CHAPTER 2

LITERATURE REVIEW AND THEORETICAL CONSIDERATION

Conversion methods of burning coal in the form of lumps is both mechanically difficult and thermally inefficienct. If however, the coal is finely powdered, it then behaves as a semi-fluid, which can be both transported and burnt far more easily. Powdered or as it is more commonly called pulverized coal, on account of both ignition and safety problems. However, if the powdered coal is dispersed in an oil this serious limitation to its use is eliminated. The huge handling cost, one of the most significant elements in the transportation of coal, can only be reduced when coal is finely powdered and transported as a liquid or as a semi-liquid at ordinary atmospheric temperatures. Coal-in-oil fuels (dispersion and mixtures) also have the same advantages as liquid fuels, and savings in oil consumption of up to 70 % are possible.

Slurry fuels are suspensions of finely ground coal in one or more liquids such as water, fuel oils or methanol. Coal concentrations vary but, typically, approach theoretical saturation limits due to the economic need of maximum heating value contributed by the coal in the fuel. Limiting factors to coal concentration are particle packing and viscosity characteristics of the fuel.

The concept of a coal slurry is not new; patents for utilizing coal-oil fuels were first granted in 1879. However, the relatively low price of oil compared to that of coal caused little interest in this fuels other than at times of oil supply shortage. Examples of such shortage occured during the two World Wars. Coal-oil fuels were used in the United States during the 1920's and there was some later usage in other countries before

cheap oil reduced their attractiveness.

Higher oil prices in the early 1970's prompted renewed interest in coal-slurry fuels. Coal-oil fuels which permit partial replacement of oil with coal were the main subject of interest. Current potential applications for such coal-slurry fuels as oil replacement are: (a) industrial steam boilers; (b) utility boilers; (c) blast furnaces and process kilns and (d) diesel engines.

Coal-slurry fuels have an immediate attraction compared with pulverized coal in that they can be handled in a similar manner to heavy fuel oil. They may, therefore, enable the continued use of existing oil-fired boilers with a minimum of retrofitting, i.e. modification or replacement of equipment, or where there is no space for pulverized coal-handling equipments.

Semicommercial plants to produce coal-slurry fuels are available in the USA, Canada, Sweden, Japan, Italy, China and other countries. The examples of coal-oil mixture commercial applications include: (a) Florida Power Corporation's Bartow power plant, in operation since 1982 (b) Japan COM company operates a 900,000 tonnes per year plant and supplies two 265 MW utility boilers of Tokyo Electric Power etc.

## 2.1 Types of coal-slurry fuels

Several coal-slurry fuels (CSF) made of combinations of various liquids and coal are described in the technical literature. The ones referred to are:

a) Coal-oil-mixture fuels (COM)-a suspension of coal in fuel oil which may contain up to 10 % by weight of water, sometimes COM'S are referred to as coal-oil dispersions (COD).

b) Coal-oil-water fuels (COW) and coal-water-oil fuels (CWO)-suspensions of coal in fuel oil and 10 % or more water. Oil is the main liquid component in COW's and water in CWO's.

c) Coal-water fuels (CWF)-a suspension of coal in water, also referred to as coal-water-mixtures (CWM) or coal-water-slurries (CWS).

d) Coal-methanol-mixture fuel (CMF)-a suspension of coal in methanol.

e) Coal-methanol-water fuel (CMW)-a suspension of coal in methanol and water.

## 2.2 Preparation of coal-slurry fuels (CSF)

Basic requirements for the preparation of coal-slurry fuels involve coal and carrier liquid(s) storage, coal handling, size reduction, an additives package, mixing and storage of coal-slurry fuel. Preparation techniques differ in the method of size reduction of coal, the particle size distribution in the fuel, the use and type of coal beneficiation, the order of mixing of the components and the utilization and type(s) of additives.

### 2.2.1 Size reduction of coal

Coal-slurry fuels typically require a particle size distribution (PSD) with 75-80 %, -74 microns (200 mesh), the standard boiler feed size or finer. The rheological properties depend on particle size distribution. To maximize the concentration of coal in the slurry, a broad size distribution is desirable. Multimodal distributions are used to enhance particle packing efficiency. This points to the importance of grinding technology in fuel preparation for the attainment of desirable fuel properties.

Grinding mills are divided in two main classes: mechanical and fluid energy mills. Mechanical mills employ direct mechanical action on individual coal particles or assemblies of particles and operate on impact, crushing or attrition principle such as hammer mill, szego mill and ball mill etc. Fluid energy

mills employ the kinetic energy of particles accelerated by compressed air or superheated steam jets to grind the material by impact against other particles or target plates on the chamber walls. Fluid energy milling consumes large amounts of energy and may not be economical for CSF preparation.

There are two basically different ways of preparing coal-slurry fuels. One is to stir dry-ground coal into liquid, e.g. fuel oil, the dry-grinding route; the other is to mix coarsely crushed coal with liquid, e.g. fuel oil and grind the mixture, termed the wet-grinding route. Each method has its advantages and disadvantages; the dry route offers lower grinding energy requirements at the expense of requiring dried coal at additional energy cost and an extensive dust separation plant; the wet route avoids dust hazards and nuisance and provides a thoroughly homogenized product from a relatively simple plant, but may need separate equipment to remove oversize product and contaminants.

### 2.2.2  Coal beneficiations

One of the main obstacles to burning coal or coal-slurry fuels in boilers designed for oil or gas is the introduction of mineral matter and sulfur into the boiler. Ash, formed during the combustion process, may result in rapid bottom ash accumulation, furnace slagging, convection and economizer tube fouling, erosion and excessive particulate emission. While equipment can normally be added to control particulate emissions, ash-related problems inside the boiler can only be alleviated by boiler modification. Any reduction in the quantity of mineral matter entering a boiler with a slurry fuel will, correspondingly, reduce the need for modifications. Combining beneficiation of coals with slurry fuel preparation will allow such coals to be used and will also result in higher heating value of fuel.

Fine coal cleaning can be achieved either by physical or chemical methods. Physical methods are based on differences in

density between coal constituents or particle surface chemistry. Chemical methods involve the extraction of the sulfur and the mineral matter from the coal matrix by a series of leaching steps. All physical, fine-coal cleaning processes begin with grinding the coal sufficiently finely to liberate the mineral matter. Liberation of size is different for each coal. The finer the coal, the better the mineral matter is liberate. In particular, froth floatation and selective oil agglomeration methods have been investigated with respect to coal-slurry fuel preparation.

