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DRAG REDUCTION AND FLOW PROPERTIES OF CONCENTRATED COAL SLURRIES

THE UNIVERSITY OF ARIZONA

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DRAG REDUCTION AND FLOW PROPERTIES
OF CONCENTRATED COAL SLURRIES

by

Dov Bruno Kaufman

A Thesis Submitted to the Faculty of the
DEPARTMENT OF CHEMICAL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

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ACKNOWLEDGMENTS

I would like to express my appreciation to all the people who have helped me during my graduate studies. I would particularly like to thank Dr. Donald H. White, my advisor, and Dr. Nick Schott, Mr. Sol Resnick, Dr. F. Shadman and Dr. S. J. Hansen. I am grateful to Todd Kassmussen and Dr. Gerald Harwood for the help with the manuscript.

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ABSTRACT

The rising price of oil has focused interest on developing the technology of coal utilization. Although transport of coal water slurries is commercially successful, the design of a new pipeline requires exploratory experiments and scale up calculation. In this study, coal slurries in water, kerosene, fuel no. 2, fuel no. 5 and methanol were investigated at various concentrations.

The properties of the slurries were investigated in a Brookfield viscometer and in a recirculated flow system. At high shear stress the pressure gradient of the slurry approaches the curve of the pure liquid. At low shear stress the pressure gradient departs from the pure liquid curve and drops rapidly.

At high concentration of solids the pressure gradient of coal water and coal oil slurries can be reduced by minute amounts of base or increased by minute amounts of acid. It is assumed that the base acts as a surfactant which promotes the formation of network between the coal particles, thus suppressing turbulence.

CHAPTER I

INTRODUCTION

Large reserves of coal are found in the arid, southwestern areas of the United States, where water resources are limited. Water conservation and the rising price of oil have focused interest on developing the technology of coal-oil mixtures (COM). COM technology is generally regarded as being "near-term." It is available today, and will be replaced when a better alternative is found. The end use of COM has two major advantages over other forms of coal utilization: (1) modification of combustors for the burning of COM is relatively inexpensive; and (2), combustion of COM results in less air pollution than does the burning of coal alone. There are additional benefits as well: COM can be transported in pipelines; it can be burned in existing boilers and blast furnaces; and, once a decision has been made to utilize COM, it can be "on-line" in a short period of time, thus shortening the lead time for reduced oil consumption. However, more research to reduce inherent technological and economical uncertainties is necessary before large scale commercial application becomes a reality.

In 1977, the utility sector in the United States used approximately 1.8 million barrels of residual fuel per day (Legassie, 1979). Potentially, the utilization of coal-oil mixtures could displace one third of this residual fuel use with coal. While geographic, environmental and economic factors might further reduce this amount,

savings of 350,000 to 500,000 barrels of oil per day could still be realized. Although this represents only 5% of the 8 million barrels imported daily, the nearly immediate commercial availability of the technology makes it attractive when compared to such alternatives as synthetic fuel which requires huge investments and lead times of six to eight years. Even in the context of long-term considerations, CUM technology might prove to be more beneficial than the utilization of coal alone. Therefore CUM research could offer the potential of both short-term relief for the energy crisis and a long-term fuel resource.

A major cost-reducing factor in the use of CUM is the possibility of its direct transport from the mine to the user site in pipelines. While the transport of coal in water suspension is environmentally acceptable and commercially successful, it requires special facilities to dewater the mixture. Subsequent use of this water requires treatment to make it suitable for industrial use; alternatively, the water can be evaporated in solar ponds. CUM, on the other hand, can be utilized in the form in which it is transported without further treatment.

While only a small fraction of the coal mined today is transported as a slurry via pipeline, the proportion is expected to increase considerably in the future. Coal production is expected to double in the next decade as a result of a continuing increase in oil prices. Pipeline conveyance of coal is attractive as it has proven to be less detrimental to the environment and more economical in the long run than traditional methods of transportation. Therefore, the motivation for applied research in the field of coal transport has been renewed in

the past five years.

The science of rheology, the study of the deformation and flow of matter, has been extensively applied to the flow of particle suspensions during the past century. The widespread use of suspensions in industrial processes such as the production of food, cosmetics, cement and other materials has motivated this research. While significant amounts of data have been generated, the complex rheological properties of most materials are still not well understood. Accordingly, predictive rheological models are still plagued with uncertainties.

Some advances have been made in rheology. For example, the pressure drops that occur at various points along pipelines have been correlated with other parameters which determine the flow of coal in water suspensions. However, scaled up validation studies are needed in the predictive modeling requisite for optimal design of such complex systems as long distance pipelines.

One way to reduce the cost of coal-water and coal-oil suspension transport is the addition of chemicals to the slurry. These additives lower the viscosity of the suspension reducing the energy needed to pump it. However, research in this area has been almost non-existent.

The study presented in this thesis was concerned with the flow behavior of coal-water and coal-oil suspensions from an engineering viewpoint. Pressure drops of coal slurries flowing in a pipe were measured as a function of various physical parameters. In addition increasing our knowledge of the behavior of coal slurries, the goal of this research was to find an effective drag-suppressing chemical additive

and to determine its effects under a variety of flow conditions. Although, the variability of the coal particle surface was found to complicate the relationship between the additive and the resultant suspension flow, an hypothesis is presented to explain this phenomenon.

CHAPTER II

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF SUSPENSIONS

II-1 Rheology of Suspensions

Although rheology, as a formal science, is relatively new, mankind has dealt with the problems of fluid flow for many centuries. Examples of rheology applications range from irrigation projects to the water clock. Rheology, as previously stated, is the science of deformation and flow of matter. Deformation is defined as the altering of shape or size due to force applied on the system. If the deformation is continuous with time, the material is said to flow. As a science, rheology can predict the required force on a system to produce a certain deformation, or flow. Conversely, it can also predict the deformation or flow resulting from the application of a certain force. In general, rheology deals with the studies of the functional relations between the stress, τ , and the rate of strain, $\dot{\gamma}$, of a system.

$$\tau = f(\dot{\gamma})$$

Depending on the physical structure, chemical properties, and the thermodynamic state of the system, the function between the stress and the resulting strain changes substantially. The most simple case is the Newtonian fluid case where η is a constant called the coefficient of viscosity:

$$\tau = \eta \dot{\gamma}$$

The first major step in describing the flow properties of suspensions was made in 1906 when Albert Einstein analytically derived the coefficient of viscosity for dilute Newtonian solid-fluid mixtures:

$$\eta_m = (1 + 2.5C_v)\eta_o$$

The viscosity of the mixture, η_m is a function of the viscosity of the pure fluid, η_o , and the volumetric solids concentration, C_v . Einstein's equation, based upon calculations of the energy dissipated in the suspension, can fairly predict an effective viscosity for a solid-liquid mixture up to 5% solids concentration by volume. When deriving this theoretical equation, the assumptions were:

1. Solid particles are hard and spherical.
2. The interparticle distance is large.
3. The kinetic energy of the particles is negligible.
4. No liquid slip on surfaces.
5. No settling effects. (Einstein, 1906)

The value of 2.5 in the above equation is a commonly accepted constant, although values as large as 5.5 (Happel, 1957) or even 8 have been suggested. As will be discussed later, many investigators have attempted to verify Einstein's equation. They have found that at very low concentrations, where the volume fraction of the solids is the only variable, the relationship holds true. At higher concentrations, experimental evidence indicates that other factors must be considered. They attempted to find a formula similar to Einstein's equation for the relative viscosity, η_r , of the form:

$$\eta_r = \frac{\eta_m}{\eta_o} = f(C_v)$$

Some theoretical studies of suspension rheology proposed models to describe the fluid-particle dynamics of concentrated suspensions. In these studies the suspensions consist of neutrally buoyant, equally sized, rigid, spherical particles in an incompressible Newtonian fluid. Inertial forces were considered to be negligible and the flow to be laminar.

The first model proposed was the cell model. The local fluid velocity around the particles is the solution to Stokes equation, when the boundary conditions are the particle size and no slip at the surface of the particles. Simha (1952) used this model, but was forced to adopt an empirical parameter, determined by experimental data. Happel (1957) assumed that the particles are surrounded by a layer of stagnant fluid and found the velocity at the edge of the stagnant layer. His boundary conditions required that the normal component of the fluid velocity and the tangential stress be the same at each point on the surface of the stagnant layer, as are those of the macroscopic flow. Although Happel's assumption seems more reasonable than Simha's, the model developed by Happel does not reduce to Einstein's formula on the limit of very dilute concentration. Neither model can describe real suspensions, but they have added insight to the understanding of suspensions in a qualitative sense.

Another approach suggested by Frenkel and Acrivos proved to be closer to experimental results at high concentrations than other models.

The flow in the gap between two closely spaced spheres was examined to obtain the viscous energy dissipated as the gap narrows. The calculation of the energy dissipation leads to an asymptotic expression of the relative viscosity of the form:

$$\mu_r = \left[\frac{2}{3} \left(1 - \left(\frac{C_v}{C_{vmax}} \right)^{\frac{1}{3}} \right) \right]^{-1}$$

$C_{v \max}$ is the maximum solid concentration achievable and its range is between 0.63 - 0.84, depending on the configuration of the packing. This formula describes fairly well the suspensions at high concentrations ; but as the concentration decreases, the formula begins not to fit experimental results.

The results of many rheological investigations have been summarized by Rutgers (1962) and Thomas (1965). Both found that the data from experiments differ widely as seen in Figures II-1 and II-2. The scatter of the data at higher concentrations cannot be discarded as experimental error but should be assumed to be caused by factors other than the volume fraction of the solids in the suspension.

