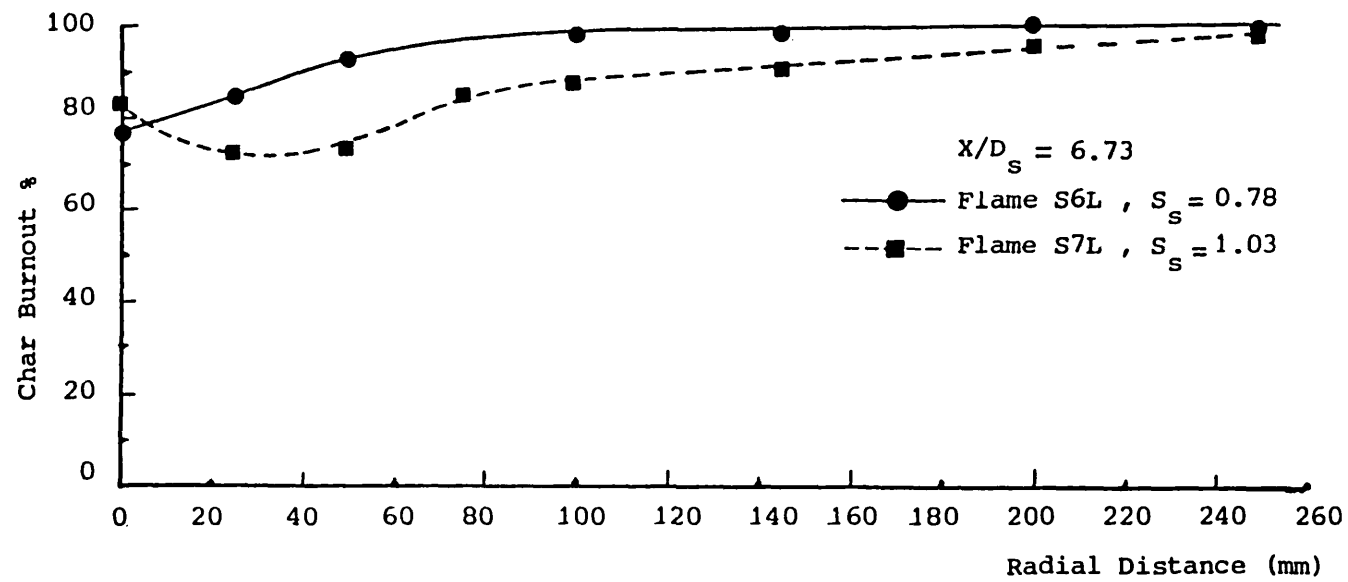
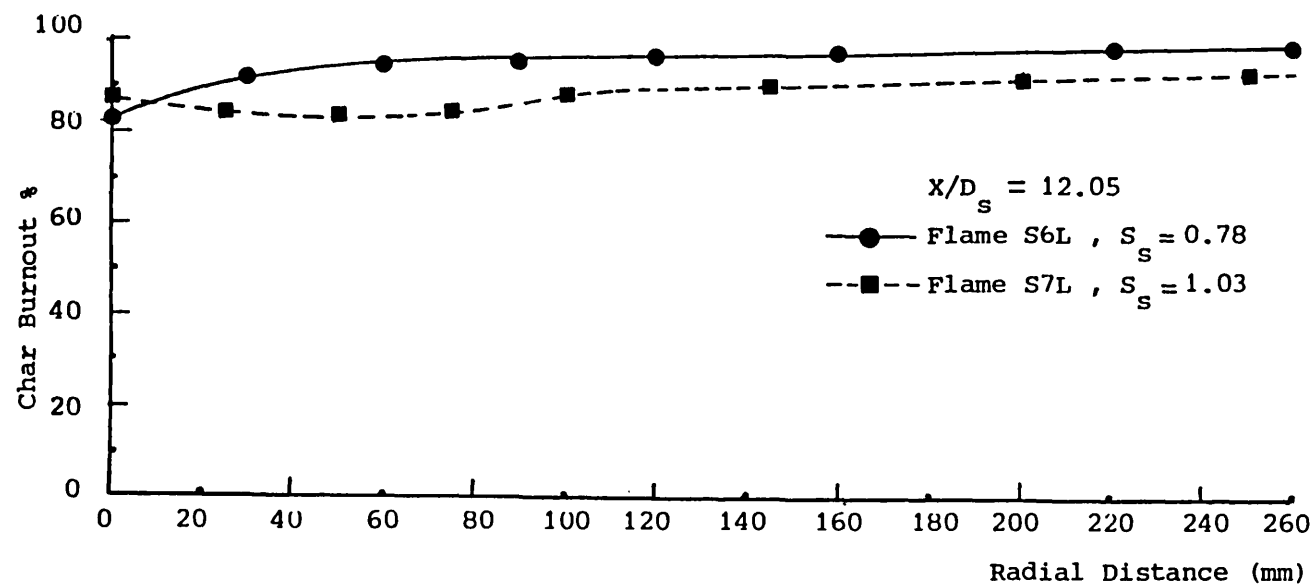


Fig. (4.16): Radial Char Burn-out Profiles:

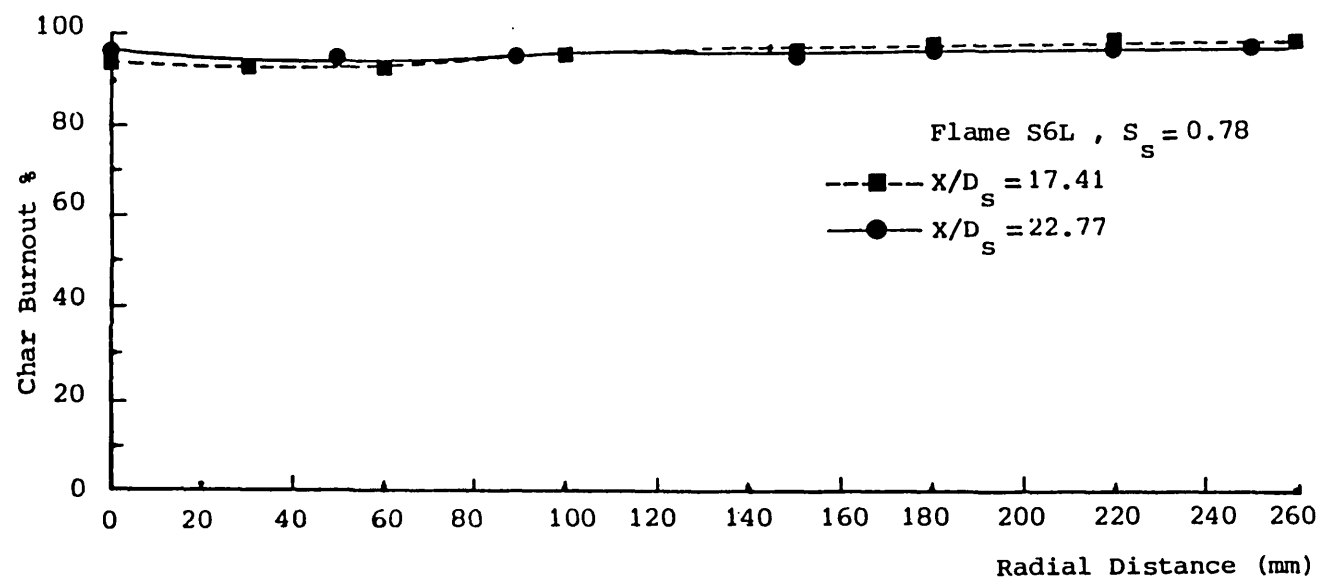
(a): $X/D_s = 1.34$, Flames S6L & S7L



(b): $X/D_s = 6.73$, Flames S6L & S7L



(c): $X/D_s = 12.05$, Flames S6L & S7L



(d): $X/D_s = 17.41$ and $X/D_s = 22.77$ Flame S6L.

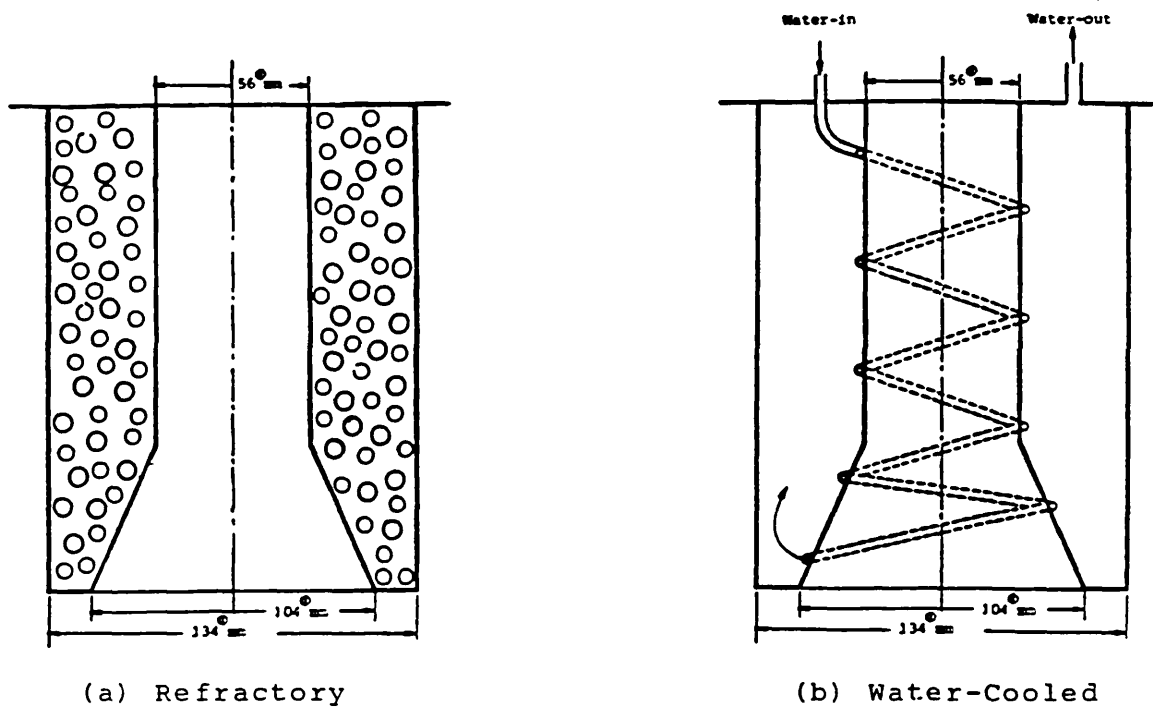


Fig. (4.17): Schematic of the furnace Quarls.