Froth floatation is the only process for fine coal (-28 mesh) cleaning in large-scale commercial operation. It is based on the hydrophobic or hydrophilic properties of coal and its associated impurities. Coal cleaning is achieved by passing small air bubbles through a dilute coal-water suspension. The hydrophobic coal particles, when contacted with air bubbles, are captured and floated to the surface where they are removed as a concentrate. Tailings are passed to a thickener for mineral matter removal and water recycle. Chemical " collectors " are added during a conditioning stage to establish more hydrophobic surface on the coal, thus enhancing the separation. " Frothers " are added to change the surface tension of the water and to reduce bubble coalescence.

Selective oil agglomeration (Spherical agglomeration) to the process which a suspension of finely ground coal in water is contacted with oil into fine droplets and allows the hydrophobic coal particles to collect onto these droplets, leaving the hydrophilic mineral matter behind in water. The economics of selective oil agglomeration as a beneficiation step in fuel preparation is viable but its attractiveness for CWF preparation is limited. It is not economical to recover the oil or solvent prior to CWF preparation. Thus, the method is really limited to the preparation of fuels containing coal, water and oil, either

CWO or COW fuels. In both cases, the heating value of the oil is recovered during combustion.

## 2.3 Slurry properties

Following preparation, the slurry fuel has to exhibit properties which one compatible with pumping, on-site storage, ground or sea transportation, storage on users' premises, and atomization for combustion. Pumping and atomization characteristics are governed, respectively, by the low and high-shear rheological properties of the fuel. Properties important for storage and transporation are related to stability of the slurry. Finally, erosivity of the slurry and, hence, the service life of the slurry handling equipment and burner nozzle is related to ash and particle size characteristics in the fuel.

### 2.3.1 Rheological properties

In the specification of CSF characteristics for use as a boiler fuel, it is desirable to have a fuel which is stable, pumpable, and easily atomized to achieve high combustion efficiencies. These requirements have motivated the investigation and understanding of rheological properties of CSF. A theoretical understanding of the factors influencing coal slurry rheology are type of coal, its concentration, the particle size distribution, properties of the continuous phase, the temperature and the additives package used in the formulation of the slurry. It is, therefore, important to understand the various phenomena involved in the preparation and handling of coal slurries to achieve the highest possible coal concentration at a given slurry viscosity level while maintaining slurry stability.

In CSF, each solid particle moves with the average velocity of the surrounding fluids. That is, we shall treat the solid particles as fluid elements with regard to their

instantaneous motions, but shall investigate very carefully the
hydrodynamic interaction among particles in relative motion and
in close proximity to one another. The presence of particles in a
flowing liquid results in a greater dissipation of energy and
increased viscosity. Einstein calculated the energy loss by
viscous dissipation in a liquid due to the presence of particles
and derived the equation

$$\mu_r = \mu/\mu_0 = 1 + 2.5\phi \qquad (1)$$

where $\mu_0$ is the viscosity of the continuous phase, $\mu_r$ is the
relative viscosity, $\mu$ is the absolute viscosity and $\phi$ is the
volume fraction of solids in the suspension. This equation
applies only to very dilute suspension behaved as a Newtonian
fluid. Coal slurry fuels, at low coal concentrations ($\sim$10 %); for
example, coal-oil mixture falls into this category.

Frankel and Acrivos (1) derived such equations for
spherical particles in highly concentrated suspensions

$$\mu_r = 1 + C \left[ \frac{(\phi/\phi_M)^{1/3}}{1 - (\phi/\phi_M)^{1/3}} \right] \qquad (2)$$

where $\phi_M$ is the maximum attainable solids volume fraction in the
particular suspension and $C$ is a constant depending on the assumed
geometrical arrangement of spheres. Experimental data suggest a
value of $C = 9/8$. The equation is valid when $\phi/\phi_M \longrightarrow 1$, i.e. for
highly concentrate slurries. Coal-slurry fuels, especially
coal-water slurry fuels, fall into this category.

$$\mu_r = \left[ 1 + 0.75 \left( \frac{\phi/\phi_M}{1 - \phi/\phi_M} \right) \right]^2 \qquad (3)$$

Both correlations indicate that the relative viscosity
of suspensions is only a function of the reduced volume
concentration, $\phi/\phi_M$. The relative viscosity is lowered when this

ratio is lowered by increasing $\phi_M$ . Increasing the $\phi_M$ through an optimum particle size distribution is the route successfully. Their approaches involve the determination of the mixture of sizes which gives the maximum packing volume fraction, i.e. multimodal distribution.

Studies relate to the rheological properties of coal-oil mixture appeared in the technical literature during the Second World War and again in the post-1973 period. Work done in the interventing period is rare and refers mainly to pipeline transportation of COM's. All investigators are agreed that at low concentrations(~10%), COM's are Newtonian fluids, provided that the base oil is Newtonian and at high coal concentration they observed the development of yield stress and suggested the Bingham model for rheological behavior and have equation

$$\tau - \tau_y = k\dot{\gamma} \tag{4}$$

where $\tau$ is shear stress, $\tau_y$ is yield stress, $k$ is plastic viscosity and $\dot{\gamma}$ is shear rate.

Munro et al. (2) suggested Newtonian behavior up to 30% solids and Bingham plastic behavior beyond. They use #4 oil and a subbituminous coal. Rheogram as well as viscosity are given.

Papachristodoulou et al. (3,4,5) studies COM rheology with four different oils and one bituminous coal. Newtonian behavior was observed up to 30 % coal and Bingham plastic beyond. Data for one COM are illustrated in Figure 2.1. At higher concentrations, yield stress up to 350 Pa was measured. The physical explanation of Bingham plastic behavior is that a network is formed inside the fluid as a result of interparticle forces, and an external stress equivalent to the yield stress has to be applied for the network to be destroyed and the flow to occur. The effects of coal concentration, particle size and temperature were established. The viscosity increases with coal

loading and decreasing temperature is given in Figure 2.2. It is interesting to note that a very important factor in the viscosity build-up is the viscosity of the base oil (continuous phase) at the same temperature and the behavior the oil, the faster the viscosity increases with coal concentration, particularly so in highly loaded slurries, that showed in Figure 2.3 and 2.4 . Figure 2.5 showed that the COM yield stress decreases with increasing particle size. Multimodal distributions were shown in Figure 2.6 to reduce both slurry viscosity and yield stress.

Low and Bhattacharya (6,7) also observed ageing effect for brown coal-oil suspensions and that ageing was influenced by the moisture content in the coal. The dry brown coal-KC 220 oil suspension showed almost negligible increase in apparent viscosity, while a suspension of similar concentration, but containing brown coal with 10 wt% moisture content (based on dry coal) , showed very significant increase in apparent viscosity. In the same paper, they also showed that with other parameters being constant, the apparent viscosity and yield stress of brown coal-KC 220 oil suspension increased sharply when moisture content exceed 10 wt% (Figure 2.7). They explained that the increases in both the apparent viscosity and yield stress were due to the aggregation of coal particles and that this aggregation was enhanced in the presence of water diffused out from the coal into suspension.