Hydrodynamic interaction of particles, particle rotation, collisions between particles, double and higher order agglomerate formation, and mechanical interference between the solids have to be accounted for. In addition to all of these factors, whose degree of influence on flow properties depends on the solid liquid ratio, the random structure of the suspension makes it difficult to represent the

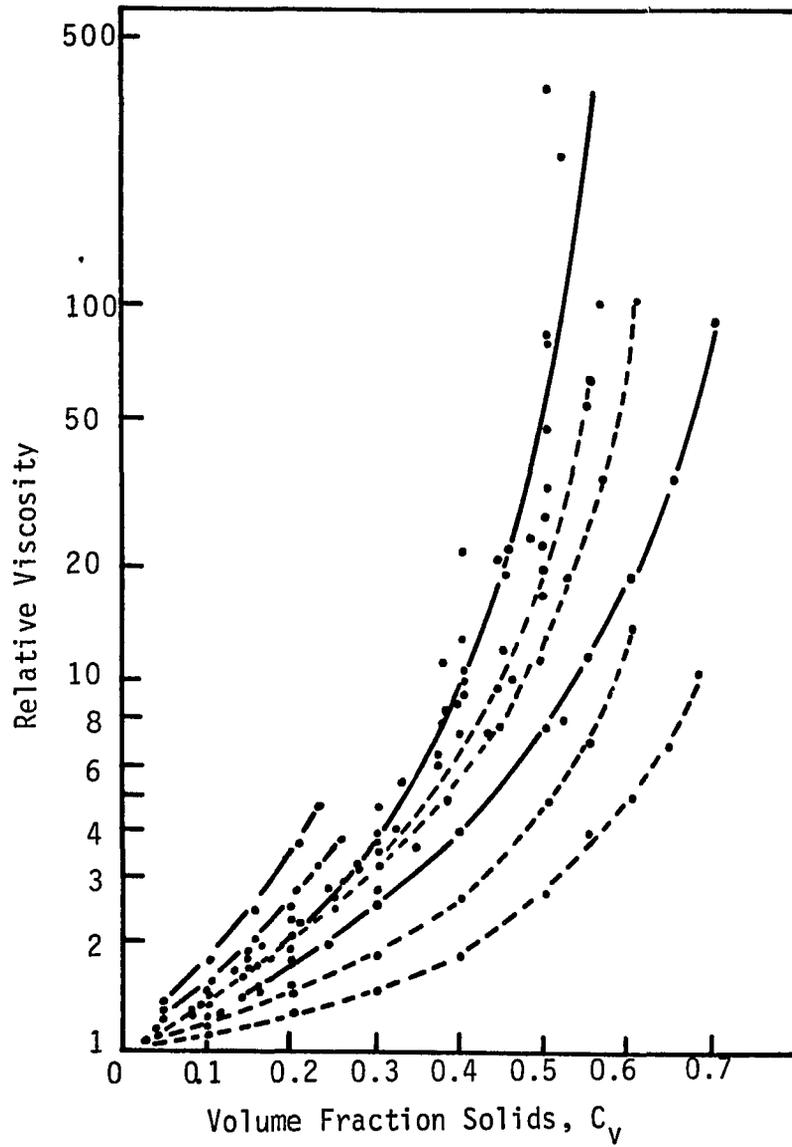


Figure II-1: Relative viscosity data collected by Rutgers.

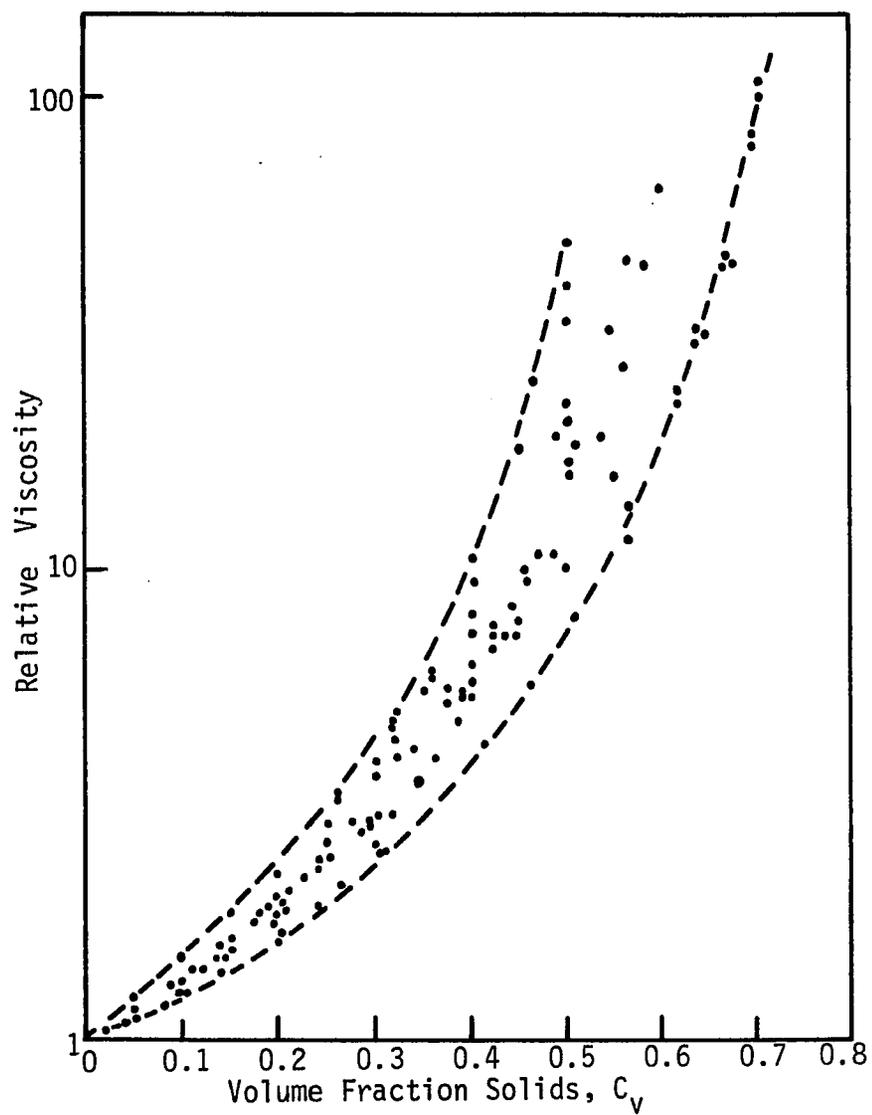


Figure II-2: Relative viscosity data collected by Thomas.

rheology of liquid-solid mixtures by simple models.

Many of the existing theoretical and experimental equations can be expressed as a power series:

$$\mu_r = 1 + B(C_v) + C (C_v)^2 + \dots$$

The constant B is usually assumed to have the value of 2.5 as determined by Einstein. The second coefficient C of the power series is less accurately known since it includes complicated interactions. Accounting for hydrodynamic interactions of spheres in a suspension, Guth and Simha (1936) obtained a value of 14.1. Saito (1950) determined that the second coefficient has the value of 12.6, by calculating the effect of mutual volume of exclusion. Taking into account hydrodynamic forces and doublet formations due to collisions, Vand (1948) arrived at a value of 7.35, while Manley and Mason suggested 10.05. Brenner (1972), Hinch and Leal (1975), and Batchlor and Green (1972) proposed similar expressions.

Expressions such as that of Mooney (1951) have a closed form. Mooney accounts for hydrodynamic interactions and the crowding effect of spheres upon each other. Mooney's equation:

$$\mu_r = \exp\left(\frac{2.5C_v}{1-KC_v}\right)$$

approaches Einstein's at low solid concentrations. The constant k must be determined experimentally; its value is in the range of

$$1.35 < k < 1.91.$$

Eyring et al. (1964) suggest that at large concentrations, the rearrangement of the particles in a sheared suspension becomes important. An exponential term is added to account for particles transferring from one sheared plane to another:

$$\mu_r = 1 + 2.5C_v + 10.05C_v^2 + 0.00273 \exp(16.6C_v)$$

Although these equations are somewhat successful in describing the rheology of suspensions at medium range concentrations, they prove to be inadequate at higher densities of solid particles. The experimental data proves that other factors such as particle size distribution, fluid properties, etc. become important as the solid concentration increases.

The study of Durand and Condolius (1952) is one of the most extensive that has been done in the field of hydraulic transportation. The effects of the major flow parameters were measured and correlated mathematically. They tested slurries composed of solids having specific gravities ranging from 1.5 to 3.95. Their system employed pipes with diameters ranging from 2 to 700 mm and volumetric concentrations of solids within the range of 2 - 22.5%. They found that the pressure gradient of a slurry, ΔP_m , is greater than that of water, ΔP_w , at the same velocity by a factor that is proportional to the concentration of the solids.

$$\Delta P_m - \Delta P_w = f(C_v)$$

The excess pressure gradient caused by the presence of solids decreases when the velocity increases; this effect is shown in Figure II-3. Durand and Condolius' experimental results fit a correlation between the excess pressure gradient and other parameters:

$$\frac{\Delta P_m - \Delta P_w}{\Delta P_w C_v} = 176 \left(\frac{\sqrt{gD}}{V} \right)^3 \left(\frac{1}{C_D} \right)^{1.5}$$

Worster (1952) conducted a simultaneous study of the parameters which are associated with large coal particles conveyed in a slurry. His correlation is similar to the one of Durand and Condolius, but it also accounts for the specific gravity of the solids:

$$\frac{\Delta P_m - \Delta P_w}{\Delta P_w C_v} = 120 \left[\frac{\sqrt{gD}}{V} \left(\frac{\rho_s - \rho_l}{\rho_l} \right) \right]$$

Durand and Condolius' equation can be modified for coal slurries with the result:

$$\frac{\Delta P_m - \Delta P_w}{\Delta P_w C_v} = 81 \left[\left(\frac{gD}{V^2 \sqrt{C_D}} \right) \left(\frac{\rho_s - \rho_l}{\rho_l} \right) \right]$$

This equation is the same as the Worster correlation if the drag coefficient C_D is taken as 0.4.

Discarding the data for saltation, Zandi and Govatos (1967) concluded that heterogeneous suspensions can be best correlated by two equations:

$$\frac{\Delta P_m - \Delta P_w}{\Delta P_w C_v} = 6.3 \left(\frac{gD(S-1)}{V^2 \sqrt{C_D}} \right)^{0.354} \quad \text{for } \frac{gD(S-1)}{V^2 \sqrt{C_D}} < 0.1$$

$$\frac{\Delta P_m - \Delta P_w}{\Delta P_w C_v} = 280 \left(\frac{gD(S-1)}{v^2 \sqrt{C_D}} \right)^{1.78} \quad \text{for } \frac{gD(S-1)}{v^2 \sqrt{C_D}} > 0.1$$

Zandi and Govatos correlation was tested at solids concentrations up to 50% by volume.

Rose and Duckworth (1969) have developed a more sophisticated correlation for the prediction of the pressure gradient. Their correlation is based upon the mechanical energy balance and sums up all the forces acting on the system including the hydrostatic head, pressure change due to kinetic energy or acceleration, and pressure drop due to friction, where each parameter is calculated by graphical methods.

The Rose and Duckworth correlation appears to be a powerful method for estimating the pressure drop, provided that all solids are suspended and the system is Newtonian. Its disadvantages are the excessive calculations required and the large number of experimental values which need to be determined.

These and similar correlations, such as those of Wasp et al. (1968), Graf and Acaroglu (1969), and Carstens (1969), Guessler (1967) and others, attempt to describe the different regimes and correlations between the parameters governing flow. Most of them deal with aqueous, Newtonian systems with solids concentrations of 10 - 40% by volume.