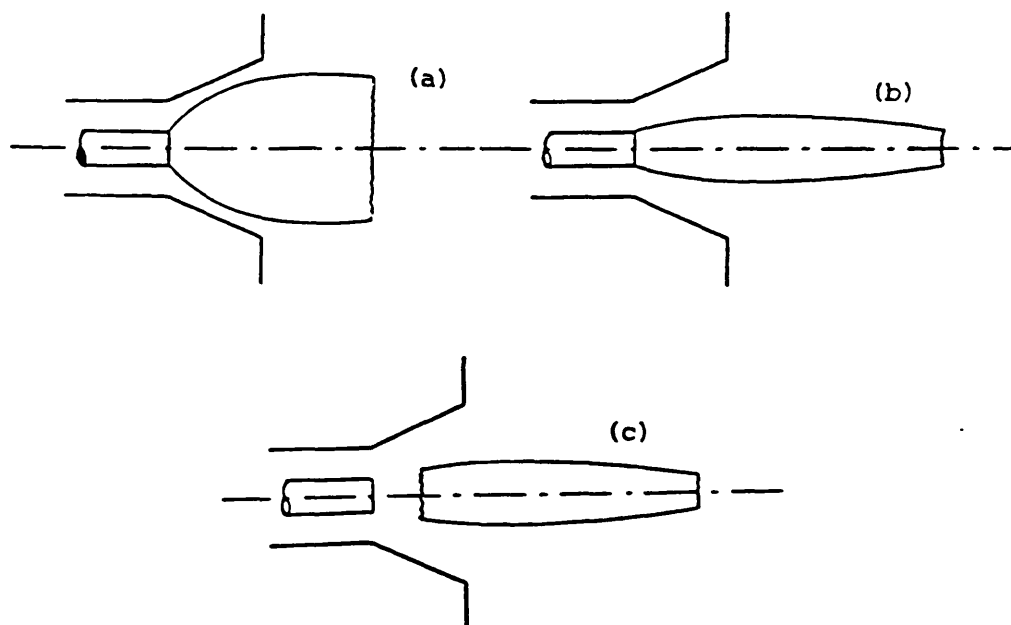


Fig. (4.18): Flame Types

- (a) Type II Flame
- (b) Type I Flame
- (c) Type I Flame (Lifted-off)

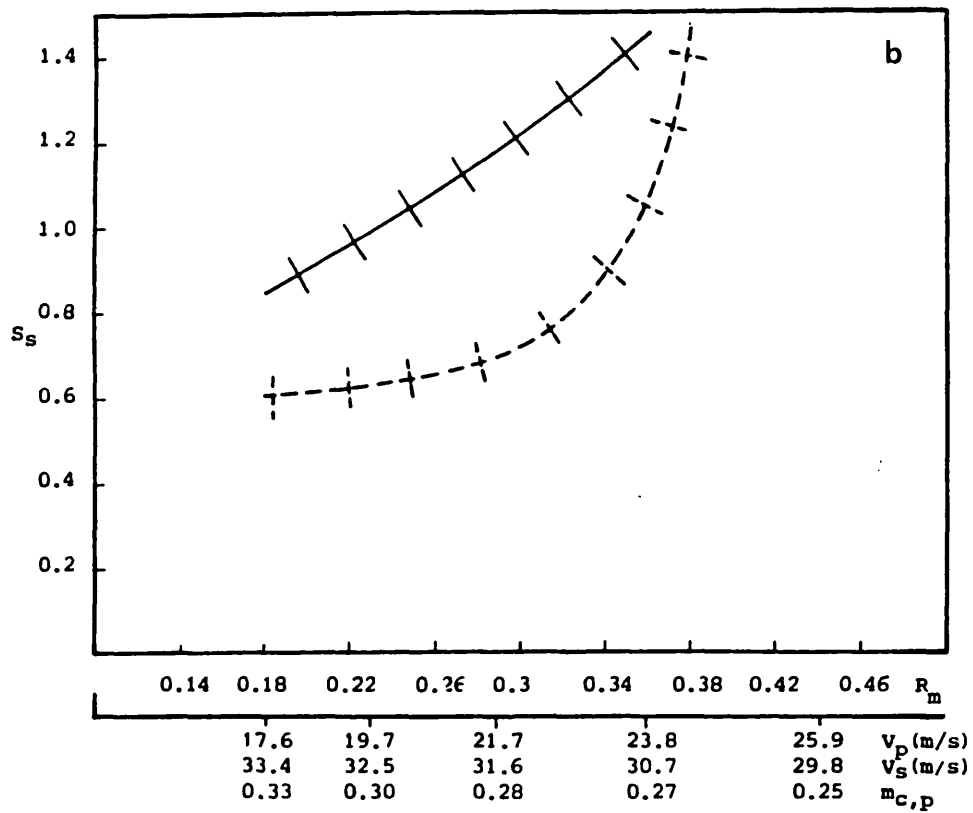
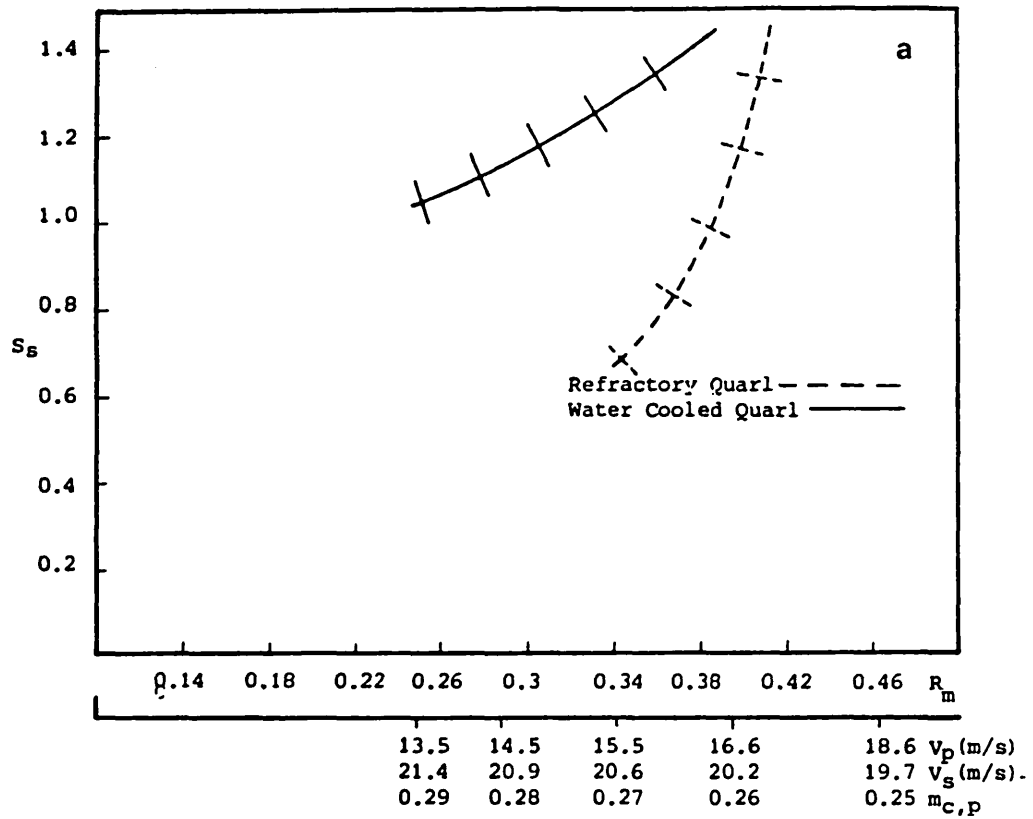
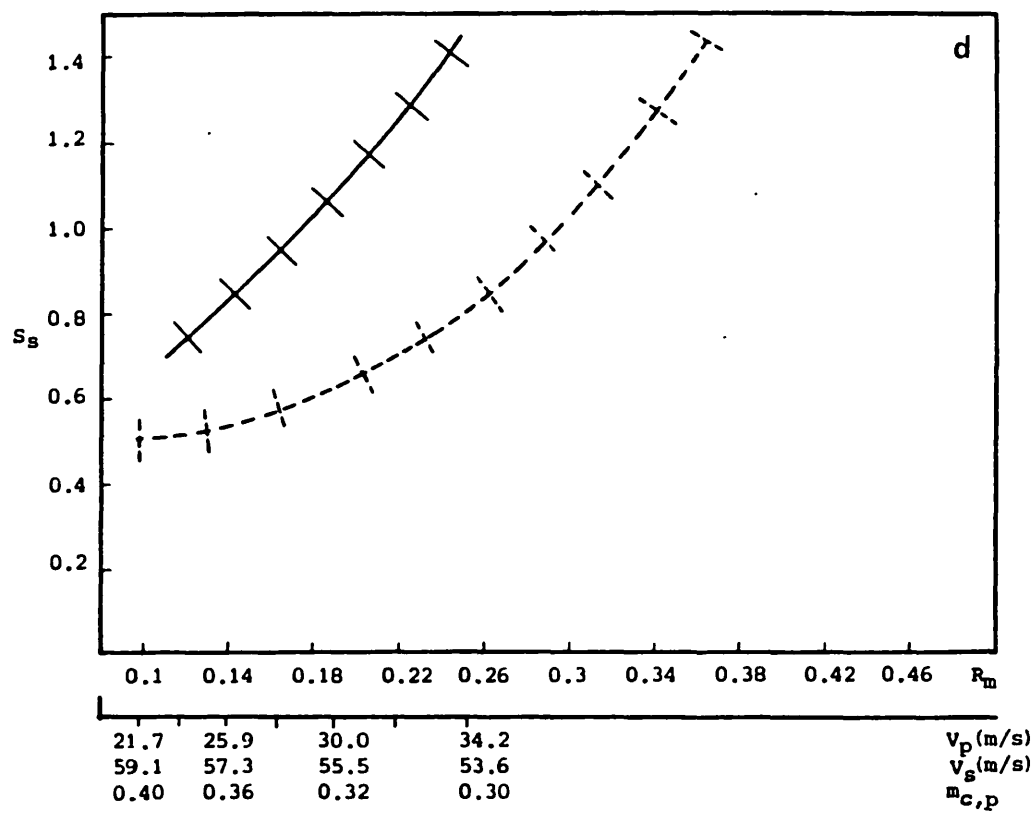
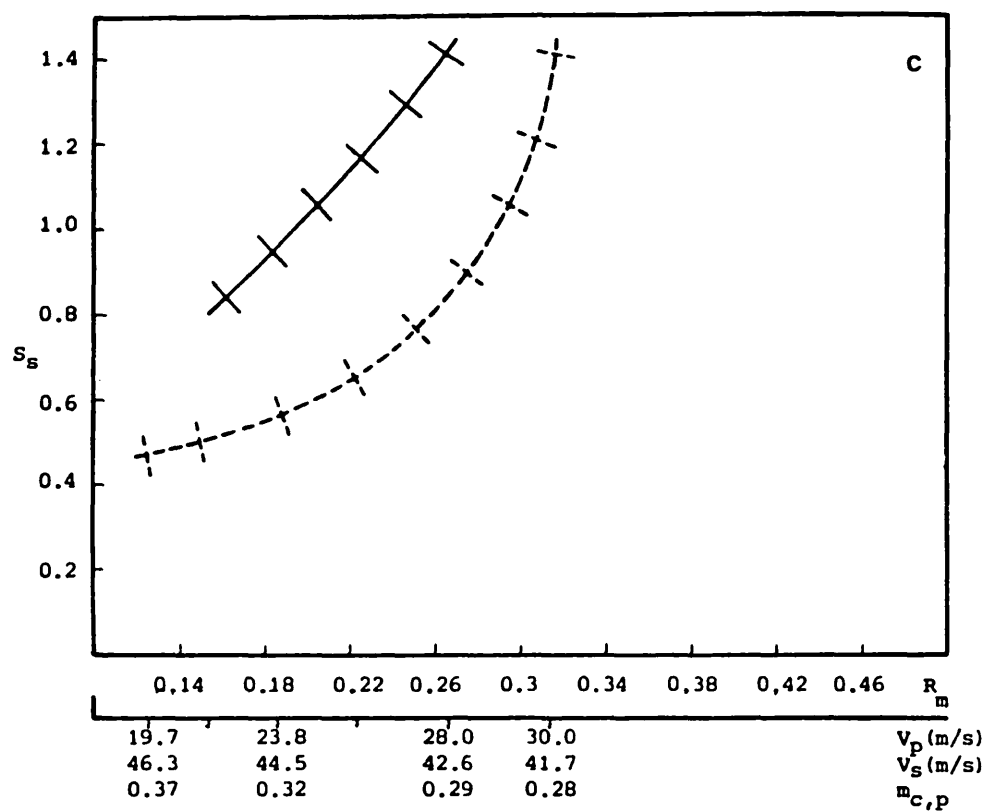