Reject and Franke (8) measured COM rheology by pumping tests and observed that the pore volumes in brown coals were much higher than that of bituminous coals and anthracite coal. They showed that at identical concentration and temperature, higher viscosities were obtained with brown coal slurries than with bituminous or anthracite coal slurries. They explained that lignite-fines have a porous surface, and a part of the oil penetrates into the pores, hence, this becomes a
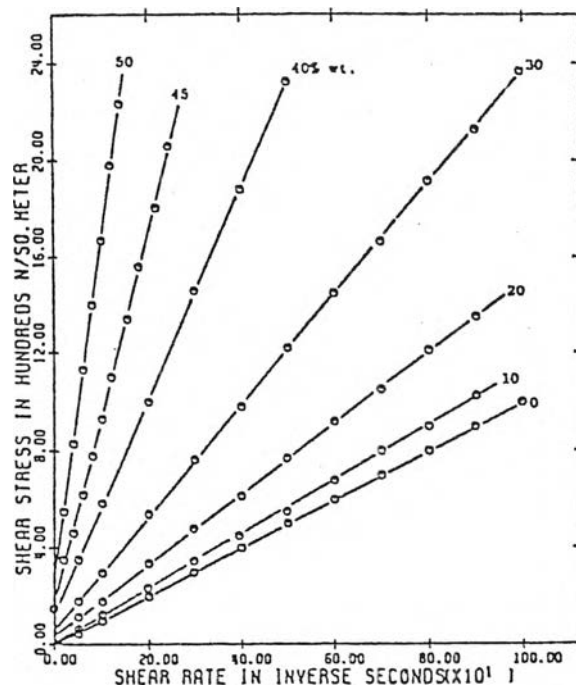
Figure 2.1   Rheogram of coal in heavy #6 oil; various coal
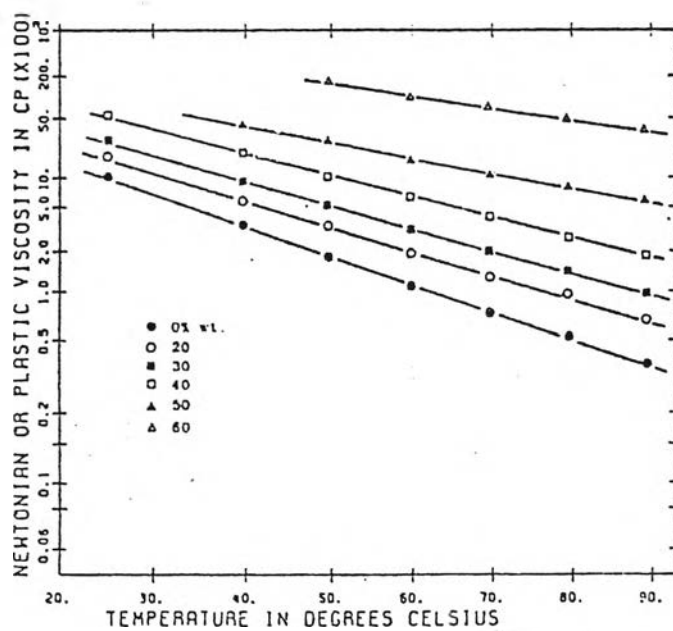concentrations, 40 °C. (4)

Figure 2.2   Variation  of viscosity with temperature for coal
$(d_{60}$ $=$ $10$ $\mu m)$   in  light  grade 6 oil;  various
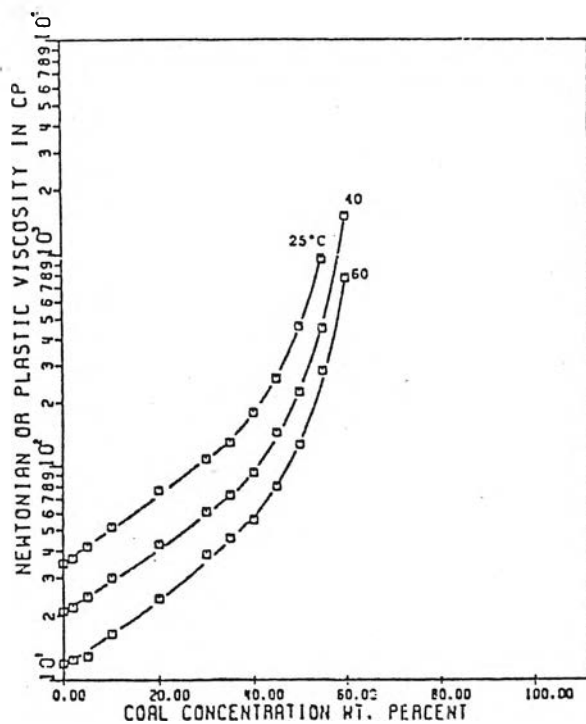concentrations. (4)

Figure 2.3  Viscosity (Newtonian or plastic) as a function of

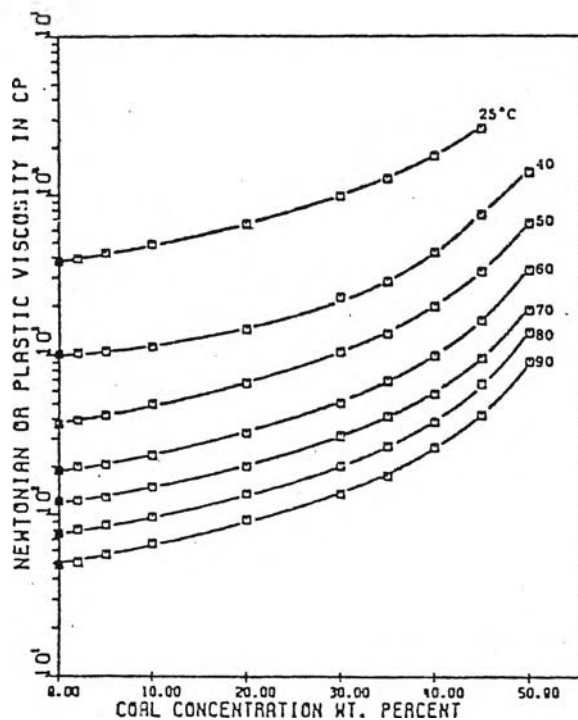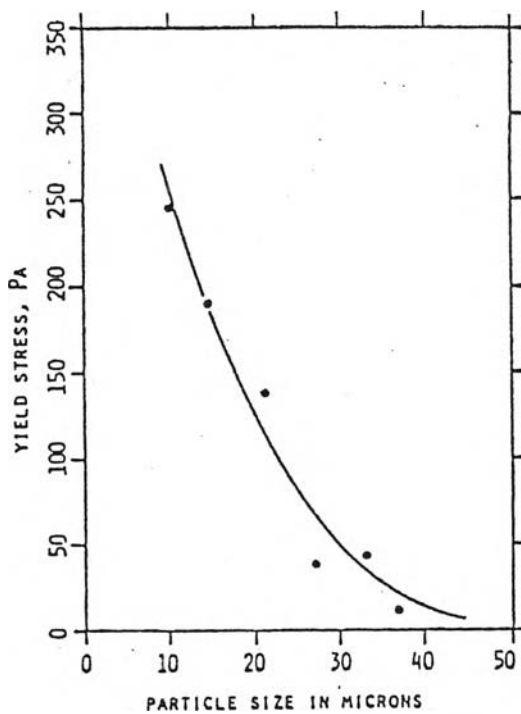coal concentration for #4 oil; various temperatures.(4)