Several good review articles are available, including those of Jinescu (1974), Jeffrey and Acrivos (1976), the series of articles by Thomas (1965), Rutgers (1962), Mih (1971), and Chenn (1980). These and such books as those of Govier and Aziz (1972), Bain and Bonnington (1970), Colorado School of Mines (1963), and Soo (1967) describe many of

the theories and experimental results of suspension flow.

This large body of data and theoretical work, aimed at discovering a general approach to solid-liquid flow, suggests that, to date, there is no single theory which can accurately predict flow conditions in suspensions. Experimental work is still needed to study concentrated suspension flow and surface chemistry, and the surface forces that exist between solids and liquids.

II.2 Parameters Governing Slurry Conveyance

Today, we can say that we understand the flow of homogeneous, newtonian laminar flow systems; but, we can only correlate the flow of turbulent systems, and most theories on the topic are semi-empirical. Therefore, it is not surprising that most applied research on slurry transportation is still in a stage of experimental data gathering and classification.

To date, no single comprehensive theory exists on transportation of solid-liquid suspensions that can accurately predict the operating conditions within a slurry pipeline. Slurry pipeline designs are based upon experimental data and cautious scale-up operations. The difficulties in a theoretical approach to suspension research result from the multitude of parameters governing the flow, our inability to measure interface forces, and the complexity of mathematical equations describing the forces which act upon the system.

The entrainment of solid particles by a liquid flowing in a pipe is controlled by the following parameters:

- | | |
|-------------------------------|--|
| 1. Pipeline parameters: | Diameter Inclination Pipe Roughness |
| 2. Liquid parameters: | Density Viscosity |
| 3. Solid particle parameters: | Density Size distribution Shape |
| 4. System parameters: | Velocity of flow Solid-Liquid concentration ratio |
| 5. Non hydrodynamic forces: | Brownian motion Electroviscous effects London-Van der Waals forces |

The parameters influencing the rheology of suspensions are examined in detail in this chapter. This chapter provides a review of previous theories and literature on the flow of suspensions and their properties. Hydrodynamic parameters are discussed first, and later the non-hydrodynamic forces are presented. In a qualitative way, the review presents the state of the art in research on solid particles entrained by liquids.

Pipeline Parameters

Pipe Diameter

In Poiseuille flow when inertial effects are negligible, a neutrally buoyant sphere translates parallel to the tube axis, with the same velocity as the liquid. Near the wall, hydrodynamic interactions between the sphere and the wall will cause it to translate and rotate more slowly. In suspensions of solids with sufficient high solid concentration, which depends on the ratio of the solid particles diameter

to the pipe diameter ($C_v = 0.35$ at $D_p/D = 0.002$ for example), a pronounced deviation from the parabolic velocity profile was observed. (Karnis, Goldsmith and Mason, 1966).

Even though the velocity of the particles was equal to that of the liquid, the velocity near the wall was larger than predicted. A core region was observed throughout which the velocity was constant and the particles moved along straight paths parallel to the axis without rotating; this is shown by curve 1 in Figure II-3. As the solids concentration C_v or the ratio between the particle diameter and the pipe diameter increase, the core region becomes larger and the velocity profile approaches plug flow in the limit, described by curve 2 in Figure II-3. The velocity profiles were found to be independent of the flow rate. Pressure drops of suspensions, measured in different pipe diameters, also show that the pressure losses are less than the expected values. This phenomenon can be explained by the formation of a plug flow region even at low Reynolds numbers, similar to the observation of Karnis et al.

Pipe Inclination

Taking the extreme case - a vertical pipe, the velocity of the solid particles differs from that of the water. The difference in velocity is approximately equal to the settling velocity of the particles in still water. The actual settling velocity can be easily measured at the desired concentration and pipe diameter, thus eliminating wall and concentration effects. The settling velocity of the solids at various densities for different particle size is shown in Figure II-4.

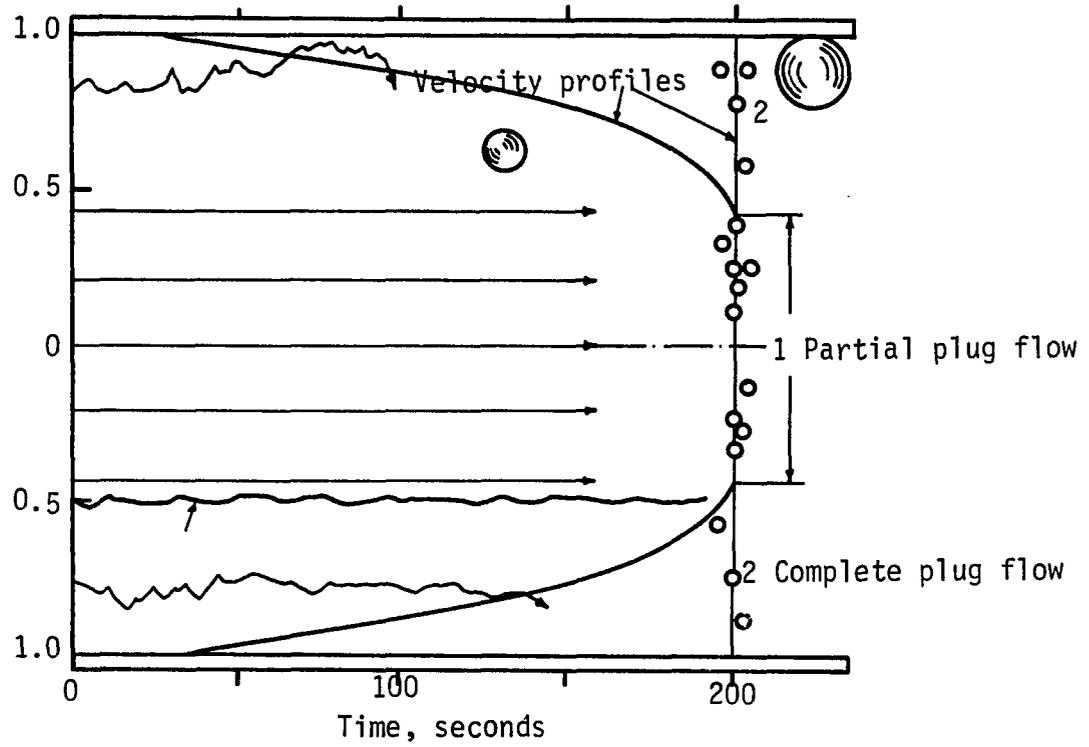


Figure II-3: Velocity profiles in concentrated suspensions of rigid particles.

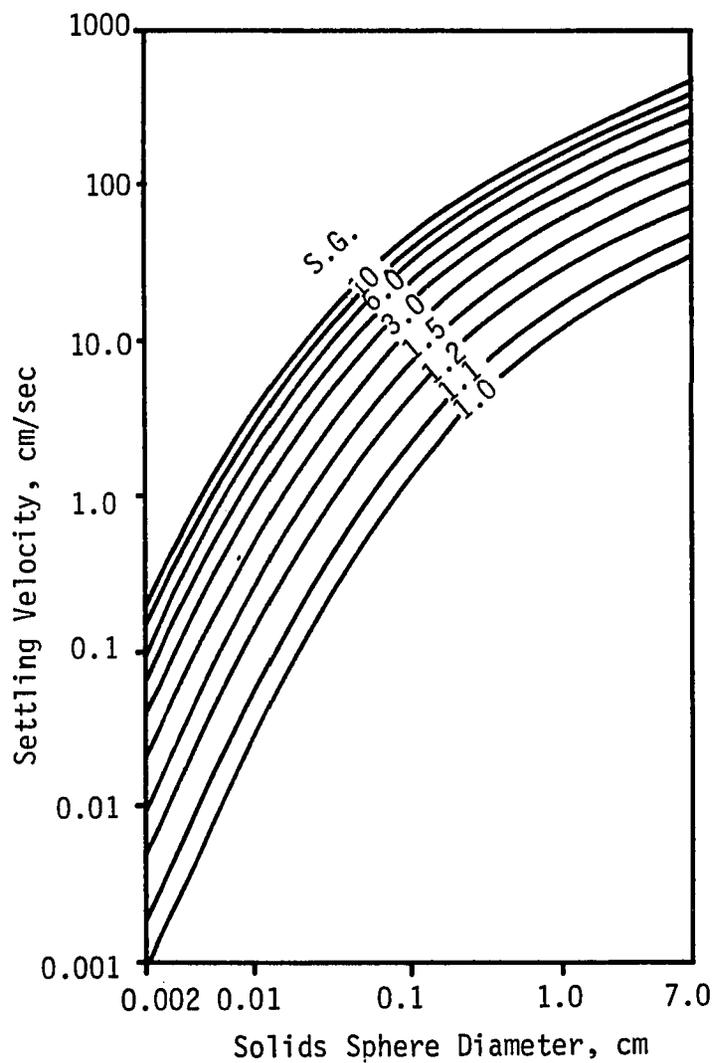


Figure II-4: Settling velocity of particles as a function of sphere diameter and specific gravity.

The lower velocity of the solids in an upward flow results in a larger local concentration of solids (q) than the average concentration (C). These interdependent values of concentration and velocity are more conveniently expressed as ratios q/C , V_s/V , and V/V_s as seen in Figure II-5 and Figure II-6 (Bain and Bonnington, 1970).

The presence of solids in the upward flow has two effects:

(1) The velocity of the water is greater than the velocity of the average mixture; thus the frictional pressure drop of a mixture is greater than that for water alone.

(2) The static head due to the vertical column of mixture is greater than that due to the average mixture.

For downward flow the situation is reversed and the particles have an excess velocity over the liquid velocity.

Pipe Roughness

The influence of pipe roughness on the suspension flow was not thoroughly researched. It is believed that pipe roughness has a greater effect on the flow of a slurry than it does on the flow of homogeneous fluids.