Fig. (4.19): Stability Performance for Refractory and Water-Cooled Quarls, 15% Excess Air

(a): $m_c = 7.78$ Kg/hr

(b): $m_c = 11.68$ Kg/hr



(c): $m_c = 15.47$ Kg/hr

(d): $m_c = 19.40$ Kg/hr

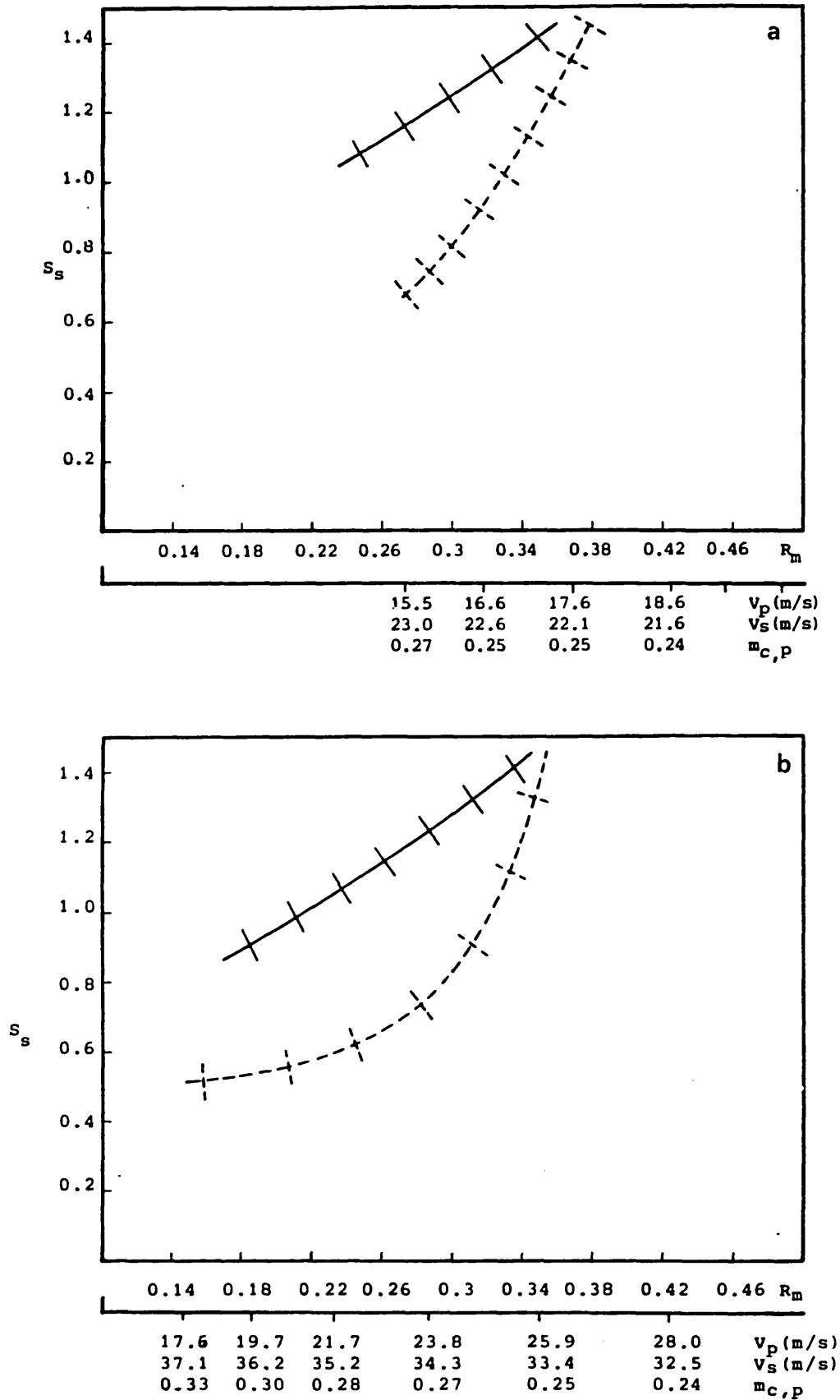
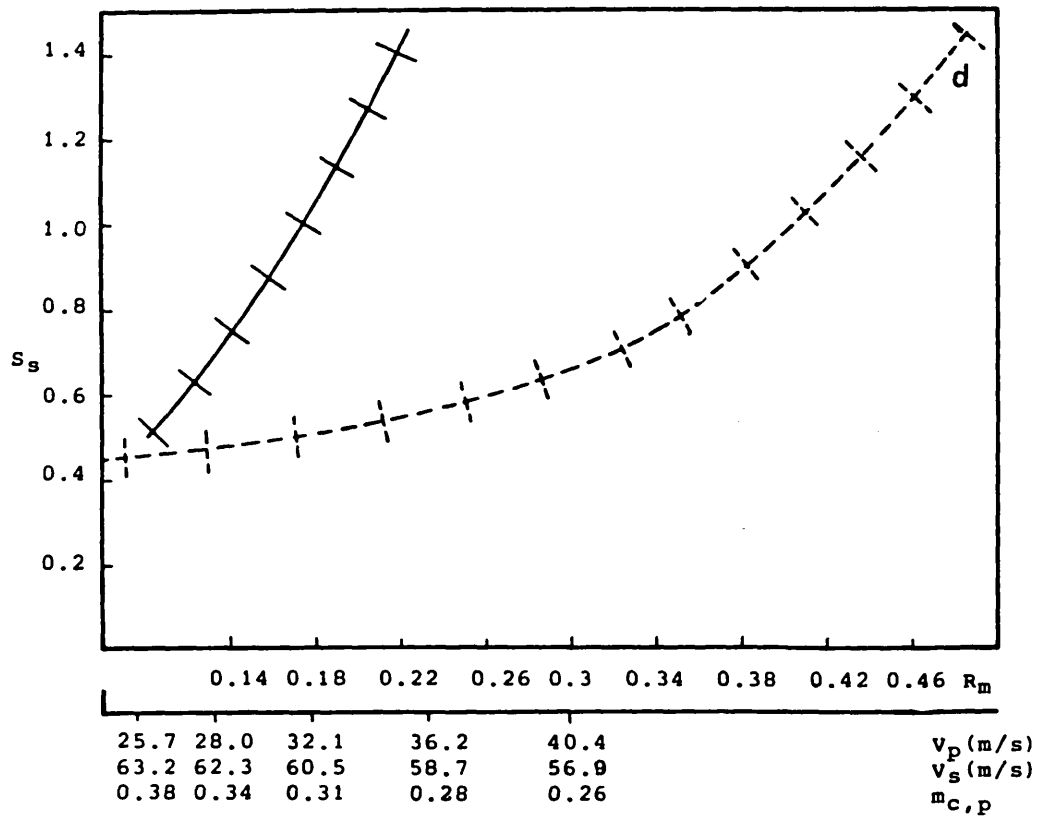
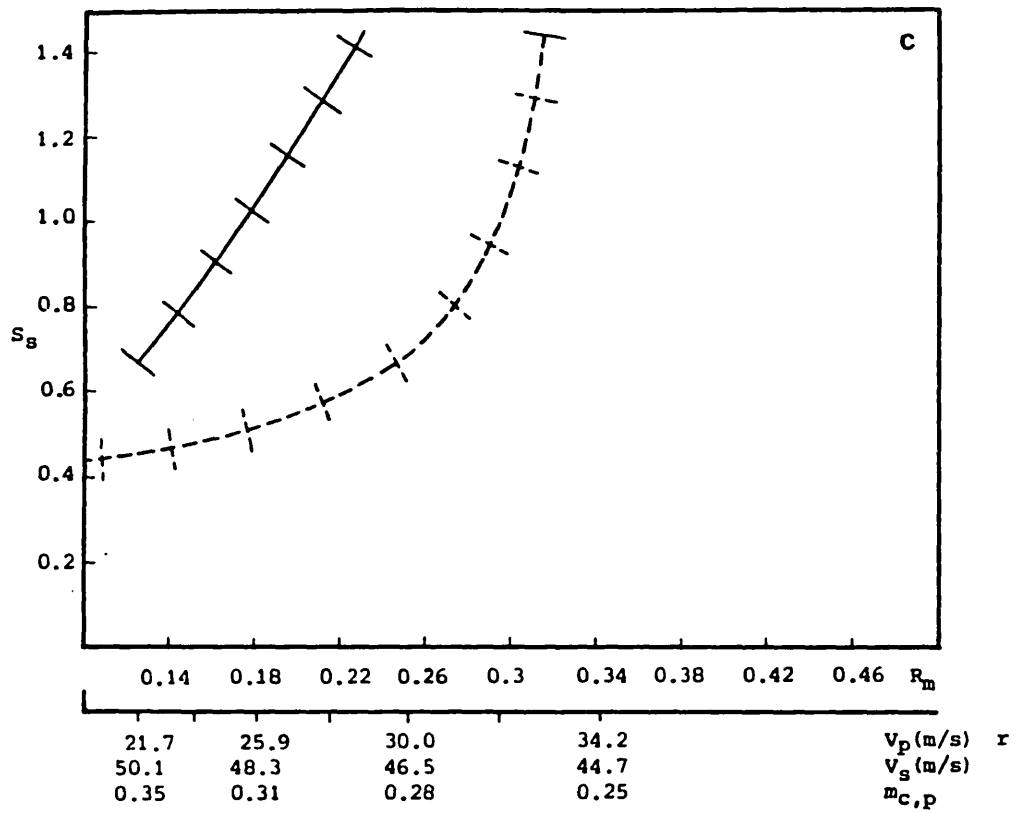