Figure 2.4  Viscosity (Newtonian or plastic) as a function of

coal   concentration   for   heavy   #6 oil;   various

temperatures. (4)

Figure 2.5  Variation of yield stress with median particle size:
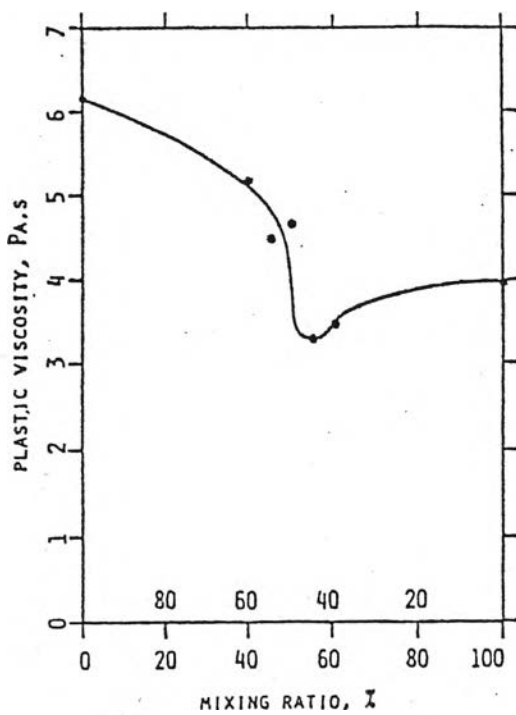60 wt.% coal, light grade 6 oil. (4)



Figure 2.6  Variation of viscosity with mixing ratio of the  37
and 14 um median particle size slurries; 60 wt% coal,
80 °C, light grade 6 oil. (4)

significant factor because this effectively reduces the volume of free oil in the suspension which acts as a lubricant between coal particles. This also effectively increases the volumetric concentration of solids in the suspension. In addition, the moisture from the coal also promotes the formation of aggregates, as shown in Figure 2.8 and 2.9. Bituminous coals show , on the other hand, smooth surface so that sufficient fuel oil remains to give a slipper plane.
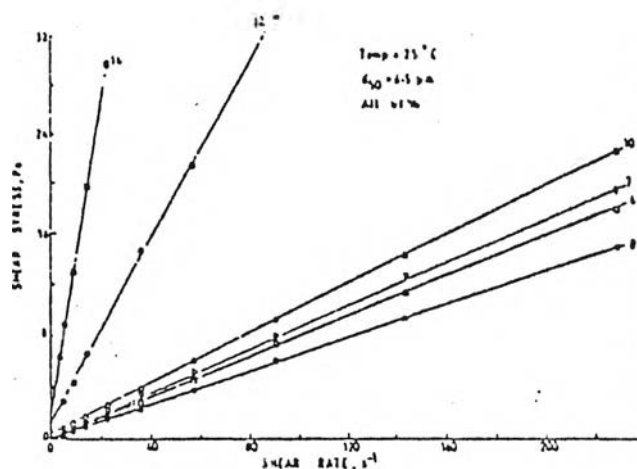


Figure 2.7 Effect of moisture content on 35 wt% brown coal-oil suspensions. (7)

Anderson et al. (9) compare the handling characteristics of COM's with those of fuel oil. They suggested that rheological characterization has shown COM containing upto ca. 50 wt% of coal to be non-Newtonian. A minimum handling temperature of 65 - 70 °C was found for an experimental 40 wt% COM in heavy fuel oil with a minimum storage temperature of 40 °C. An experimental COM containing 40 wt% of coal in heavy fuel oil was readily handled by conventional road tankers at 70 °C.

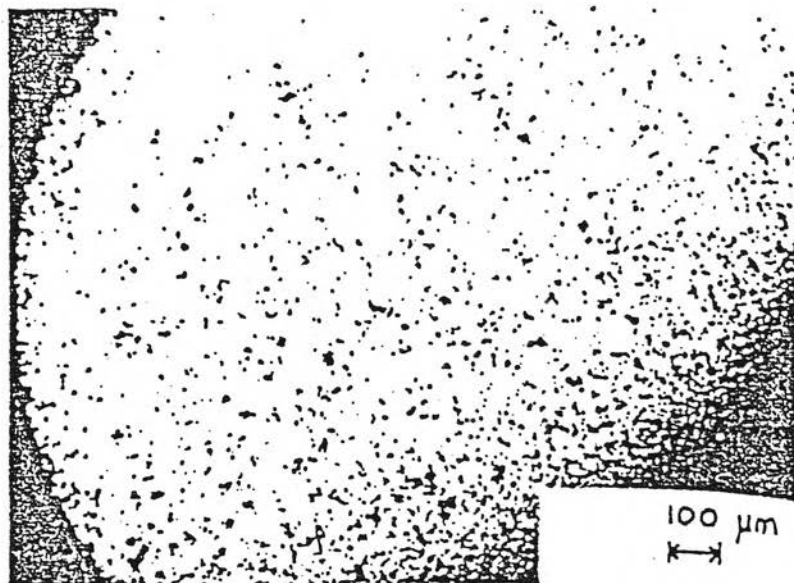Takeshita et al. (10) measured oil adsorption, defined

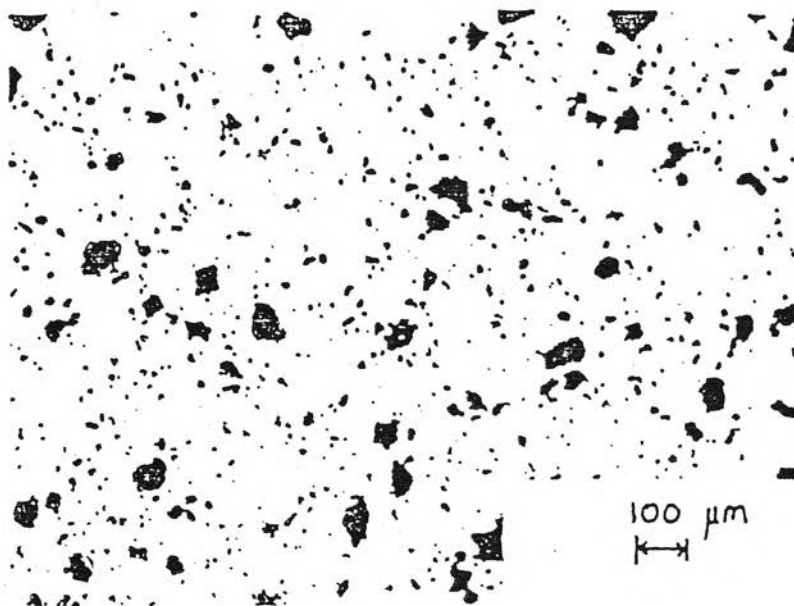Figure 2.8   Dry brown coal in KC 220 oil. (7)