Liquid Parameters

Density and Viscosity of the Fluid

The properties of the carrier fluid of a suspension are important in understanding and predicting the behavior of suspensions. At low concentration of solids, the viscosity of the mixture is directly proportional on the fluid viscosity, as we have seen from Einstein's

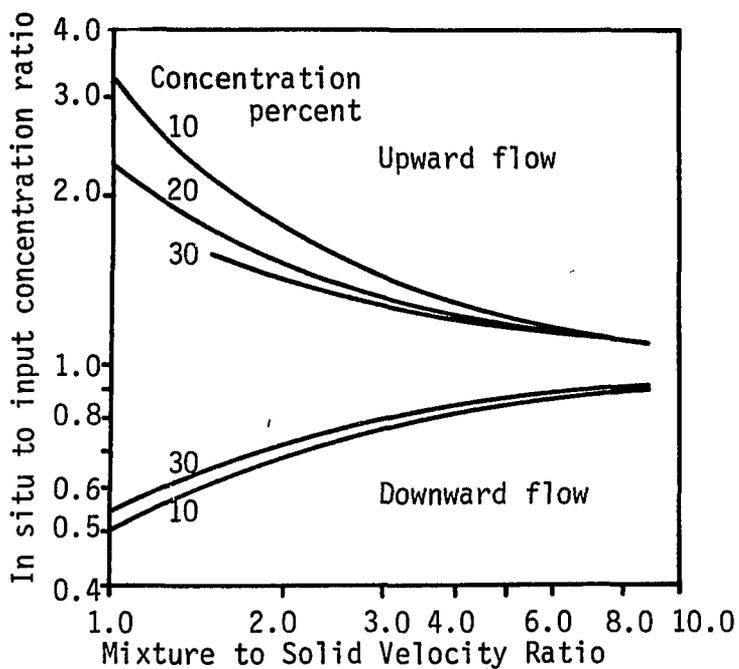


Figure II-5: Holdup effect on concentration ratio.

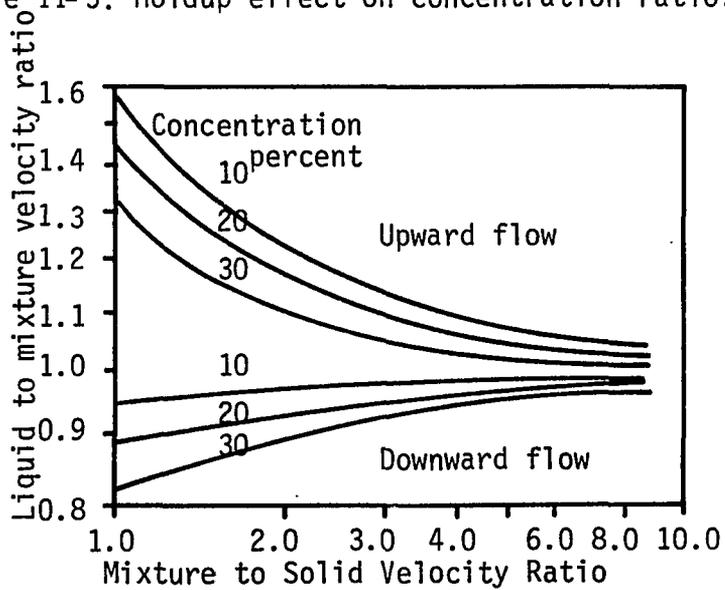


Figure II-6: Holdup effect on velocity ratio.

equation.

For higher concentrations, the relative viscosity (the ratio of viscosity of mixture to that of the fluid) is dependent on a power series equation of solids volumetric concentration C_v such as the equations developed by Batchlor, Guth and Simha, Saito, Manley and Mason, and others.

Experimental correlation, such as the ones developed by Durand and Condolius or by Worster, are based upon the relation of the difference between the mixture pressure drop and the pure fluid pressure drop to the other properties of the suspension.

Experimental work with different liquids indicates that if the liquid is not Newtonian, the addition of solids will increase the non-Newtonian characteristics of the suspension.

The physical properties of the fluid becomes less important as the concentration of the solids increases and the particle size decreases. In both cases, the forces between the particles will determine the behavior of the slurry. These factors will be explained later in the chapter when non-hydrodynamic effects are described.

The density of the fluid is only relatively important to the particle density.

Solid Particle Parameters

Density

The relative density of the particles and carrier fluid is one of the parameters which determines the suspension flow regime. Figure II-4 illustrates the effect of relative density on the particle settling

velocity. Lighter particles are suspended uniformly throughout the cross section of a horizontal pipe, while heavier particles tend to concentrate in the lower part; thus, a gradient, in the direction of the gravity vector, is produced in the solid concentration.

Particle Shape

The shape of a suspended particle can affect a suspension's viscosity. The rotational movement of non-spherical particles tends to increase suspension viscosity, as they occupy a larger volume. Most of these suspensions will also exhibit a yield stress, suggesting parallel alignment of the particles with respect to each other and to the direction of flow. Jeffery (1922) found that, in simple shear flow, the orientation of ellipsoid particles exhibits periodic changes with time in an orbit determined by inertial forces.

Particle Size

Limiting consideration to hydrodynamic forces alone, the rheological properties of a suspension are independent of absolute particle size. Suspensions of small particles ($< 1\mu$ in diameter) exhibit higher viscosities than suspensions of larger sized particles having an equivalent solid concentration. This effect is caused by non-hydrodynamic forces that are described in detail in a subsequent section of this chapter.

Polydisperse suspensions, i.e. those of solids having a large particle size range, have been found to exhibit relatively lower viscosities than monodisperse systems (Sweeney 1954, Everson 1959).

Bimodal particle suspensions, having two distinctly different particle sizes, were tested by Chong, Christiansen and Ball (1971). These were found to exhibit considerably lower viscosities than monodisperse systems having identical solid concentrations (Figure II-7). Bimodal suspensions in particular, and polydisperse system in general, can achieve closer particle packing than can suspensions of uniformly sized particles. Accordingly, at high solid concentrations, polydisperse suspensions will have lower viscosities than monodisperse suspensions.

System Parameters

Flow Velocity

The velocity of suspension flow first determines whether a mixture will flow or plug the pipe. In addition to the two known regimes of turbulent and laminar flow, Newitt et al. (1955) described and classified several subregimes of slurry flow which were based upon particle size, material density, mean flow velocity and pipe diameter. For a given system, the parameters are particle diameter and slurry velocity (Figure II-8). Govier and Charles (1961) related the regime classification to flow velocity and pressure drop (Figure II-9). The homogeneous and heterogeneous regime classifications are of greatest practical value. The solid-liquid transport mode can be further classified into four subregimes:

- Homogeneous suspension flow
- Heterogeneous suspension flow
- Saltation (moving bed)
- Stationary bed

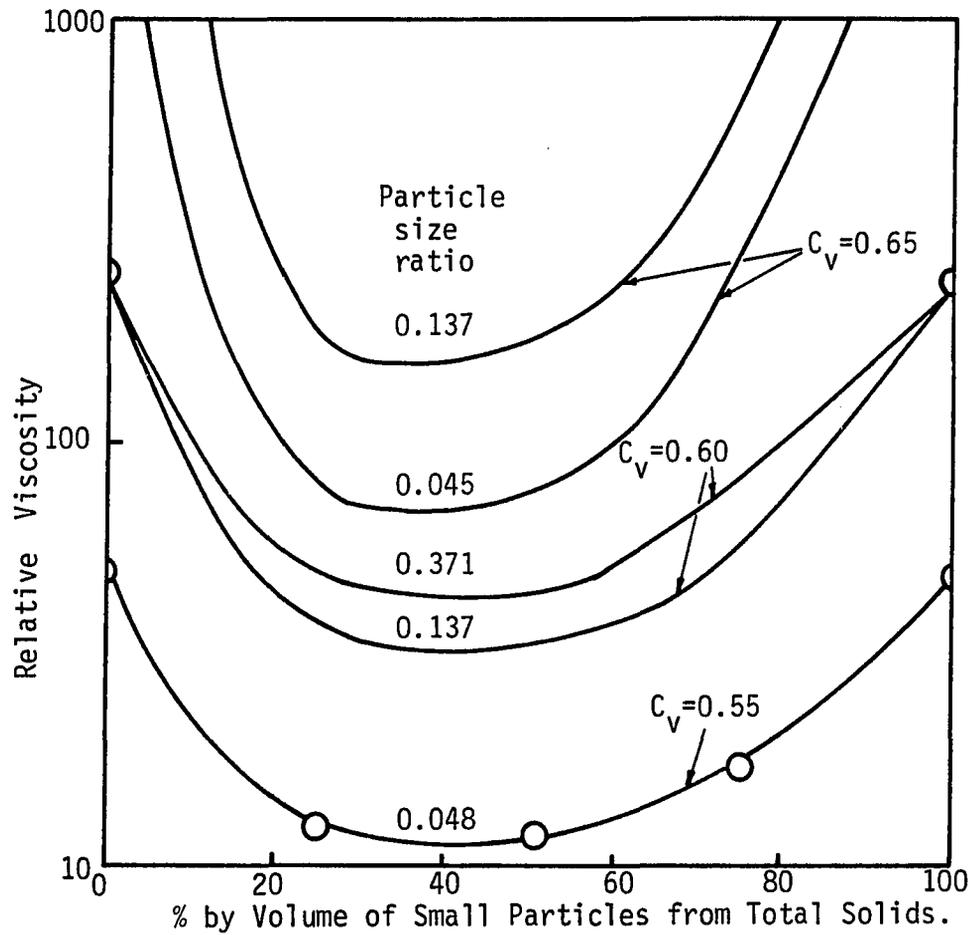


Figure II-7: Relative viscosity of a bimodal suspension as a function of solid composition.

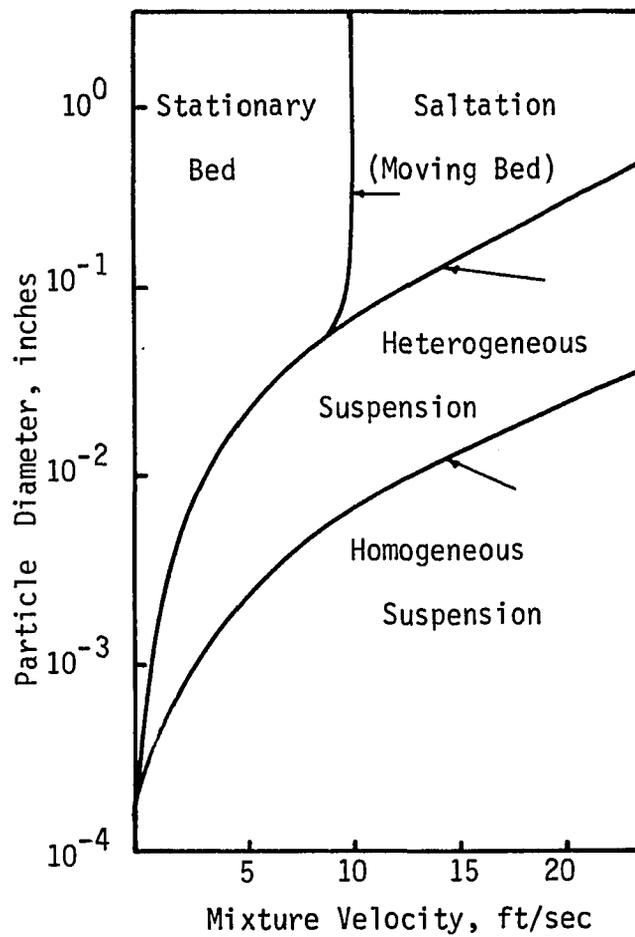


Figure II-8: Classification of flow regimes for sand (Density=2.65).