Fig. (4.20): Stability Performance for Refractory and Water-Cooled Quarls, 25% Excess Air

(a): $m_c = 7.78$ Kg/hr

(b): $m_c = 11.68$ Kg/hr



(c): $m_c = 15.47$ Kg/hr

(d): $m_c = 19.40$ Kg/hr

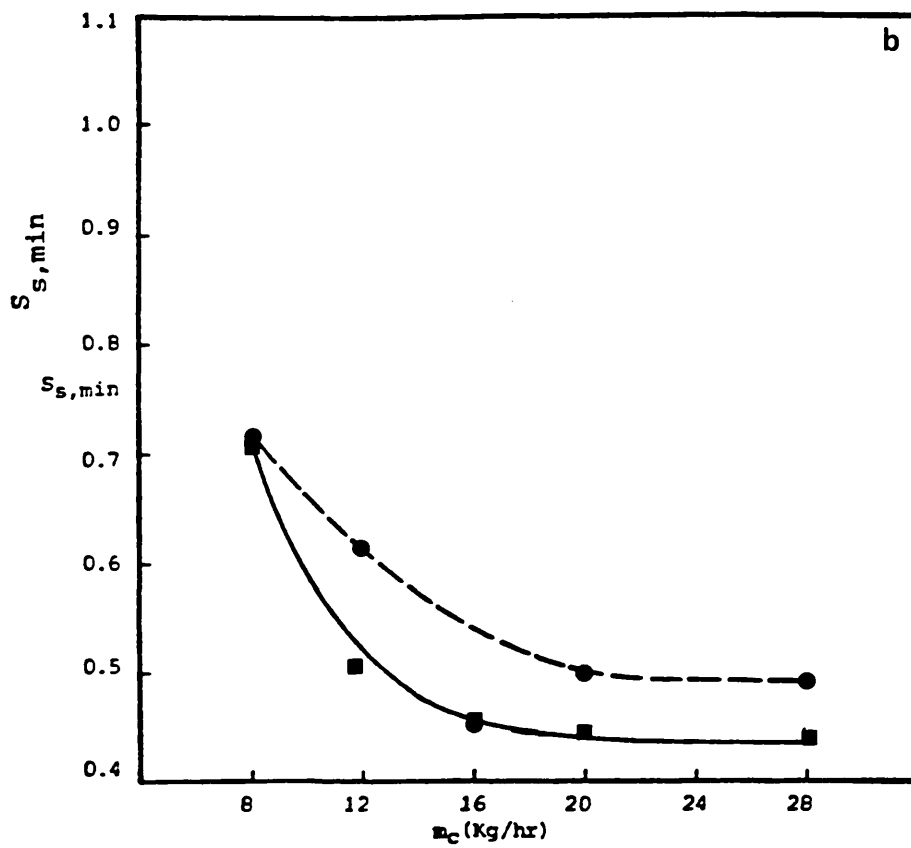
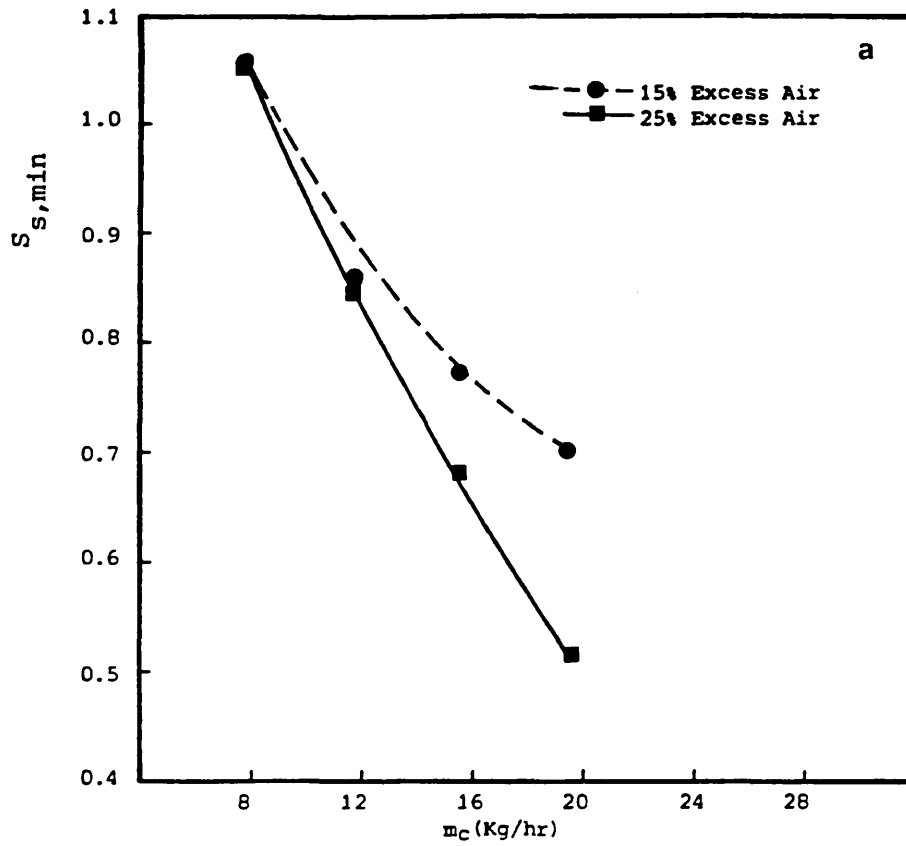


Fig. (4.21): Effect of Burner Load on Minimum Swirl Number for Stable Combustion

(a): Water-Cooled Quarl

(b): Refractory Quarl

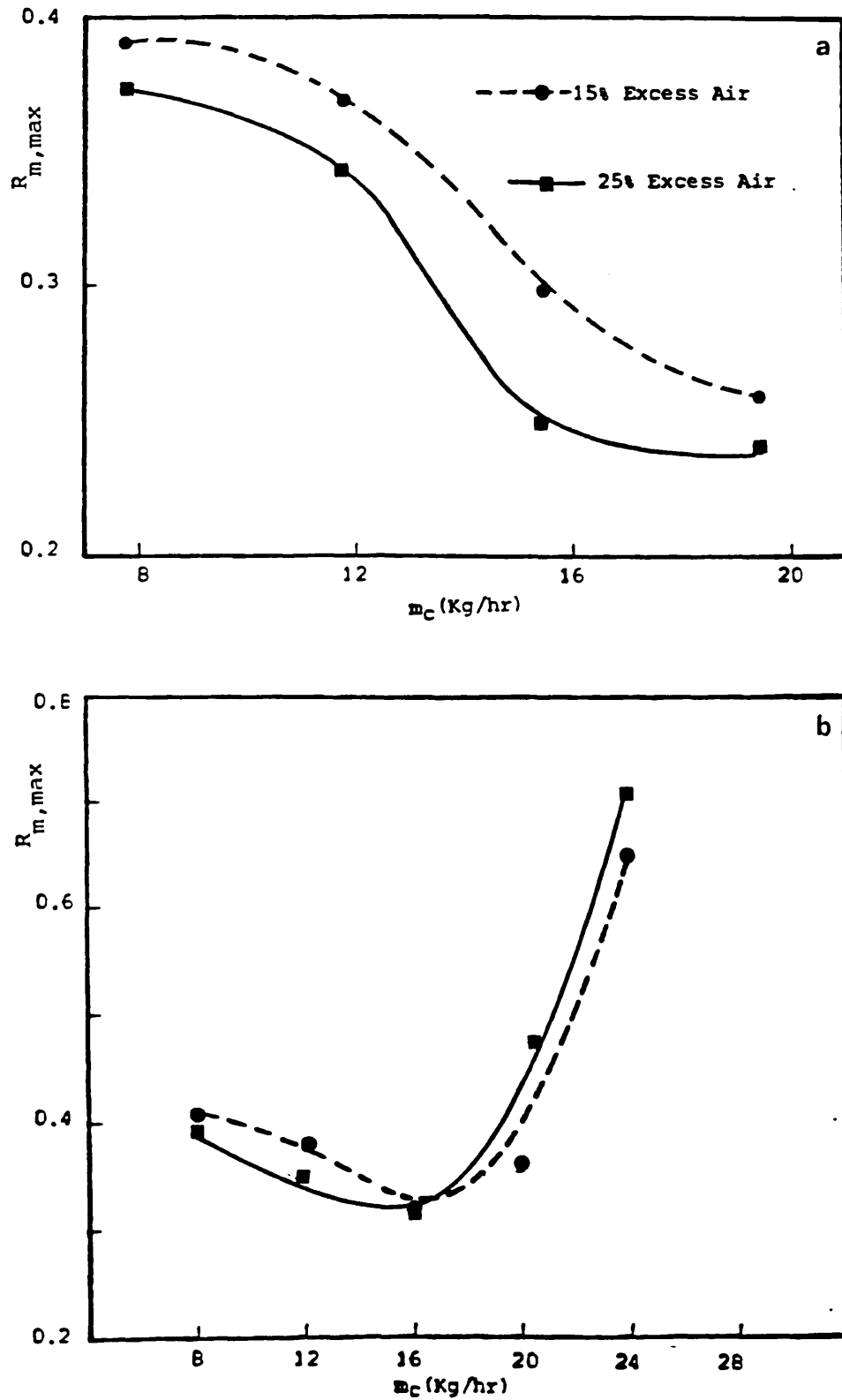


Fig. (4.22): Effect of Burner Load on Maximum momentum ratio for Stable Combustion