Figure 2.9   20 wt% moisture content brown coal in KC 220 oil. (7)

as a minimum quantity of heavy oil needed to wet a 100 g of coal powder and to give a briquette, and showed that if coal-type is the same, the oil-adsorption increases with a decrease of particle size as being expected from the increase of the specific surface area and the results show that the effect of the properties of the coal-surface on the COM-viscosity was larger than the particle-size. Therefore, it can be persumed that the coal having large oil-adsorption attract oil so tightly to retain or immobilize that the oil contributing to the fluidity of COM consequently decreases and the COM more viscous as a result.

### 2.3.2 Stability

There have been many definitions of the term stability. In industrial processes and technology , the term is frequently used to mean a tendency to resist sedimentation. On the other hand, in colloid science, the term is usually used to mean preservation of the state of independent particles and the measurement is usually defined in terms of a very low rate of aggregation or coagulation.

Stability of coal slurry fuels are performance aspects of concern in considering their use as an oil substitute for industrial boilers , coal particles suspended in liquids tend to settle out under the action of gravity. This is highly undesirable in coal slurry fuels, as it generates spatial disparity in coal concentration and leads to the formation of compacted sediments which cannot be easily resuspended. The stability of coal suspensions depends on the following factors: density, size, concentration, surface properties (relative hydrophilic nature), surface charge and morphology of coal, density and type of liquid.

For slurries in the dilute concentration regime, Slagle et al. (11) proposed the following correlation for maximum settling rate.

$$Q_o = \frac{g(\rho_s - \rho_d)\ d_A^2\ (1 - C_{AS}\phi_s)^{4.65}}{18\mu_1 C_{AS}} \qquad (5)$$

where $Q_o$ is maximum settling rate, g is local gravitational acceleration, 980 cm/s$^2$, $\rho_s$ is density of solids, $\rho_d$ is density of liquid, e.g. oil, $\mu_1$ is viscosity of oil, $\phi_s$ is volume concentration of solids and $C_{AS}$ is the ratio of volume concentration of aggregate to volume concentration of solids in aggregates.

$$C_{AS} = \frac{\phi_A}{\phi_S} = \frac{\text{volume of aggregates}}{\text{volume of solids in aggregates}} \qquad (6)$$

For spherical particles, the stokes settling velocity is given by

$$V_{SA} = \frac{980(\rho_s - \rho_d)(d_A)^2}{18\mu_1 C_{AS}} \qquad (7)$$

Therefore, equation 5 can be rewritten as

$$Q_o^{1/4.65} = V_{SA}^{1/4.65}\ (1 + C_{AS}\phi_S) \qquad (8)$$

Equation 5 and 8 are well applied to the settling behavior of coal-oil slurries. At very low concentrations, free settling occurs according to Stoke's law. With increased coal concentration, settling becomes a complex phenomenon as interparticle interactions take place and hinder settling. Particles may also adhere to each other to form clusters(flocs or coagula). Adam-Viola et al. (12) classified COM into three types depending on the state in which the particles exist in the suspension : (a) the particles have no tendency to adhere to each other, hence the particles are well dispersed throughout the

liquid (Figure 2.10-A) ; (b) the particles weakly interact (flocculate) and form loose, porous clusters, called flocs (Figure 2.10-B); or (c) the particles strongly interact (coagulate) and form compact, tightly-bound clusters called coagula (Figure 2.10-C). These three states of aggregation lead to three types of suspensions, as depicted schematically in Figure 2.11.

(i) Aggregatively stable suspensions: Particles do not adhere to each other due to repulsive forces and settle individually in a gravitation field. Hence they settle as a rate dependent on size. This leads to a highly classified sediment with the coarse particles at the bottom and the finest on the top. Coal slurry sediments of this type would cause particles to roll over each other and form compact sediments.

(ii) Flocculated suspensions: Particles interact weakly (flocculate) and form loose, porous cluster called flocs. They settle relatively slowly due to addition drag forces which arise from the open structure of the cluster. The sediment formed these flocs is very loose, occupying a large fraction of the original slurry volume, and can be easily brought back to a uniform solids concentration by mechanical agitation.

(iii) Coagulated suspensions: Strong interparticle attractive forces promote formation of compact and tightly bound cluster. Settling rates are relatively fast and sediment might be compact and difficult to break.