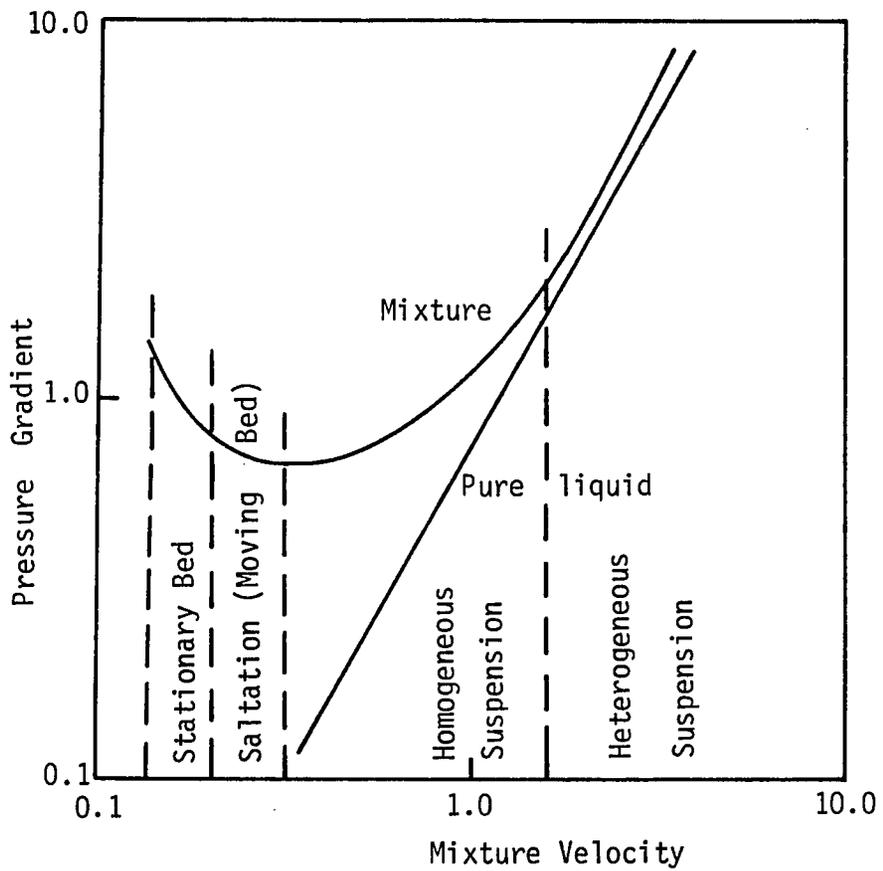


Figure II-9: Schematic representation of pressure gradient curve vs. velocity and flow regimes.

Homogeneous suspension flow is observed at high mixture velocities and at low falling velocity of the solids, i.e. solids almost neutrally buoyant. This regime is characterized by a uniform distribution of solids throughout the liquid.

Heterogeneous suspension flow occurs at lower flow velocities and for heavier particles. All solid particles are in suspension, but their vertical distribution is not uniform. Limit Deposit Velocity (Figure II-9) is the lower limit of this regime.

Because the pressure drop in this regime reaches a minimum, it is the most economical of the flow regimes. All of the existing pipelines are operated at velocities slightly higher than the Limit Deposit Velocity. Flow conditions in this regime are complex due to concentration changes with respect to the location in the pipeline cross section. This regime is described by empirical equations.

Saltation Flow When the velocity of the flow decreases more, the particles settle on the lower part of the pipe, increasing the pressure drop. The settling particles are picked up by the fluid and transported until they settle again. This type of flow should be avoided due to the danger of plugging, increased power consumption and abrasion of the pipeline.

Stationary Bed is basically the same type of flow as in porous media. This regime is never used in solid-liquid transport.

Solids Concentration

Solid concentration is the most important parameter in determining the flow of slurries. When the carrier fluid of a suspension is Newtonian, most suspensions will be Newtonian up to solid concentrations of 20-30% by volume. At higher concentrations, suspensions become dependent on the shear rate. In shear thinning (pseudo plastic behavior), viscosity decreases with shear rate; shear thickening is the increase of viscosity with shear rate. Combinations of shear thickening and thinning have been observed. Some concentrated suspensions begin flowing after the shear stress has exceeded a limiting value known as the yield stress. This behavior is called viscoplastic. The phenomenon of yield shear stress has been attributed to the formation of particle aggregate networks; these must be broken for flow to occur (Michael and Bolger, 1962). Other suspensions, when under continuous shear, exhibit thixotropy; i.e., viscosity decreases with time. This property is caused by a reversible breakdown of internal structure under shear. Thixotropic behavior is mainly caused by particle flocculation. Rheopexy, a reversible increase in viscosity with time, has also been observed in suspensions. Its causes are less known than those for thixotropy.

Non-Hydrodynamic Effects

Experimental data for concentrated suspensions cannot be explained in terms of purely hydrodynamic effects. The non-hydrodynamic forces become pronounced in suspensions of small particles, with a high ratio of solid-liquid interfacial surface. These consist of electrical

forces from charged particles, London - Van der Waals forces and Brownian motion.

Brownian Motion

Brownian motion, being translational and rotational in nature, is more pronounced for small particles than for large ones. Brownian motion is considered important in suspensions of particles with diameters of 1μ or smaller, and for dilute systems of non-spherical particles.

Electroviscous Effects

When a charged particle is immersed in an electrolyte, it becomes surrounded by a thin layer of ions adjacent to its surface. This layer, called Stern layer, is of opposite charge to that of the particle. The Stern layer is surrounded by a more diffuse outer layer called Gouy or Debye Huckle layer.

The parameters associated with the electroviscous effects are the potential or the charge density at the surface of the particles and k^{-1} Debye length, which measures the thickness of the ionic cloud.

An increase in the electrolyte in the bulk will decrease the Debye length, as the dissociated ions are better able to shield the charge of the particle. These values can be determined by electrophoretic measurements.

London - Van der Waals forces

Forces of attraction between particles are required to explain the flocculation of particles. It is a common misconception that London

- Van der Waals forces act over very short distances.

It has been shown that the potential energy of attraction between two small spheres of radius R , separated by distance D , is the same as for two larger spheres with radius fR separated by a distance fD .

London-Van der Waals forces are responsible for the association of gas particles to form condensate; similarly colloid particles flocculate due to the same forces. The full theory of stability is the well known Deryagin-London-Verwey-Overbeck (DLVO) theory.

DLVO Theory

The literature on dispersion stability and the DLVO theory is quite extensive, but the majority of investigations, both theoretical and experimental, are devoted to aqueous systems. As a result, non-aqueous systems are less understood. Two review articles, from which most of the following material was drawn (Lyklema, 1968 and Russel, 1980), explain in detail the theoretical concept of the DLVO theory for both polar and non-polar solvents. Experimental results supporting the theory are also described.

The Deryagin-Landau-Verwey-Overbeck theory is generally accepted as the basis theory of colloidal stability. It states that the interactions between colloidal particles is a superimposition of electrostatic repulsion and van der Waals attraction. The DLVO theory adds the repulsive forces and the attractive energies as scalars. The stability of a system depends on the potential energy barrier formed by the opposing forces. The higher the potential energy barrier, the more stable is the dispersion.

In aqueous dispersions, the electrostatic repulsion between the dispersed particles is the dominant factor promoting stability. The particles do not aggregate because they are charged and repel each other. The surface charge can result from dissociation of surface groups, adsorption of potential determining ions and ionized surfactants. The surface charge can be controlled by the concentration of the relevant ionic or adsorbative species in the solution.

A charged hydrophobic colloidal particle is not yet a sufficient condition for stability. The surface charge must be compensated for by an equal amount of opposite counter charge in the surrounding medium. The surface charge and the counter charge form an electrical double layer, neutralizing each other. The distribution of the counter charge is also an important factor in determining the stability of the dispersion. If the counter charge extends far from the particle, two particles approaching each other will be subject to the repulsive force while they are still far apart. When the double layer is compressed, the particles can approach and even aggregate before repulsive forces are felt. According to the DLVO theory, the solvent affects the ionic distribution only through its dielectric constant, but impurities and dissolved electrolytes can also have a great impact.

In non-aqueous suspensions, only dissociation of surface groups and adsorption of ionic surfactants can have a significant effect on stability; the adsorption of potential determining ions is restricted to solvents having moderately low dielectric constants. In non-polar solvents (when an adsorbable surfactant is absent), the dissociation of

surface groups appears to be the dominant mechanism determining stability, and protons are almost always responsible for charge transfer.

When adsorbable surfactants, water, or other impurities are present in a non-polar solvent, they can have a considerable influence upon particle surface charge sign and magnitude. Water is not soluble in non-polar solvents and tends to adsorb on particle surfaces, which become more basic (i.e., more positive).

If the particle charge results from the adsorption of ionic surfactant, its sign depends upon the relative adsorbability of the surfactant cation and anion. Carbon black in benzene becomes positive by the adsorption of oleic and fatty acids, while carbon black in xylene and heptene acquires a negative charge due to adsorption of Aerosol OT. In general, cation active surfactants may be expected to render polar particles negative and non-polar particles positive.

In non-polar solvents, the electrical double layer becomes very thick. This means that the repulsive forces exerted on charged particles are also low, but have a longer range. Thus, dispersions with non-polar solvents could exhibit the same behavior as ones with polar solvents.

As direct measurements of the surface charge are not available, the only way it can be assessed is via electrokinetic measurements, usually electrophoresis. However, in the case of low conductivity solvents, electrophoresis is an extremely difficult technique. Moreover, adsorbed water and the non-homogenous structure of the coal could lead to distortion and erratic values. Therefore, these measurements are not relevant to our study, as the coal particles include

many impurities and water.

The DLVO is presented only in a qualitative way to support the theory of stability and drag reduction by ionic surfactants, that will be presented in chapter V. As coal particles include many impurities, water, and trace elements, a quantitative analysis is impossible.

II-3. Coal Suspensions and Drag Reduction

The first major application of transporting a slurry via pipeline took place in 1914. An 8 inch pipeline was built in London to deliver lump coal from the Thames to a power station 1750 feet away. In 1951, the Pittsburgh Consolidation Coal Company built a 108 mile long, 10 inch pipeline at Cadiz, Ohio. The pipeline transported 4000 tons per day of finely crushed coal from the mine to the Cleveland Electric Illuminating Company. Today, the pipeline from Black Mesa, Arizona to the Mojave Power Plant, 273 miles long, transports 5.8 million ton of coal per year. Another slurry pipeline, to be the longest of its kind, is now under design. The proposed pipeline between, Wyoming and Arkansas, will be 1355 miles long will transport 25 million tons of coal per year. These examples illustrate that pipeline transport of coal slurries is not only technologically available, but it also provides environmental and economical answers to the growing demand of coal.