(a): Water-Cooled Quarl

(b): Refractory Quarl

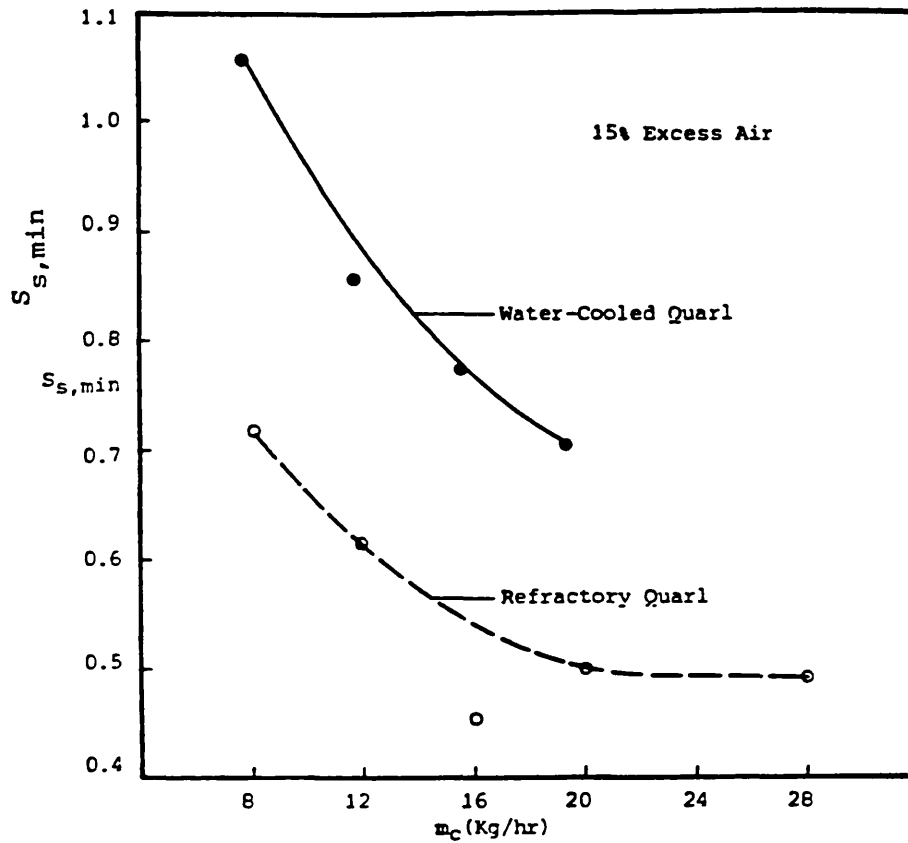


Fig. (4.23): Effect of Quarl Cooling on Minimum Swirl Number for Stable Combustion.

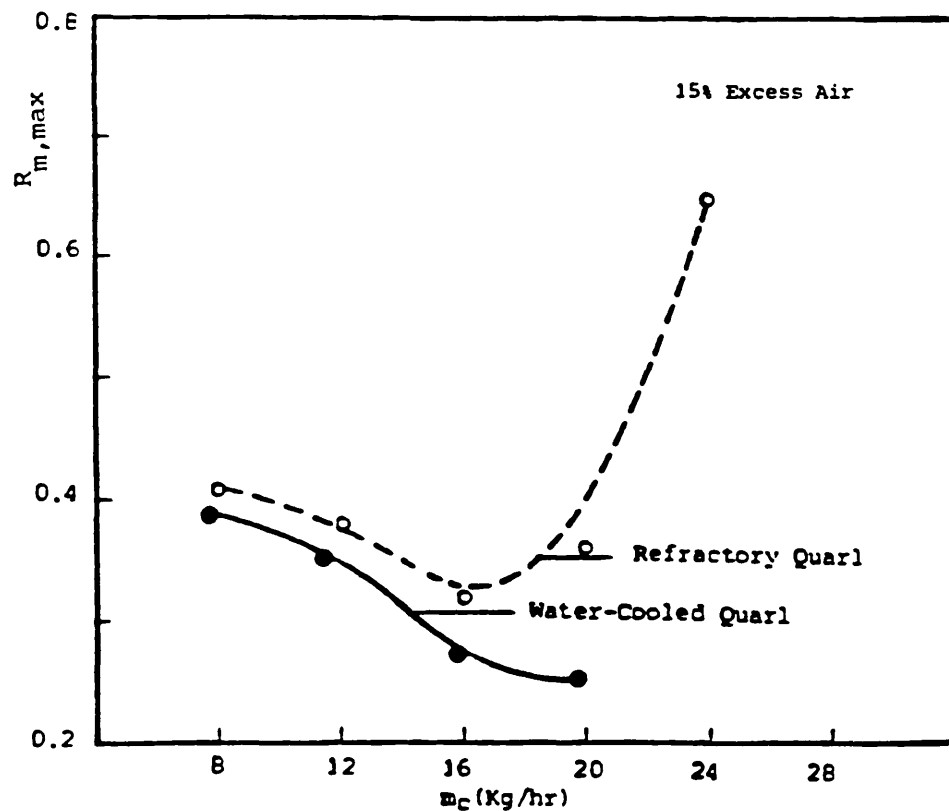


Fig. (4.24): Effect of Quarl Cooling on Maximum Momentum Ratio for Stable Combustion.

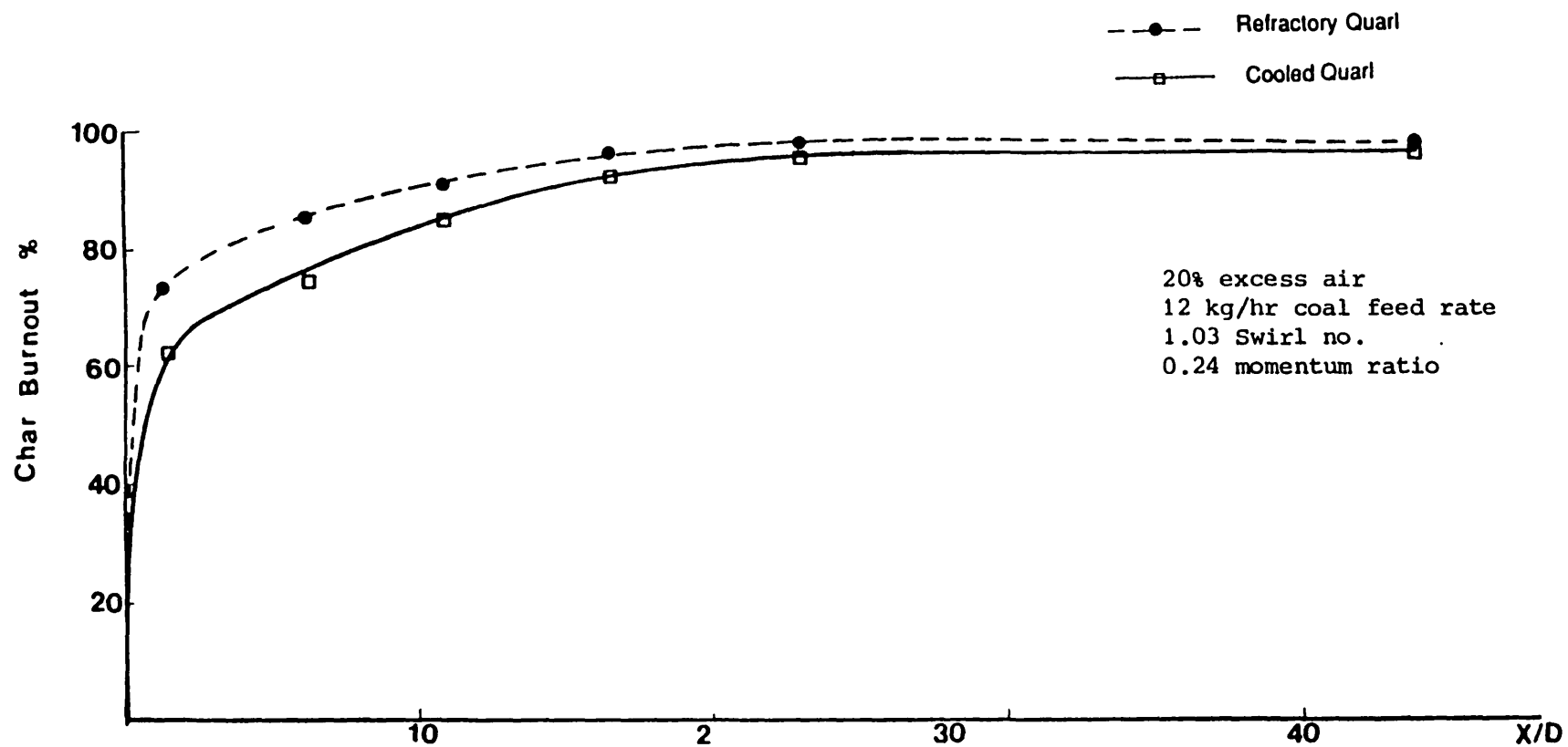


Fig. (4.25): Effect of the Cooling of the Quarl on Char Burn-out.

Chapter 5

CONCLUSIONS AND FURTHER WORK

This Chapter summarizes the major findings of this thesis and gives recommendation for further work.