Stability of the colloid, considered as its resistance to settling out of coal particles and must be kept in either a suspended state, or loosely packed network which is easily redispersible. Usually, stability of the colloid can be promoted by some combination of the following tactics: (a) finer grinding of the coal; (b) selecting oil that gives a stable suspension without the need of needing a stabilizer ; and (c) using additive or stabilizer. COM's containing fine coal,70-80% -200 mesh (74 microns), stabilized by additives and COM's containing ultrafine
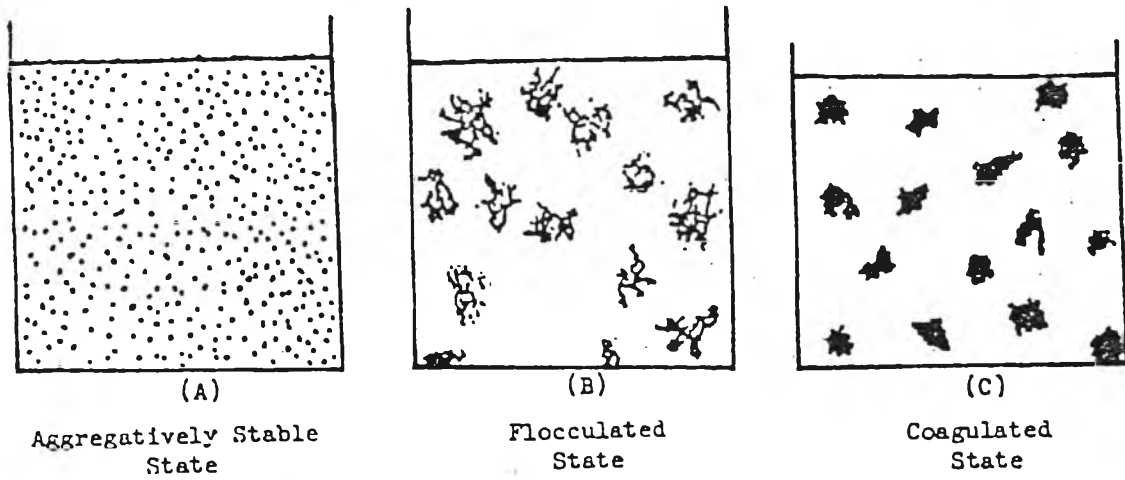
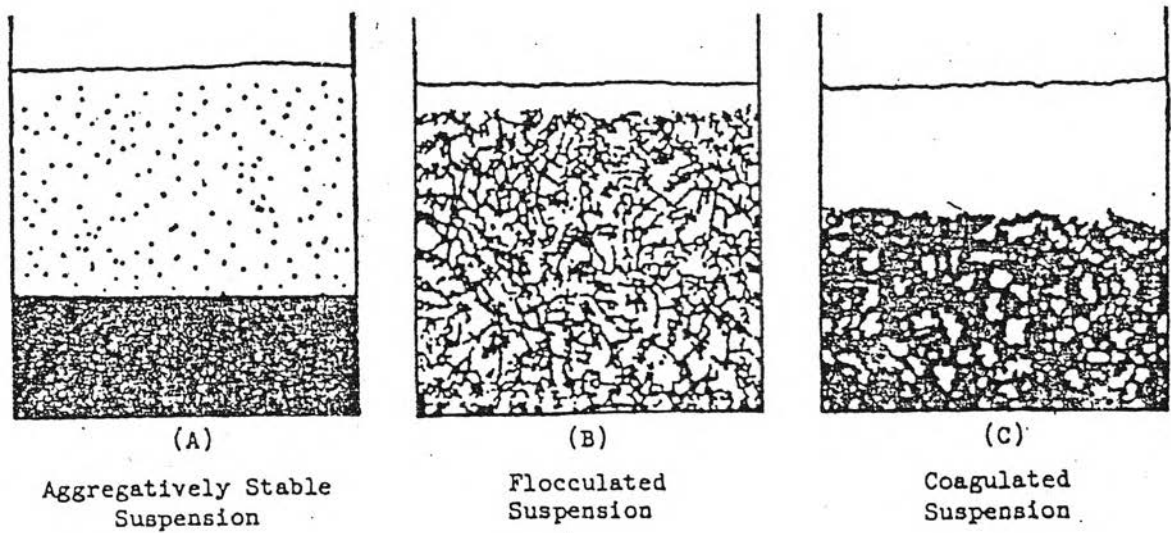Figure 2.10   States of particle aggregation. (12)



Figure 2.11   Type of coarse suspensions. (12)

coal, typically with a median size of 15 microns, stabilized by no additives. Advantages of ultrafine slurry include reduced abrasiveness, improved combustion characteristics and no expense for additives, but grinding costs are higher. Bienstock et al.(13) showed the influence of the base oil viscosity on the stability of COM that the mixtures prepared with the higher-viscosity oils are relatively more stable than those prepared with lower-viscosity oils. Lord et al. (14) summarized the promoting stabilization by searching for additives to create the gel-like structure. The values of yield stress in the gel are required to prevent settling of spherical coal particles. A first order approximation of the required yield stress in the gel shows the direct dependence on particle size as

$$\tau_y = D_p \times g(\rho_s - \rho_1)/3g_c \qquad (9)$$

where $\tau_y$ is required yield stress, $D_p$ is particle diameter, g is gravity acceleration, $g_c$ is gravitational constant, $\rho_s$ is density of solid particles and $\rho_d$ is density of liquid carrier. The addition of additives create the gel structure which led to be small clusters of particles, called flocs. The flocs tend to group into clusters of flocs, called aggregates or flocculate. The formation of aggregates, led to a network formation, in Figure 2.12 and 2.13, so that a stable COM is really a loosely dispersed flocculated network of coal in oil that possesses a certain reactive stability.

In summary, the addition of chemical stabilizers govern the rate of network formation, the extent of network formation and the forces of aggregation between components of the network that control the rheology or flow properties of the mixture.

Rowell et al. (15,16,17) showed that stability in highly concentrated slurries, as in slurry fuels, is achieved by promoting formation of networks through weak interparticle
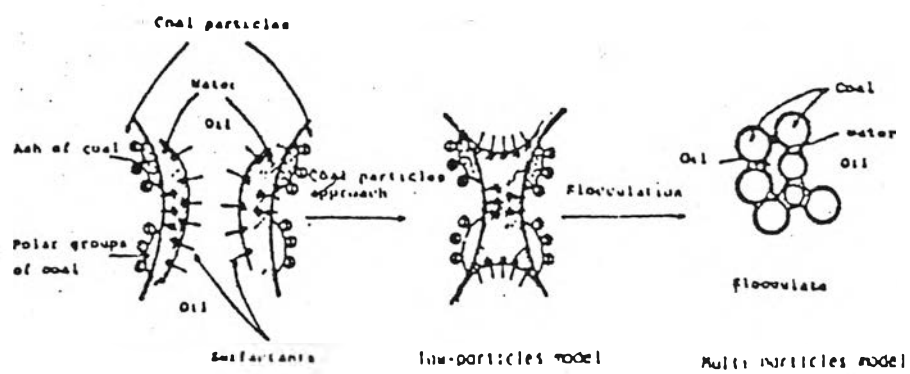
Figure 2.12  Formation  of  Stabilized  network  structure
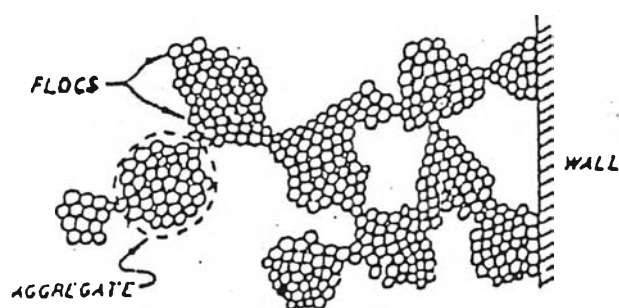(Flocculates). (22)



Figure 2.13  Floc-aggregate structural model. (26)

interactions which lead to yield stress in the slurry and prevent settling. They also have been used sedimentation columns in screening the effectiveness of additives. The sedimentation ratio after 24 h. settling, SR is

$$SR = \frac{\text{bottom-sampled wt\% coal in treated slurry}}{\text{bottom-sampled wt\% coal in untreated slurry}} \qquad (10)$$

It was found to be an effective screening parameter for the effective additives on COM stability. The most effective stabilizers were tertiary amine cationic surfactants which include the group $>N-CH_2-CH_2-O-$ , this group can be part of a straight chain. The tertiary amines useful in the present invention are represented by the formula:

$$R_1 N \Big\langle \begin{array}{l} (CH_2CH_2O)_n H \\ (CH_2CH_2O)_m H \end{array}$$
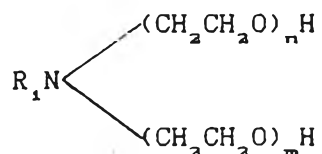
wherein $R_1$ is alkyl containing from 12 to 22 carbon atoms. The polyethylene oxide groups should be relatively long so that m+n totals between 5 and 20, perferably between 5 and 10.