In recent years, most of the research on the properties of coal slurries has been conducted by the mining companies and utilities in an effort to find ways of reducing the cost of coal transport. Pure rheological researchers have not investigated coal slurries because of

the complexity of the coal surface structure, the reduction in particle size during flow, the porosity of coal, etc. By using coal as the solid phase in the investigation of the rheological properties of suspensions, many parameters which influence the flow must be included. Therefore, in order to simplify their experiments, many researchers have used solids other than coal, such as glass, plastics and sand. Because rheological research on coal slurries has been limited to applied research designed for scale up, and other specific purposes, only general data is available in scientific literature.

Coal-Water Slurries

Worster (1952) was among the first to investigate suspensions of coal and water. His correlations produced, with coarse coal particles are similar to those reported by Durand and Condolius. Guessler (1967), in his Ph.D. dissertation presented data on coarse coal particles entrained by water. Figure II-10 is a typical example of 0 - 10 mm coal particles in a 160 mm pipe under conditions of constant mass solid flow. Guessler discovered that finer particles appear to act as a turbulence suppressor, causing a reduction of the pressure gradient to the level of water alone; this becomes even even lower at high flow rates. These data, for particles of 0 - 3 mm in a 46 mm pipe, are presented in Figure II-11.

Bain and Elliot (1964), reviewed the then available technology and the problems associated with the pipeline transport of coal. They noted that coal slurries of 50 - 60% solids by weight, can be transported at relatively slow velocities (and even under laminar conditions) when

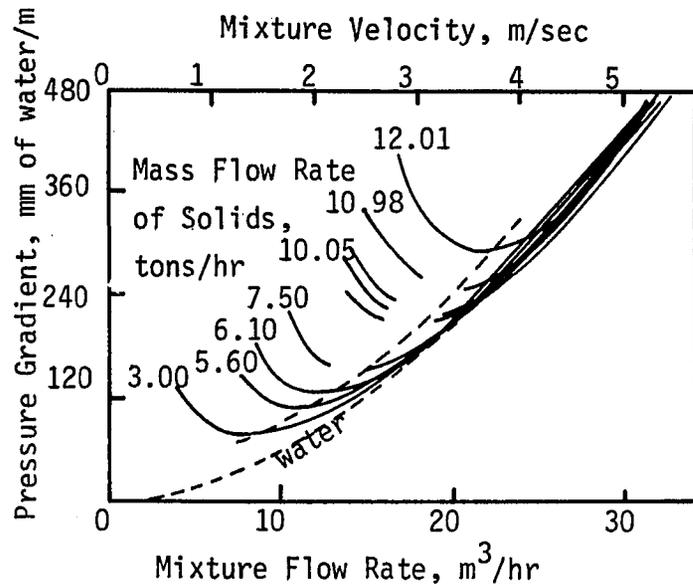


Figure II-10: Pressure gradient of coal- water suspensions of 0 to 3 mm coal particles.

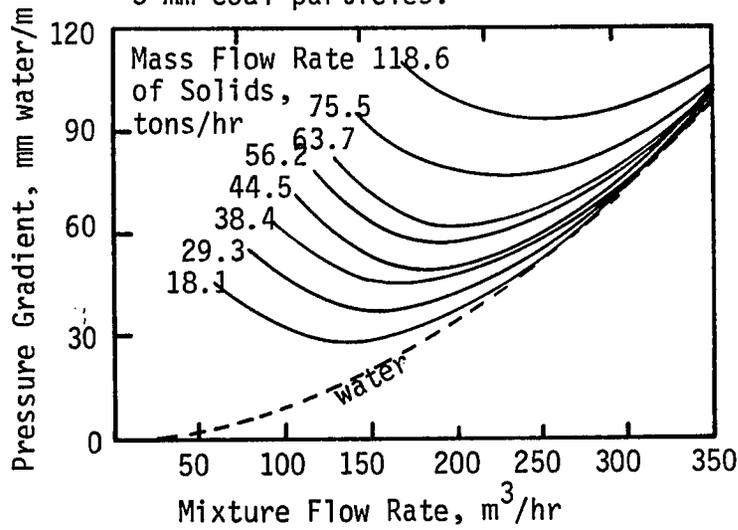


Figure II-11: Pressure gradient of coal- water suspension of 0 to 10 mm coal particles.

the size of the coal particles is reduced. Pumping large particle size coal in a 4 inch pipe at 20-35% solids concentration, Elliot et al. (1965) noticed that settling occurs at velocities below 7 ft/sec. They also observed that, at higher concentrations, the settling begins at lower velocities. They concluded that, at high solid concentrations, there is less free space left within the mixture for settling to occur. In a later paper, Elliot and Gliddon (1970) point out that optimum flow properties of coal-water mixtures can be obtained by adjusting the size distribution of the solids to give the greatest packing density. He also observed that slurry mixtures containing bimodal particle size distributions and suspensions of very small particles, behave like Bingham plastics at high solid concentrations and remain homogeneous, even under conditions of laminar flow. Experiments in 4 inch pipelines, with 52% solids (by weight), demonstrated that laminar flow occurs at velocities of 3 - 5 ft/sec. Below these velocities, sharp fluctuations of the pressure gauges indicated incipient settling. A sharp transition to turbulent flow conditions occurred at 5 - 6 ft/sec. At higher concentrations (58 - 60% solids), the settling was not noticeable, even at velocities of 0.5 - 0.6 ft/sec.

Elliot and Gliddon (1970) also described, for the first time, the effect of pH on coal-water slurries. Their standard mixture had a pH of 6.7. A rapid decrease in pressure drop occurred when the pH was increased to above 8. The effect, which is completely reversible by adjusting the pH, was wrongly attributed to the presence of clay particles, which possess surface active properties.

Coal-Oil Slurries

The rapidly expanding interest in transportation of coal by water slurry pipeline has brought into focus a number of technical problems relating to flow and stability, liquid solid separation, slurry preparation, maintenance, etc. There are also economic, political and environmental problems associated with acquiring and disposing of the large volumes of water required by slurry systems. An obvious solution to some of the problems mentioned above is the transport of coal via pipeline with a hydrocarbon liquid fuel as the carrier fluid. While the dispersed phase of a coal-oil slurry consists of finely divided solids into droplets, most investigations have emulated the principles of solid particle emulsion research, where the inner phase is formed by liquid droplets. Therefore, to ensure a better understanding of coal suspensions, a short background on the theory of emulsions is mandatory.

Theoretical background of emulsions

While theoretical interpretation of emulsion behavior has developed with a basis in classical thermodynamics, theoretical prediction of emulsion properties is not yet possible. Generation of a stable emulsion is an empirical art. The major variables which influence the formation of a stable emulsion are:

1. the method of preparation, and
2. surfactant additives.

Several methods of emulsion preparation are known. Most of them involve the application of brute force to break up the bulk fluid into

small droplets. The three most commonly used methods are mixing, colloid milling and homogenizing. In mechanical mixing, the components are emulsified by the intense shear force of the mixer. The droplets produced by mixing are approximately 5μ in diameter, depending upon the components, mixer type and shear force. A colloid mill is a mixer which develops a strong shearing flow between a high-speed rotor and a stator. A colloid mill emulsion achieves dispersion of approximately 2μ droplets. A homogenizer is a device which forces flow through a small orifice under high pressure. A homogenized emulsion contains droplets of 1μ and smaller. Other methods of preparing emulsions include ultrasonic cavitation, electric dispersion, condensation and spontaneous emulsification.

The emulsification process itself can be regarded as two distinct phases:

1. the formation of new droplets, and
2. the stabilization of the droplets once they are formed.

The total free energy of emulsification is given by a correlation of Aveyard and Vincent (1977):

$$\Delta G_{\text{form}} = \gamma^{\alpha\beta} (\infty) \cdot \Delta A - T\Delta S_{\text{disp}}$$

where ΔA is the change in the total area of the interphase, $T\Delta S_{\text{disp}}$ is the entropy gained in the system, and $\gamma^{\alpha\beta}$ is the interfacial tension. The first term of the correlation is the most significant one; the second term can sometimes be neglected. ΔG is usually large and positive, meaning that external work is required to form an emulsion. Spontaneous

emulsions will occur when G is negative, implying that $T\Delta S$ is greater than ΔA . This happens when the interfacial tension is very small.

The work required to create a new interface is given by:

$$W = \dot{\gamma} dA$$

As the original interface is negligible, the surface created is given by:

$$\Delta A = GV/d_0$$

V = Volume of the internal phase

d_0 = droplets diameter

Therefore, the work required is:

$$W = \dot{\gamma} GV/d_0$$

In practice, the power required to produce an emulsion is several orders of magnitude greater than the calculated figure. This is due to the work invested in mixing the fluid.

The emulsions are controlled by several factors:

1. concentration,
2. stability,
3. droplet size,
4. viscosity, and
5. surface tension.

Other factors are the preparatory variables; these include emulsifying agents, mode of addition, agitation and temperature.

Interfacial tension is lowered when an emulsifying agent is absorbed at the interface. Interfacial tension varies inversely with the concentration of the emulsifying agent and tends to attain a limiting value (Gopal, 1968). The initial location (what phase) of the

emulsifying agent and the addition order of the bulk phases are important variables in emulsion formation. Adding an aqueous phase to oil yields an w/o emulsion, while adding oil to water forms an o/w emulsion.

The time, intensity and type of agitation are important parameters which can give emulsions different properties. Prolonging the type of agitation beyond an optimum time will not improve an emulsion's stability. This effect is expected as emulsification is an equilibrium between the disruption and re-combination of the droplets of the dispersed phase. As the number of droplets formed increases, the collisions among them become more frequent until an equilibrium is reached between the coalescence and disruption processes. The emulsification process increases with temperature, as both viscosity and interfacial tension decrease with a rise in the emulsion temperature.

Selection and use of emulsifying agents

Four general classes of emulsifying agents are known:

1. simple inorganic electrolytes;
2. surface active soap and detergent-type compounds;
3. macromolecular agents such as protein, gums, and starch; and
4. finely divided solid to form a monoparticulate layer to coat the droplets.

McCutcheon's Annual of Detergents and Emulsifiers (1975) gives a compilation of commercially available surfactants. The available synthetic emulsifying agents are grouped as anionic, cationic, nonionic, amphoteric and water insoluble.

The nonionic surfactants offer an advantage over other agents.

Their efficiency is less sensitive to changes in pH and to the effects of electrolytes. They usually have a hydroxyl group and ether linkages which create hydrophilic action.