5.1 Principal Conclusions from the Literature Review

- * It is generally recognized that the parameters which significantly influence the pyrolysis process, the composition and the amount of volatiles released are coal type, the thermal history of the coal particles, the ambient conditions and the particle size.
- * Rapid heating of pulverized coal particles to high temperatures results in volatiles yields in excess of the proximate content. There is no simple way of estimating the actual volatile yield since simulation of real conditions is the only reliable way of obtaining such information.
- * The volatile yield is inversely proportional to the ambient pressure.
- * The reactivity of the char has conventionally been based on the external surface area of the particle. Although convenient, this mode of reactivity estimation requires the reaction regime to be known. An 'intrinsic reactivity' approach avoids such complications, but requires a knowledge of the internal surface area of the char. The presence of oxygen dominates the burn-out levels of the coal particles especially in the 'tail' of the flame.
- * The controlling mechanism for the overall combustion process is the physical

mixing of the air and the fuel.

5.2 Summary of the Measuring Techniques.

- * The test coals are characterized with respect to their size distribution, proximate and ultimate contents, heating values, coal rank, and free swelling indices.
- * The char samples are extracted from the combustor with the aid of water-cooled/ water-quenched probe.
- * Even at a moderate temperature of about 1700 K, the ash tracer method under estimates the weight loss by up to $\simeq 5\%$.

5.3 Conclusions from the Inflammation Measurements.

- * The present study presents devolatilization and combustion information from a large scale laboratory furnace, for UK Gedling pulverized bituminous coal pulverized to a size distribution of 80% by weight under 75 μm .
- * The volatile matter is released rapidly but not instantaneously because time is required for both heating and pyrolysis of the particles to take place.
- * The smallest particles rise in temperature and ignite so rapidly that a distinctive preliminary devolatilization phase cannot be anticipated. The ignition of the largest particles is delayed with respect to devolatilization time scales.
- * Both heterogeneous gas-phase, volatiles combustion in the gas phase and heterogeneous char combustion may occur simultaneously.
- * 3% of the original volatile matter leaves the combustor in the unburned residue.
- * It may be concluded that the initial loss of volatiles is in the form of

hydrocarbons (heavy oil, tars, etc.) with later loss being hydrogen and carbon monoxide.

- * Carbon consumption correlates well with coal weight loss while, coarser bound nitrogen evolves at a slightly slower rate.
- * The 'Q' factor for Gedling coal burning in the present combustor has a maximum estimated value of 2.4.
- * The heat release rate can be used as an indication of flame efficiency as well as of the char burn-out.
- * The axial measurements of the char burn-out show that there exists an optimum value of the swirl number for which the furnace exit burn-out (i. e. the combustion efficiency) is a maximum for fixed ratio of primary to secondary momenta, R_m , and excess air level. The same conclusion can also be drawn for the effect of the excess air level. The burn-out, however, is insensitive to momentum ratio, R_m , values in the range of (0.16-0.28).
- * The radial data for swirl number of $S_s=0.78$ and $S_s=1.03$ both indicate the existence of a central flame core, probably surrounded by an annular inner recirculation zone (IRZ), and an outer recirculation zone. An increase of the swirl resulted in the particles being flung farther away from the axis in the early stages of the flame. Further downstream, the burn-out profiles become flat.
- * The affect on stability performance employing a water-cooled quarl and refractory quarl has been investigated. The char burn-out profiles in their upstream region exhibit sharp variations.
- * Flame stability data for a fixed burner load and excess air has been plotted in terms of the swirl number and the momentum ratio.
- * There exists a minimum swirl number below which a stable pulverized coal

flame is not possible. The value is associated with the establishment of an internal recirculation zone (IRZ).

- * There exists a maximum value of the ratio of the primary stream to secondary stream axial momenta beyond which a stable flame is not possible due to the coal particles transgressing the IRZ in a residence time of a too short duration.
- * Flame stability is enhanced by lowering the inlet primary air velocity (longer residence times), and by increasing the excess air level.
- * The main advantage of the water-cooled quarl is the elimination of slagging and the associated practical difficulties.
- * The main disadvantage is the decrease of stability margins as compared with those of the refractory quarl. A cooled quarl requires relatively higher swirl numbers and lower momentum ratios in order to sustain stable flames.
- * The preceding observations are mainly attributed to the elimination of heat transfer consequent of the cooled quarl walls to the incoming coal stream and the ensuring reduction of the volatiles yield in the near burner zone.

5.4 Recommendations for further work.

- * The ash tracer technique for determination of the coal particles burn-out levels should be complemented by using a more stable ash component, e.g. (Al_2O_3) or (TiO_2), as a tracer.
- * The temperature / time history of the coal particles affects their burn-out levels. Characterization of the residence times in the furnace are therefore desirable.
- * The inflame measurements should be extended to evaluate the influence of coal properties, coal condition, and specific cut size ranges, on the coal particles

behaviour as well as on the char burn-out levels.

* In pulverized coal flames, the near burner aerodynamic field influences the mixing rate of fuel and oxygen and the particles heating rates, and it controls the combustion of volatiles and char. It is recommended therefore that an LDA system, be developed capable of two phase velocity measurements in a pulverized fuel combustor.

References

- Annamalai, K. and Durbetaki, P. (1977): "A theory on transition of ignition phase of coal particles"; *Comb. and Flame*, 18, p. 411.
- Anthony, D. B. and Howard, J. B. (1976): "Coal devolatilization and hydrogasification"; *AIChE J.*, 22, p. 625.
- Anthony, D. B., Howard, J. B., Hottel, H. C. and Meissner, H. P. (1975): "Rapid devolatilization of pulverized coal"; 15th Symposium (Int.) on Combustion, The Combustion Institute, p.1303.
- Asay, B. W., Smoot, L. D. and Hedman, P. O. (1983): "Effect of coal moisture on burnout and nitrogen oxide formation"; *Comb. Sci. and Tech.*, p. 15.
- Ashu, J. T., Nsakala, N. Y., Mahajan, O. P. and Walker, P. L., Jr. (1978): "Enhancement of char reactivity by rapid heating of precursor coal"; *Fuel*, 57, p. 250.
- Badzioch, S. and Hawksley, P. G. W. (1970): "Kinetics of thermal decomposition of pulverized coal particles"; *Ind. Eng. Chem. Process Des. Dev.*, Vol.9, No.4, p. 521.
- Bandyopadhyay, S. and Bhaduri, D. (1972): "Prediction of ignition temperature of single coal particle"; *Comb. and Flame*, 18, p. 411.
- Baum, M. M. and Street, P. J. (1971): "Predicting the combustion behaviour of coal particles"; *Comb. Sci. and Tech.*, 3, p. 231.
- Beer, J. M. (1962): "Combustion of pulverized coal"; 2nd Symposium on Fumes and Industry, Inst. of Fuel, London, June.
- Beer, J. M. (1964): "The effect of fineness and recirculation on the combustion of

- low volatile pulverized coal"; J. Inst. Fuel, 37, p. 286.
- Beer, J. M. (1986): "Clean combustion of coal, research and applications. An overview of recent developments in USA"; J. Inst. of energy, 59, p. 3.
- Beer, J.M. and Chigier, N. A. (1969): "Stability and combustion intensity of pulverized-coal flames. Effect of swirl and impingement"; J. Inst. Fuel, 42, p. 443.
- Beer, J. M. and Chigier, N. A. (1972): "Combustion aerodynamic"; Applied Science Publishers Ltd, London.
- Beer, J. M. and Lee, K. B. (1965): "The effect of the residence time distribution on the performance and efficiency of combustors"; 10th Symposium (Int.) on Combustion, Combustion Institute, p. 1187.
- Bilger, R. W. (1977): "Probe measurements in turbulent combustion."; Progress in aeronautics and astronautics, 53, p. 49.
- Blakwood, J. D. and McTaggart, F. K. (1959): "Reactions of carbon with atomic gases"; Aust. J. Chem., 12, p. 533.
- Bortz, S. (1983): " Background and programme outline for IFRF burner field aerodynamics project"; IFRF Doc. nr G14/a/2.
- Bradley, D., Dixon-Lewis, G., El-Din Habik, S., and Mushi, E. M. J. (1984): "The oxidation of graphite powder in flame reaction zones"; 20th Symposium (Int.) on Combustion, Combustion Institute. p. 931.
- British Standard (1977): " BS1016 : Methods for analysis and testing of coal and coke."; The British Standards Institution.
- Cassel, H. M. and Liebman, I. (1959): "The cooperative mechanism in the ignition of dust dispersions"; Comb. Sci. and Tech., p. 213.
- Chen, M. Fan L and Essenhigh, R. H. (1984): "Prediction and measurement of

- ignition temperatures of coal particles"; 20th Symposium (Int.) on Combustion, Combustion Institute, p. 1513.
- Chen S. L., Heap M. P., Pershing D. W. and Martin G. B. (1982): "Influence of coal composition on the fate of volatile and char nitrogen during combustion"; 19th Symposium (Int.) on Combustion, Combustion Institute, p. 1271
- Chukhanov, Z. F. (1954): ; (Izv, Akad, USSR, Otd, Tech., 8, 7.) reviewed by Yellow, P. C. (1965), BCURA monthly Bulletin, 29, No. 9, p. 285.
- Cogoli, J.G., Gray, D. and Essenhigh, R.H. (1977): "Flame Stabilization of low volatiles fuel"; Comb. Sci. and Tech.,16, p.165.
- Earnest, C. M. (1985): "Thermal analysis in the coal industry"; International Instrumentation-Research, Perkin-Elmer, USA, p. 57.
- Essenhigh, R. H. (1961): "A short history of pulverized fuel firing"; J. Inst. Fuel, 34, p. 16
- Essenhigh, R. H. (1977): "Combustion and flame propagation in coal systems: A review"; 16th Symposium (Int.) on Combustion. The Combustion Institute, p.353.
- Essenhigh, R. H. (1981): "Fundamentals of coal combustion"; in Chemistry of Coal Utilization (Elliot, M. A., Ed.), p. 1153.
- Essenhigh, R. H., Froberg, R., and Howard, J. B., (1965): "Combustion behaviour of small particles"; Ind., Eng., Chem., 57, p. 33.
- Farzan, H. and Essenhigh, R.H. (1982): "High intensity combustion of coal"; 19th Symposium (Int.) on Combustion, Combustion Institute, p. 1105
- Field, M. A. (1969): "Rate of combustion of size-graded fractions of char from a low-rank coal between 1200 K and 2000 K"; Comb. and

Flame, 13, p. 237.