Particulary suitable stabilizers used in the present invention include the compound of the formula:

$$H_{33}C_{16}N \Big\langle \begin{array}{l} (C_2H_4O)_m H \\ (C_2H_4O)_n H \end{array}$$
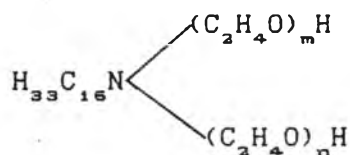
wherein m+n is 10 available under the trade mark Ethomeen C-20 and the compound of the formula:

$$H_{25}C_{12}-N \Big\langle \begin{array}{l} (C_2H_4O)_m H \\ (C_2H_4O)_n H \end{array}$$
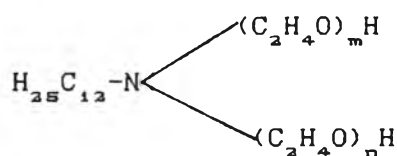
wherein m+n is 5 and is available under the trademark Ethomeen C-15.

## 2.4 Combustion of coal-oil mixture droplets

The anticipated depletion of the world's oil supply has given rise to greater use of coal, which is estimated to be more abundant than oil. However, coal has some difficulties in its use, such as transportation, storage, pollutants and ash. One of the effective methods to avoid these weak points is to mix coal particles with oil, that is, the adoption of coal-oil mixtures (COM). The COM can be used in oil furnaces, with minor modifications, and may be transported over long pipelines. Therefore, many investigations of COM combustion have been completed in the past decade as well as studies concerning its blending, transportation, stability, etc.

The combustion of various coal-oil dispersion is complex process, and takes place in two stages: (i) release and combustion of volatile matter, called gas-phase combustion and (ii) combustion of the residual char, called solid-phase combustion. Alabaf(18) proposed the combustion phenomena of COM as shown in Figure 2.14 and 2.15.

### (i) Combustion of volatile matter

In the first stage, coal-oil dispersion fuel atomizes through the burner nozzle. As the fuel enters the furnace, it is heated by convection from the surrounding gas and radiation from the flame and furnace walls and begins to volatilize. Both physical and chemical changes occur.

Coal particles in the dispersion become plastic, and as plastic, and the fuel evaporates the coal particles coalesce. The coal volatiles produce swelling as a result of bubble formation. Some of these burst at the outer surface, and some internally to produce a hollow sphere. The release of gases internally, which cannot escape fast enough through the pores of the outer shell, eventually burst out of the sphere and produce a large hole. By
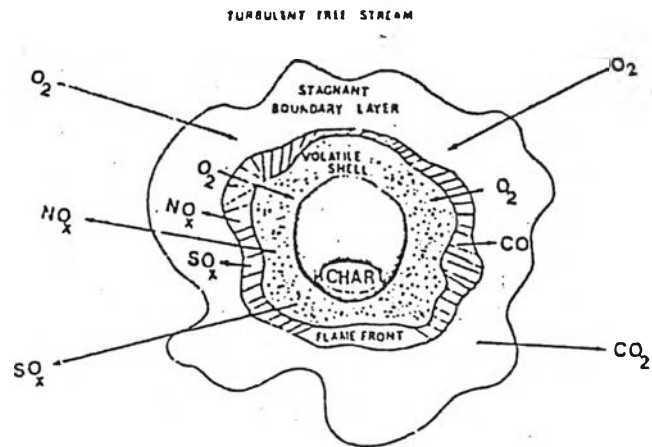
TURBULENT FREE STREAM

Figure 2.14   Proposed   burning   droplet for Coal-in oil fuels
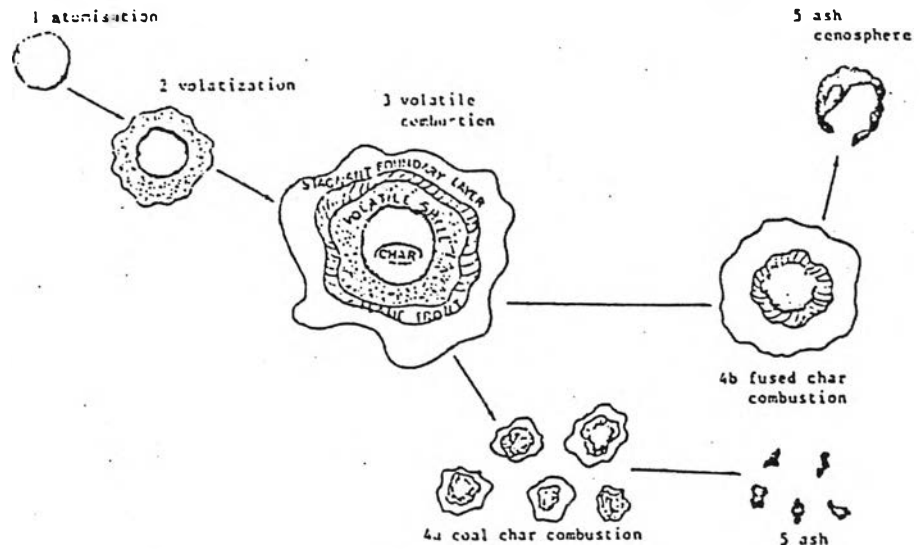(coal-oil dispersions and coal-oil mixtures). (18)

Figure 2.15   Proposed combustion pathways for Coal-in-oil fuels
(dispersions and the mixtures). (18)

this time the shell is sufficiently firm to prevent collapse, and any remaining volatiles are released more easily.

As a result of the volatilization, a flame front is initiated and the combustion of the volatile shell surrounding each fuel droplet starts (Figure 2.14). The volatile shell consists of a mixture of combustible gases, carbon dioxide, and water vapour. Apart from carbon monoxide and hydrogen, the combustible of gases are mainly hydrocarbons and hence burn rapidly. After the combustion of the volatile matter in the dispersion is complete, a carbon char is left.

### (ii) Combustion of carbon char

The second stage of combustion involves the burning of this carbon char. The burning out of carbon particles in the dispersion is the primary reason for significant differences of flame length, emissivity, heat release and flame temperature between fuels. The combustion of the carbon char of medium and high volatile coal-oil dispersions takes place at the surface of the oil droplet size fused cenospheres. Volatile combustion in the earlier stages of combustion causes pores to be formed in the surface of char particles, and combustion takes place on both the internal and external surface of the char, with oxygen diffusing through the pores. The combustion of these chars is slow, due to their relatively low external surface area to volume ratio, giving rise to longer flames than for the constituent fuel oil which burns to smaller particles.