One successful means of choosing a proper emulsifying agent is the Hydrophilic-Lipophilic Balance (HLB) method. The HLB method is based on the assumption that the emulsifying efficiency of a surfactant is related to the polarity of the molecule. When the hydrophilic part of the molecule is the dominant one, the surfactant tends to dissolve in the aqueous phase. When the lipophilic part dominates, the surfactant will dissolve in the organic phase. Properly balanced surfactants will concentrate at the interphase.

The HLB method is represented by an arbitrary empirical scale in which surfactants are assigned a numerical value. Increasing HLB numbers correspond to greater hydrophilicity. The surfactants are also classified according to HLB numbers (Becker, 1965):

| <u>Range</u> | <u>Application</u> |
|--------------|--------------------|
| 3-6 | w/o emulsifier |
| 7-9 | wetting agent |
| 8-18 | o/w emulsifier |
| 13-15 | detergent |
| 15-18 | solubilizer |

Bancroft's Rule (empirical) states that the emulsifying agent is preferentially soluble in the external phase. Davis (1963) assigned HLB values to structural groups of surfactant's molecules. The value of HLB numbers can be calculated by the relation:

$$\text{HLB} = 7 + [\text{hydrophilic group number}] - [\text{lipophilic number}]$$

Coal Oil Slurries - Rheological Properties and Stability

The main concern of most researchers is not with the optimization of the flow property of coal-oil mixtures, but rather with the prevention of solid particle settling. It is also generally assumed that homogeneous mixtures exhibit improved flow characteristics. Consequently, an extensive research program is underway to discover chemical or physical ways of preventing coal particle settling and to ensure homogeneity of the slurry.

Moreland (1963), one of the pioneer researchers of coal-oil mixtures, compared the results obtained from pipeline data with viscosities obtained in the laboratory and discovered that, at low velocities, the apparent viscosity in the pipeline is higher than that measured with the viscometer. At concentrations greater than 20% by volume, the apparent viscosity measured in the pipeline becomes lower than the laboratory data. Moreland concluded that viscosities of coal slurries determined by a viscometer cannot be used to predict the pressure gradient in a pipeline.

In a review of work on the rheology of coal-oil slurries, Munro et al. (1979) came to the conclusion that the results of most previous investigators are incomplete and inconsistent. Munro et al. used a Stormer viscometer which had been modified to a concentric rotary viscometer. Measurements taken in laminar flow show that, up to a solid concentration of about 30% by weight, the slurries are Newtonian in

nature. Their results indicate a gradual increase in slurry viscosity up to a concentration of 30% wt., above which, the viscosity increases rapidly.

Batra et al. (1978) tested the viscosity of coal and no. 6 fuel oil suspensions in a rotational viscometer and concluded that, at high solid concentrations, the viscosity of the mixture increases rapidly as in coal-water suspensions. A small amount of water (2-5% by weight), when homogenized with the mixture, stabilizes the mixture significantly.

Ekman and Bienstock (1979) emphasize that the viscosity of the oil has a significant effect on the viscosity of the slurry, and the oil often exhibits time and shear dependent plastic behavior. At high solid concentrations the viscosity of the COM increases rapidly as shown in Figure II-12. They also reported that slurries of coal in No. 6 fuel oil at concentrations higher than 20% become non-Newtonian. At 40% and higher solids concentrations, the non-Newtonian behavior becomes a dominant feature of the COM.

Castillo and Williams (1979) tested finely ground coal in glycerin and in Aroclor 1254 (a chlorinated biphenyl) in a Weissenberg Rheogoniometer K17, operating in a cone and plate mode. They concluded that coal suspensions are Newtonian for solids concentrations up to 20%. The transition to non-Newtonian behavior set in at approximately 30% solids concentration. The onset of non-Newtonian behavior is accompanied by an abrupt increase in viscosity. Surfactant addition increased the viscosity at all concentrations, but the most dramatic change occurred at 20%, when the suspension also became non-Newtonian. Castillo and

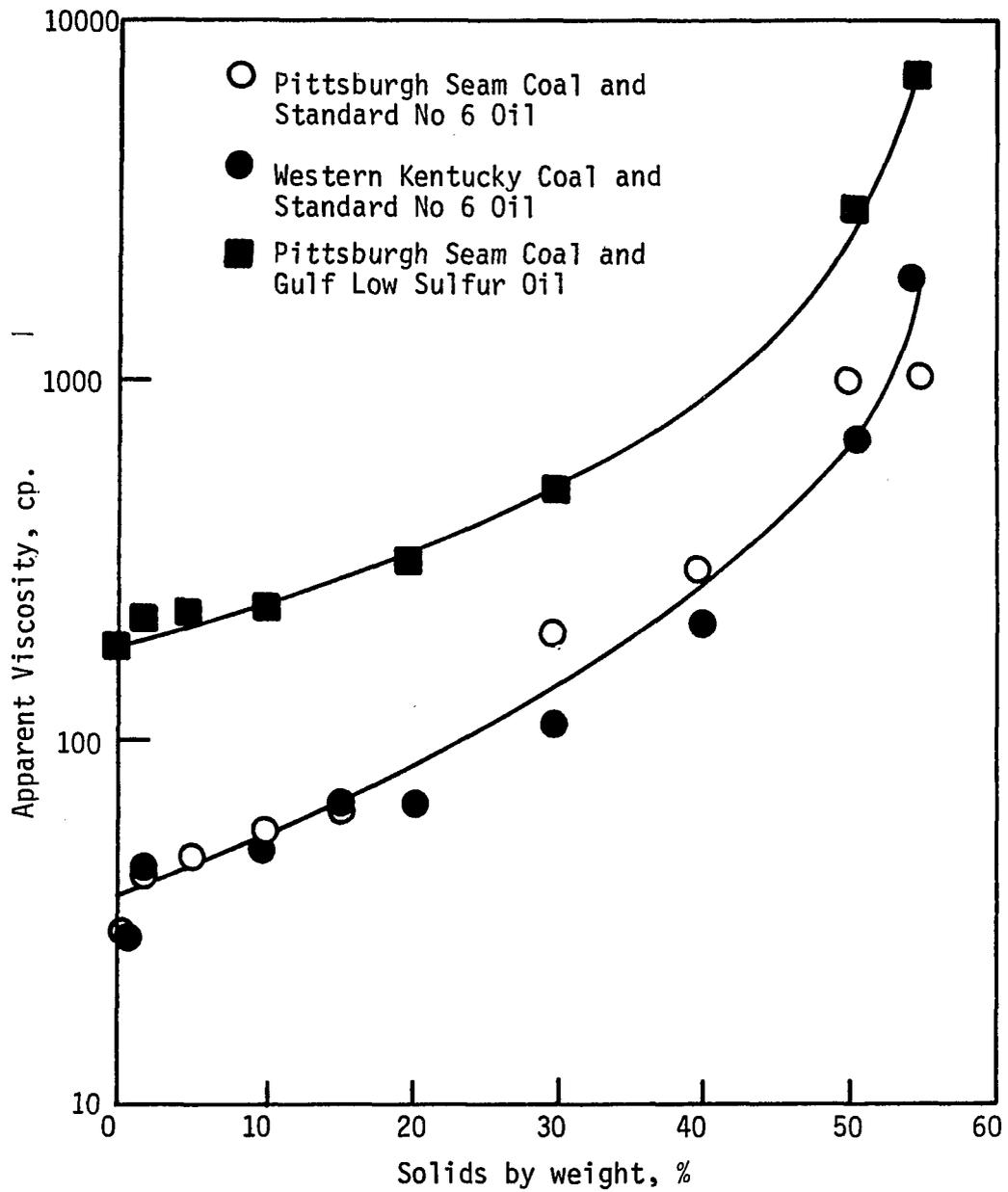


Figure II-12: Viscosity of COMs as a function of solids concentration.

Williams suggest that trapped air in the suspension, and a small amount of positive charge on the surface of the coal, could explain the suspension behavior.

Miyazaki et al. (1979) noticed that at flow velocities of 23-42 cm/sec in a 21.4 mm pipe, there is a linear dependence between the pressure drop and the mean velocity of the coal-oil slurry (Figure II-13). Data obtained with a plate and cone viscometer shows that COMs exhibit non-Newtonian behavior. The rheograms indicate that COMs are pseudo plastic fluids.

Also, Halowaty (1979) mentioned that the friction head loss of a 50% by weight coal in a No. 6 fuel oil is a linear function of the flow velocity between 0.4 to 1.4 ft/sec, the characteristics of a Bingham flow (or a pseudo plastic fluid). Isao Koyama (1979) and Kenichi et al. (1979) reported similar results. Kenichi's results are reproduced in Figure II-14.

John P. Doohar et al. (1978 and 1979), of the Adelphi Center for Energy Studies, researched coal-water-oil emulsions (COW) and coal-oil emulsion (COM). His studies show that COW are much more non-Newtonian in nature than COM. Photomicrographs of emulsions show fine coal particles adhering to the water droplets, stabilizing the structure. Large particles of coal fill the interstices between the water droplets, offering an added steric stabilization, which results in a pseudoplastic, thixotropic emulsion.