Field, M. A. (1970): "Measurements of the effect of rank on combustion rates of pulverized coal"; Comb. and Flame, 14, p. 237.

Field, M. A., Gill, D. W., Morgan, B. B. and Hawksley, P. G. W. (1967): " The combustion of pulverized coal "; BCURA, Leatherhead, Surrey, England.

Fyans, R. L. (1977): "Rapid characterization of coal by thermogravimetric and scanning calorimetric analysis"; Thermal Analysis Application Study 21, Perkin-Elmer.

Gavalas, G.R. (1981): "Analysis of char combustion including the effect of pore enlargement"; Comb. Sci. and Tech., 24, p.197

Gavalas, G.R. (1982): " Coal pyrolysis"; Elsevier Scientific Publishing Company.

Godoy, S, Hirji, K.K.A., Ismail, M.A. and F.C.Lockwood (1986): "Stability limits of pulverized coal firing"; J. Inst. Energy, March, p.38.

Godoy, S., Hirji, K. A. and Lockwood, F. C. (1988): "Combustion measurements in a pulverized coal-fired furnace"; Comb. Sci. and Tech., Vol. 59, p.165.

Godoy, S, Ismail, M.A. and F.C.Lockwood (1989): "Measurements in a cylindrical pulverized coal furnace"; Paper to be Submitted to Comb. Sci and Tech.

Goldberg, P. M. and Essenhigh, R. H. (1978): " Coal combustion in a jet-mix stirred reactor"; 171th Symposium (Int.) on Combustion, The Combustion Institute, p. 145.

Gray, D., Cogoli, J. G. and Essenhigh, R. H. (1974): "Problems in pulverized coal and char combustion"; No.6, Adv. Chem. Ser. 131, 72, p. 72, American Chemical Society, Washington, D. C.

- Gupta, A.K., Lilley, D.G. and Syred, N. (1984): "Swirl flows"; Abacus Press. ISBN 085626 1750.
- Hagiwara, A. and Bortz, S.(1984): "Studies on the near field aerodynamic of swirl burners"; IFRF Doc.nr. F. 259/a/1.
- Hampartsoumian, E., Pourkashanian, M., and Williams, A. (1988): " Combustion rates of char and carbonaceous residues"; British Flame Days, Furnace Combustion Research and its applications.
- Harding, N. S. (1980): "Effect of secondary swirl and other burner parameters on nitrogen pollution formation in a pulverized coal combustor."; Ph. D. Dissertation, Dept. of Chemical Eng. Brigham Young University, Provo, Utah, USA.
- Harding, N. S., Smoot, L. D. and Hedman, P. O. (1982): "Nitrogen pollution formation in a pulverized-coal combustor, Effects of secondary stream swirl "; AlchE J, 28, p. 573.
- Hassan, M.A (1983): "A study of natural gas and pulverized coal diffusion flames"; Ph. D. Thesis, University of London.
- Hassan, M.M.A., Hirji, K. A., Lockwood, F. C. and Moneib, H.A. (1985): "Measurements in a pulverized coal-fired cylindrical furnace"; Experiments in Fluids, 3, 153.
- Hazanov, Z., Goldman, Y. and Timnat, Y. M. (1985): "Opposed-flow combustion of pulverized coal"; Comb. and Flame, 61, p.119.
- Hertzberg, M., Cashdollar K. L., Ng, D. L. and Conti, R. S. (1982): "Domains of flammability and thermal ignitability for pulverized coals and other dusts: particle size dependencies and microscopic residue analyses"; 19th Symposium (Int.) on Combustion, Combustion Institute, p.1169.

- Hirji K. A. (1986): " Combustion measurements in pulverized coal flames"; Ph. D. Thesis, University of London.
- Hirji, K. A., Ismail, M. A., Lockwood, F. C., and Miller, J. (1989) "Burner stability limits of some pulverized fuels"; Paper to appear in Experiments in Fluids.
- Hirji, K. A., Lockwood, F. C., Rizvi, S. M. A., Offergeld, H. and Seitz, C. C. W. (1989): "Measurements and prediction of No_x emission in a coal fired combustor"; Paper to be published, Mechanical Eng. Dept., Imperial College, London.
- Howard, J. B. (1963): "Pyrrolytic reaction of coal"; chem. of Coal Utilization, Supplementary Volume, Lowry, H. H. Ed., John Wiley, New York, p. 340.
- Howard, J. B. (1981): "Fundamentals of coal pyrolysis and hydropyrolysis"; Second Supplementary Volume, Chemistry of Coal Utilization (M. A. Elliot, Ed.), Wiley, New York, Ny, 665.
- Howard, J. B. and Essenhigh, R. H. (1965): "The mechanism of ignition of pulverized coal"; Comb. and Flame, 9, p. 337.
- Howard, J. B. and Essenhigh, R. H. (1966): "Combustion mechanism in pulverized coal flames"; Comb. and Flame, 10, p. 92.
- Howard, J. B. and Essenhigh, R. H. (1967): "Mechanism of solid-particle combustion with simultaneous gas-phase volatile combustion"; 11th Symposium (Int.) on Combustion, The Combustion Institute, p. 399.
- Hubbard, E. H. (1960): "The first performance trial and first combustion mechanism trial with pulverized coal"; J. Inst. Fuel, p. 386.
- Jain, S. R. and Sundararajan, R. (1981): "New method of calculating calorific

values from elemental composition of fossil fuels"; Fuel, Vol. 60, p. 1079.

Jamaluddin A. S. (1985): " Combustion of pulverized coal as a Tuyere-injectant to the blast furnace."; Ph. D. Thesis, Dept. of Chemical Eng. The University of Newcastle, Australia.

Jamaluddin, A.S., Truelove, J.S. and Wall, T.F. (1986): "Devolatilization of bituminous coals at medium to high heating rates"; Comb. and Flame, 63, p.329.

Jost, M., Leslie, I and Kruger, C. (1984): "Flow-tube reactor studies of devolatilization of pulverized coal in an oxidizing environment"; 20th Symposium (Int.) on Combustion, The Combustion Institute, p. 1531.

Kandiyoti R. (1986): " Private Communication"; Chemical Eng. Dept., Imperial college , London.

Kimber, G. A. and Gray, M. D. (1967): "Rapid devolatilization of small coal particles"; Comb. and Flame,11, p. 360.

Kirov, N. Y. (1965): " Specific heats and total heat contents of coals and related materials at elevated temperatures"; BCURA Monthly Bulletin, 29, No. 2, p.33.

Ko, G. H., Sanchez, D. M., Peters, W. A. and Howard, J. B. (1988): "Correlations for effects of coal type and pressure on tar yields from rapid devolatilization"; 22th Symposium (Int.) on Combustion, The Combustion Institute.

Kobayashi H (1976): " Devolatilization of pulverized coal at high temperatures"; Ph. D. Massachusetts institute of technology, cambridge, Massachusetts, USA.

- Kobayashi, H., Howard, J. B. and Sarofim, A. F. (1977): "Coal devolatilization at high temperatures"; 16th Symposium (Int.) on Combustion, The Combustion Institute, p. 411.
- Laurendeau, N. M. (1978): "Heterogeneous kinetics of coal char gasification and combustion"; Prog. Energy Comb. Sci., 4, p. 221.
- Lester, T. W., Seeker, W. R. and Merklin J. F. (1981): "The influence of oxygen and total pressure on the surface oxidation rate of bituminous coal"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p.1257.
- Lewis M.H. and Smoot L.D. (1981): "Turbulent gaseous combustion. Part I: local species concentration measurements."; Comb and Flame, Vol. 42, p. 183.
- Lloyd, W. G. and Davenport, D. A.(1980): "Applying thermodynamics to fossil fuels. Heat of combustion from elemental composition"; J. Chem. Edu., 57, p. 56.
- Lockwood, F. C. (1985): " Stability limits of some pulverized fuels" Fluid Section Report, Imperial College, London.
- Lockwood, F. C. and Mahmoud, T.(1988): "The prediction of swirl burner pulverized coal flames"; 22nd Symposium (Int.) on Combustion, The Combustion Institute.
- Lockwood, F. C. and Rizvi, S. M. A., Lee, G. K. and Whaley, H. (1984): "Coal combustion model validation using cylindrical furnace data coal"; 20th Symposium (Int.) on Combustion, Combustion Institute, p.513.
- Loison R and Kissel, R. R. (1962): "Observation on experiments carried out on the combustion of pulverized fuel "; J. Inst. Fuel, p.60.

- Maloney, D. J. and Jenkins, R. G. (1984): "Coupled heat and mass transport and chemical kinetic rate limitations during coal rapid pyrolysis" 20th Symposium (International) on Combustion, the combustion Institute. p. 1435.
- McLean W. J. Hardesty D. R. and Pohl J. H. (1981): "Direct observations of devolatilizing pulverized coal particles in a combustion environment"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p.1213.
- Mentzer, M. and Ergun, S. (1973): "A study of the carbon dioxide-carbon reaction by oxygen exchange"; U. S. Bureau of Mines, Bulletin No. 644.
- Meyers, R. A. (1981): "Coal Hand-book"; Marcel Dekker Inc, New York.
- Michel J. B and Payne R. (1980): "Detailed measurement of long pulverized coal flames for the characterization of pollutant formation."; IFRF, Ijmuiden, Doc. No. F0 9/a/2.
- Mitchell, R. E. (1987): "Experimentally determined overall burning rates coal char particles"; Comb. Sci. and Tech., Vol. 53, p.165
- Mitchell, R. E. (1988): "On the products of the heterogeneous oxidation reaction at the surfaces of burning coal char particles" ; 22 th Symposium (Int.) on Combustion, The Combustion Institute
- Mitchell, R. E. and McLean, W. j., (1982): "On the temperature and reaction rate of burning pulverized fuel"; 19th Symposium (Int.) on Combustion, The Combustion Institute, p.1113.
- Morgan, M. E. and Dekker, J. S. A. (1987): "Characterization of coals for use in pulverized coal combustion"; IFRF Doc. No. K 70/a/5.
- Mulcahy, M. F. R. and Smith, I.W.(1969): "Kinetics of combustion of pulverized