In the case of the low volatile coal-oil dispersions, the low reactivity of the anthracite inhibits the formation of fused droplet size cenospheres, and the coal particles remain loosely bonded by any residual tar or oil ash at the end of the volatile combustion stage. These spherical agglomerates break up into small char particles, giving a relatively high external surface area to volume ratio in total. This more rapid combustion gives a shorter flame than with other dispersions. The increased

total surface area also gives rise to higher combustion at the end of the flame.

Mizomoto et al . (19) studies a coal-oil mixture droplet on hot surface. In the study, ignition, gas-phase combustion, and surface combustion of single droplet on a hot surface are investigated and compared with those of pure fuels. The burning processes of COM and a fuel oil droplet show in Figure 2.16.
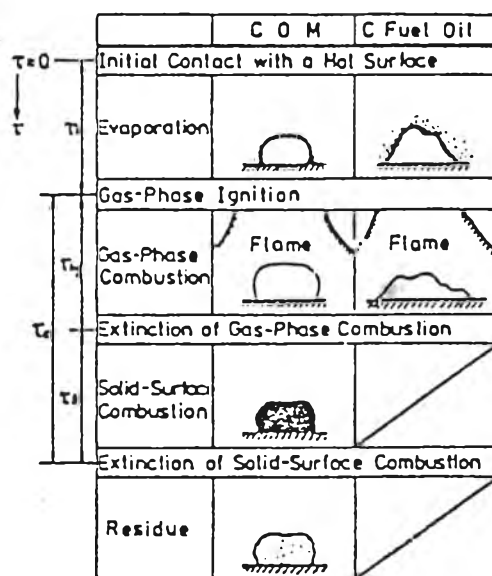
| | C O M | C Fuel Oil |
|---|---|---|
| τ=0 — Initial Contact with a Hot Surface | | |
| τ τᵢ Evaporation | | |
| Gas-Phase Ignition | | |
| τbg Gas-Phase Combustion | Flame | Flame |
| τₜ Extinction of Gas-Phase Combustion | | |
| τₛ Solid-Surface Combustion | | |
| Extinction of Solid-Surface Combustion | | |
| Residue | | |

Figure 2.16 Burning processes of a COM and a C fuel oil droplet.(19)

where $\tau_i$ is ignition delay times, $\tau_{bg}$ is gas-phase combustion times, and $\tau_s$ is surface combustion time.

The total combustion times; $\tau_t \quad \tau_i + \tau_{bg} + \tau_s$ (11)

$$\tau_t = \tau_i + \tau_{bg} \qquad (12)$$

Equation 11 can be applied for the case of COM and equation 12 can be applied for the case of fuel oil.

In general case, the droplet of initial temperature $t_i$, is suddenly introduced to the oxidizing surroundings at a high

temperatures $t_{mx}$ . The droplet temperature rises until the oil is ignited. During this combustion, the oil is at boiling point, $t_m$ . When the oil layer is completely burnt the particle surface at a temperature $t_m$ is exposed. Subsequently the particle temperature increases until the surface attains the ignition temperature $ti$ when combustion of the particle occurs. The devolatilization of the coal particle is neglected. The overall times $\tau_o$ of droplet combustion consists of the time $\tau_1$ for preheating the liquid from temperature $t_1$ up to $t_m$ , the time $\tau_2$ of liquid burning, the time $\tau_3$ for preheating the particle from temperature $t_m$ up to $t_1$ and the time $\tau_4$ of particle burning

$$\tau_o = \tau_1 + \tau_2 + \tau_3 + \tau_4 \tag{13}$$

Petera (20) proposed equation (13) for the general case in which the temperature of the surrounding is high so that $t_{mx} > t_1 > t_m$ .

In the design of industrial coal-fired boiler furnaces, it is of importance to have an assessment of the reactivity of the intended fuel. Alternatively, if it is proposed to change the fuel supply for an existing installation, it is advantageous to have a test which allows the burning characteristics of the candidate fuels to be compared with the original in terms of burning rate. Early work in this direction was done by the American company, who established a test in which the rate of weight loss of coal sample burning in air was plotted against temperature. This they named the " burning profile " test and the plot obtained typically takes the form of a curve with two or more maxima as shown in Figure 2.17 corresponding to moisture loss followed by progressive combustion. The temperature at which the maximum combustion rate occurs is taken as a measure of combustibility with lower temperature indicating more easily burned coals. Burning profile also test for assessing coal reactivity. A profile is produced,

characterized by several features, the most significant of which is the peak temperature, or temperature at which the sample is losing weight at the maximum rate. This height of the peak is related to a coal's reactivity for the kinetic reason based on the following equation:

$$R = \frac{(dw/dt)max}{Win} \tag{14}$$

where: R is reactivity; Win is initial weight of coal (mg) ; and (dw/dt)max is maximum rate of weight loss (mg/min). Therefore, if the weights of the coal are equal, the DTG peak height will indicate the relatives of the coals.
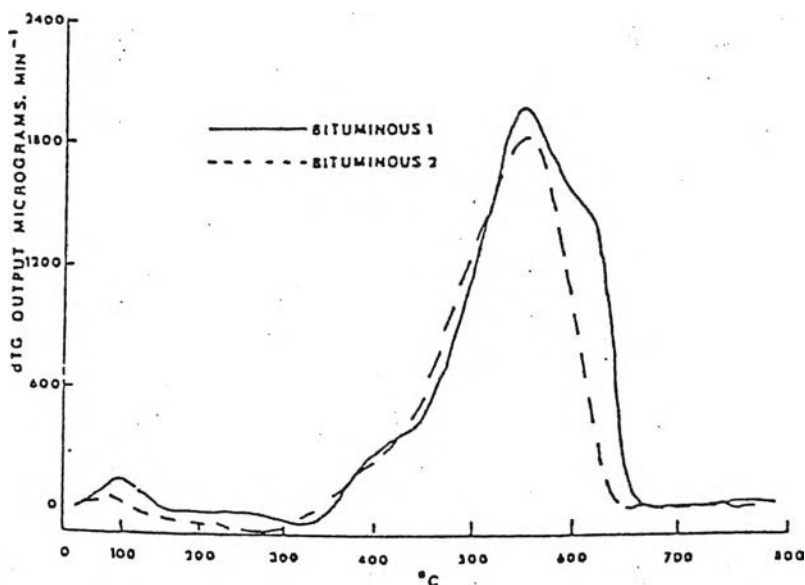


Figure 2.17  Burning profile of two bituminous coals. (23)