- fuel: A review of theory and experiment"; Rev. Pure and Appl. Chem., 19, p. 81.
- Musarra S. P., Fletcher T. H., Niksa S. and Dwyer H. A. (1986): " Heat and mass transfer in the vicinity of a devolatizing coal particles"; Comb. Sci. and Tech., 45, p. 289.
- Niksa S. (1988): "Modeling the devolatilization behaviour of high volatile bituminous coals";22th Symposium (Int.) on Combustion, The Combustion Institute.
- Nsakala N.Y., Essenhigh R.H. and Walker P.L. (1977): "Studies on coal reactivity: kinetics of lignite pyrolysis in nitrogen at 808 °C"; Combustion Science and Technology, 16, pp. 153.
- Padia A. S. (1976): " The behaviour of ash in pulverized coal under simulated combustion conditions."; Sc.D. Massachusetts institute of technology, Cambridge, Massachusetts, USA.
- Patel, M. M., Grow, D, T., and Young, B. C. (1988): "Combustion rates of lignite char by TGA"; Fuel, Vol. 67. p. 165.
- Phelan, W. J. and Bortz, S. (1984): "Studies on the influence of burner design parameters upon NO_x reduction when staging the combustion air with four diverse coals"; Report on the AP 12 Trials, IFRF Doc. No. F137/a/14.
- Phelan, W. and Flament, G. (1983): "The production of No_x emissions by staged combustion for a range of diverse coals under boiler simulated conditions"; IFRF Doc. No. FO 37/a/12.
- Quann R. J. and Sarofim A. F. (1982): "Vaporization of refractory oxides during pulverized coal combustion"; 19th Symposium (International)

- on Combustion, the combustion Institute. p. 1429.
- Radovic, L. R., Walker, P.L., Jr., and Jenkins, R. G. (1983): "Importance of carbon active sites in the gasification coal chars"; Fuel, 62, p.849.
- Rees, D. P., Smoot, L. D. and Hedman, P. O. (1981): "Nitrogen oxide formation inside a laboratory pulverized coal combustor"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p. 1305.
- Rizvi, S. M. A. (1985): "Prediction of flow, combustion and heat transfer in pulverized coal flames"; Ph. D. Thesis, University of London.
- Ronser, D. E., and Allendorf, H. D. (1965 a): "High temperature oxidation of carbon by atomic oxygen"; Carbon, 3, p. 153.
- Ronser, D. E., and Allendorf, H. D. (1965 b): "High temperature kinetics of graphite oxidation by dissociated oxygen"; AIAA Journal, 3, p.1522.
- Ronser, D. E., and Allendorf, H. D. (1968): "Comparative studies of the attack of pyrolytic and isotropic graphite by atomic and molecular oxygen at High temperatures"; AIAA Journal, 6, p. 650.
- Sarjeant, M.(1981): "P.F. flame stability"; CEGB Marchwood Eng. Laboratories.
- Schmid, C. S., Weber, R. and Roberts, P. A. m (1987): "Interactions between primary air jets and swirl generated vortices"; IFRF Doc.No. K70/a/2.
- Scaroni A. W., Walker P.L., Jr, and Essenhig R.H. (1980): " Kinetics of lignite pyrolysis in an entrained flow, isothermal furnace"; Fuel, Vol. 60. p. 71.
- Schmid, C. S., Weber, R. and Roberts, P. A. (1987): "Interactions between

primary air jets and swirl generated vortices"; IFRF Doc. No. K70/a/2.

Seeker, W. R., Wegener D. C, Lester T. W. and Merklin J. F. (1978): "Single pulse shock-tube studies of pulverized coal ignition "; 17th Symposium (Int.) on Combustion, The Combustion Institute, p.155.

Seeker, W. R., Samuelsen, G. S., Heap, M. P. and Trolinger, J. D. (1981): "The thermal decomposition of pulverized coal particles"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p. 1213.

Shapatina, E. A., Kalyuzhnyi, V. V. and Chukhanov, Z. F. (1949): reviewed by Badzioch, S. (1960), BCURA monthly Bulletin, 29, No. 8, p.285.

Skinner F. D. (1980): "Mixing and gasification of pulverized coal."; Ph. D. Dissertation, Dept. of Chemical Eng. Brigham Young University, Provo, Utah, USA.

Smith, I. W. (1978: "The intrinsic Reactivity of carbon to oxygen"; Fuel, 57, p.409

Smith, I. W. (1982): "The combustion rates of coal chars: A review"; 19th Symposium (Int.) on Combustion, The Combustion Institute, p.1045.

Smith M.(1985): "Private Communication"; Dept of Mineral Resources Eng. Imperial college , London.

Smoot, L. D. (1981): "Pulverized coal diffusion flames: A prespective through modeling"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p.1185.

Smoot, L. D. and Pratt, D. T (1979): "Pulverized-coal combustion and gasification"; Plenum Press, New York, NY.

- Smoot, L. D. and Smith, P. J. (1985): "Coal combustion and gasification"; Plenum Press, New York, NY.
- Solomon, P. R.(1980): "Characterization of coal and coal thermal decomposition"; Chapter III Report, Advanced Fuel Research, Inc., East Hartford, CN.
- Solomon, P.R. and Colket, M.B. (1978): "Coal devolatilization"; 17th Symposium (Int.) on Combustion, The Combustion Institute, p.131.
- Solomon, P. R., Hamblen, D. G., Carangelo, R. M. and Krause, J. KL.(1982): "Coal thermal decomposition in an entrained flow reactor: experiments and theory"; 19th Symposium (Int.) on on Combustion, The Combustion Institute, p. 1139.
- Suuberg, E. M. (1977): Sc. D. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, U. S. A.
- Suuberg, E, M., Peter, W. A., and Howard, J. B. (1978): "Product composition and kinetics of lignite pyrolysis"; Ind. Eng. Chem. Process Des. Dev., 17, p. 37.
- Suuberg, E, M., Peter, W. A., and Howard, J. B. (1978): "Product composition and formation kinetics in rapid pyrolysis of pulverized coal: implications for combustion"; 17th Symposium (Int.) on Combustion, The Combustion Institute, p. 117.
- Sy, O. and Calo, J. M. (1983): "Transient kinetic studies of char reactions in a gradient less reactor system-CO₂ gasification"; Am. Chem. Soc. Divn. of Fuel Chemistry reprints, 28, p. 6.
- Syred, N. and Beer, J.M. (1972): "The damping of processing vortex cores by combustion in swirl generators."; *Astronautica Acta*,17, p.783.
- Thurgood, J. R., Smoot, L. D. and Hedman, P. O. (1980): "Rate measurements in a

- laboratory-scale pulverized coal combustor"; Comb. Sci. and Tech., p. 213.
- Timothy L. D. Sarofim A. F. and Beer J. M. (1982): "Characteristics of single particle coal combustion"; 19th Symposium (Int.) on Combustion, Combustion Institute, p.1169.
- Tine, G. (1961): "Gas sampling and chemical analysis in combustion processes"; Pergamon Press, New York.
- Tognotti L. Malotti A. Petarca L. and Zanelli S. (1985): "measurement of ignition temperature of coal particles using a thermogravimetric technique"; Comb. Sci. and Tech., 44, p. 15.
- Tsai, Ching-Yi and Scaroni, Alan w. (1987) : "The structural changes of bituminous coal particles during the initial stages of pulverized-coal combustion"; Fuel, Vol 66, p. 200.
- Ubhayakar, S. K., Stickler, D. B., Rosenberg, C. W. V. and Gannon, R. E., (1977): "Rapid devolatilization of pulverized coal in hot combustion gases"; 16th Symposium (Int.) on Combustion, The Combustion Institute, p. 427.
- Vulis, L.A. (1961): "Thermal regimes of Combustion"; Translation by M. D. Friedman, MacGraw-Hill.
- Wall, T. F. (1984): "Coal properties and classification"; Pulverized Coal Combustion-Intensive Course Organized by Dr. F. C. Lockwood, Imperial College, London.
- Wall, T. F., Gururajan, V. S., Phelan, W. J., and Bortz, S. (1985): "Burnout in pulverized coal furnaces with swirled burners; Measurements in the IFRF furnace and predictions for industrial furnaces"; IFRF Doc. nr. K 20/a/215.

- Walker, P. L., Jr., Rusinko, F., Jr, Austin, L. G., (1959): " Gas reaction of carbon"; *Advances in Catalysis*, 11, p. 133
- Walker, P. L., Jr., and Hippo E. J. (1975): "Factors affecting reactivity of coal char"; *Am. Chem. Soc. Divn. of Fuel Chemistry reprints*, 20, p.45.
- Wells, W. F., Kramer, S. K., Smoot, L. D. and Blackham, A. U., (1984): "Reactivity and combustion of coal chars"; 20th Symposium (Int.) on Combustion, The Combustion Institute. p.1539
- Wen, C. Y. and Dutta, S. (1979): "Rates of coal pyrolysis and gasification reactions"; In *Coal Conversion Technology* (Wen, C. Y. and Lee, E. S., Eds.) Addison Wesley Publishing Co. , Reading, Massachusetts, p. 57.
- Wendt, J. O. L. (1980): "Fundamental coal combustion mechanisms and pollutant formation in furnaces"; *Prog. Energy Comb. Sci.*, 6, p. 201
- Wolanski, P. and Wojcicki, S. (1974): "Stabilization of coal dust-air mixture by bluff bodies"; 15th Symposium (Int.) on Combustion, The Combustion Institute, p.1295.
- Wroblewska, V., Zelkowski, J. and Wojcicki, S. (1976): "The optimum conditions for the combustion of low-calorific coal dust in swirl burners"; 16th Symposium (Int.) on Combustion, The Combustion Institute, p. 401.
- Yang, W., Eckhardt, D. A., and Skriba, M. C. (1980): "Dilute phase pneumatic transport of fine nuclear fuel powder"; *Pneumotransport*, 5, paper F3.
- Yellow, P. C. (1965): "Kinetics of the thermal decomposition of coal"; *BCURA monthly Bulletin*, 29, No. 9, p. 285.

- Young, B. C. and Smith, I. W. (1981): "The Kinetics of combustion of petroleum coke particles at 1000 to 1800 K: the reaction order"; 18th Symposium (Int.) on Combustion, The Combustion Institute, p. 1249.
- Youn, B. C. and Niksa, S. (1988): "Combustion rates for selected low-rank coal chars"; Fuel, Vol. 67. p. 155.