These results, and other viscosity data of COM gathered by Corty and Coburn (1979), Sawyer (1978), and Sadabell (1978), not only prove

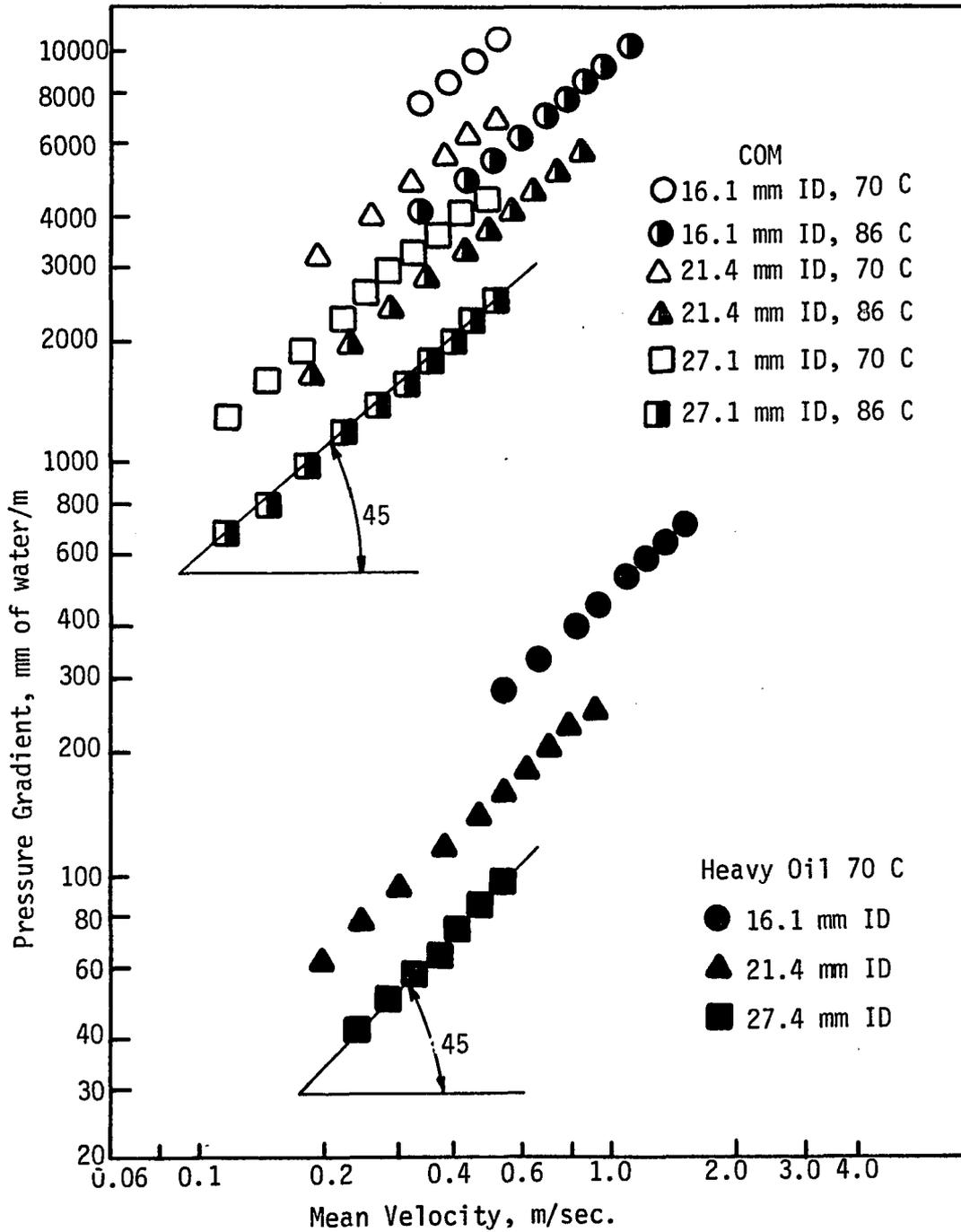


Figure II-13: Pressure gradient as a function of mean velocity of oil and coal-oil mixtures.

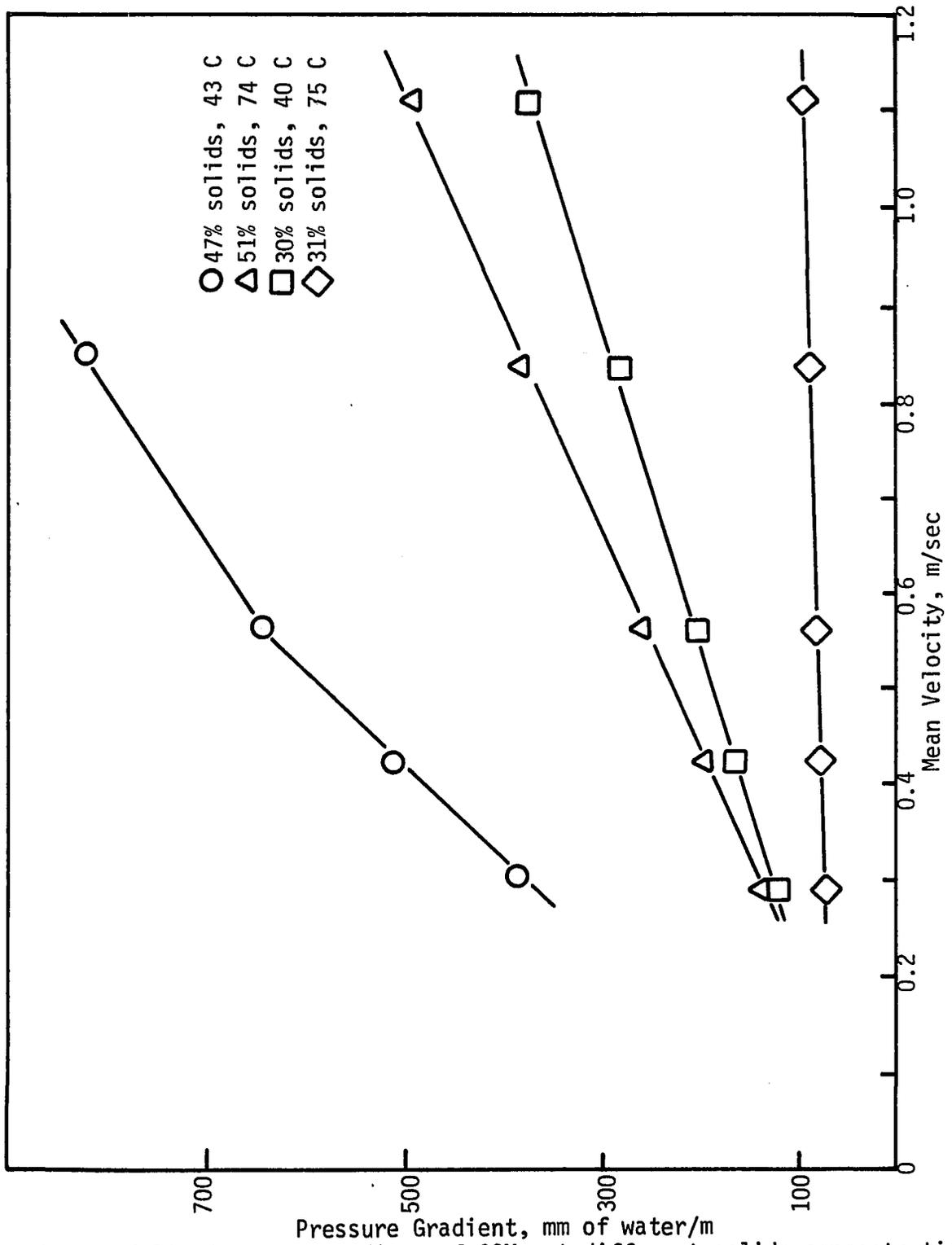


Figure II-14: Pressure gradient of COMs at different solids concentration

that COM (and in a more impressive way, coal-oil-water mixtures) exhibit non-Newtonian properties, but they also justify the assumption of the formation of a flocculated suspension or a particle network.

Coburn (1979) reported that emulsified colloidal fuels will exhibit a yield value, a hysteresis loop of shear stress between the ascending and descending curves. Scheffee (1978) developed a coal-oil and gelled water mixture; its most important property is yield stress. This mixture was stable when stored. W. C. Meyer (1979) states that, at low concentrations, no measurable yield is seen. In suspensions of 40% by volume, a yield value appears, suggesting that a flocculated state exists. Fisher (1950) also asserts that highly concentrated dispersed systems of coarse particles are stabilized as a consequence of the formation of flocculate-like networks.

Botsaris et al. (1979) mention three major parameters which govern the nature of a coal oil mixture:

1. the philicity of the coal powder,
2. the relative amounts of the liquids, and
3. the relative size of the water droplets and powder particles.

The three parameters permit the formation of several configurations which govern the physical and rheological properties of coal slurries. Large water droplets, relative to coal particles, and coal which is not fully wetted by water or oil, will create a configuration wherein the particles will orient themselves at the interface of the droplets and prevent their coalescence. If the coal particles are hydrophilic, the water may form bridges between the particles. For very

small droplets (relative to coal particles), when the coal particles are relatively hydrophilic (contact angle less than 90°), the configuration formed will be one of loose flocks or a particle network. For extremely hydrophilic coal particles (contact angle 0°) and water droplets which are slightly larger than the particles, the water droplets will engulf the coal particles and join together to form agglomerates.

Yamamura et al. (1979) showed that addition of a stabilizer to a COM with a 43% solid concentration changes the mixture properties to a non-Newtonian one. Addition of 0.5% of water (by volume) increased the thixotropic behavior of the mixture with consequent occurrence of a yield value. The yield value illustrated by the gap between the ascending and descending curves increased at 0.1% by volume water addition.

The addition of a surfactant to a COM or COWM will increase the stability of the mixture and the flocculated structure. Botsaris et al. (1979) assumes that, in a non-aqueous suspension, the orientation of a nonionic surface active agent depends on the philicity of the solid surface. The surface active agent will orient in such a way that the oleophilic part will be absorbed at the oleophilic region of the coal particle.

Therefore, the particles will become more hydrophilic and will form a three-dimensional gel-like structure throughout the suspension. Addition of water to to this suspension will enhance the formation of bridges between the particles, as reported also by Doohar et al. (1979) and by Ekman and Bienstock (1979).

Yamamura et al. (1979) assume that there is an optimum quantity of water and stabilizer for the formation of a stable suspension. If the stabilizer exceeds the required amount, the formation of inverse micelles is expected. Such micelles will consume the water present on the surface of the coal and hinder the formation of flocculates. When the quantity of the stabilizer is insufficient, the gel structure will become weaker. If the water is in excess, it will consume part of the stabilizer and, if the water content is insufficient, there will be less flocculation. The amount of water that is beneficial to the formation of a gel-like structure is between 0.1% and 0.4% by volume. The amount of surfactant depends largely on the hydrophilicity of the powder and the surfactant.

Drag Reduction

Formation of a gel structure in a moving fluid can reduce the pressure drop because of slippage of the plug flow region over the viscous sub-layer. In order to understand this phenomenon, the research done on drag reduction by polymer solutions was reviewed.

Drag reduction has been defined as the decrease in pressure loss, at constant flow rate of turbulent flow, caused by a small amount of additive to the carrier fluid. Drag reduction, or Tom's effect, is a phenomenon exhibited by many Newtonian and pseudoplastic solutions, gels, and suspensions; it represents a departure from a suspension's normal viscous behavior. Drag reduction has been observed in turbulent flow and may be achieved with several types of additives: soluble polymers in water and hydrocarbons, gasoline gelled with aluminum soap and suspensions of fine solid particles.

Tom's effect is explained by a theory which assumes that, in addition to the viscous sub-layer near the wall and the plug-flow region, exists a third region called the "elastic sub-layer". In this sub-layer, the slippage of the plug-flow region occurs. The elastic sub-layer grows until it occupies the entire pipe cross-section; simultaneously the drag reduction reaches an asymptotic value. This model provides a fairly clear explanation of drag reduction in polymer solutions. As the model can predict drag reduction in other mixtures which form gels, emulsions and suspensions, it is highly probable that drag reduction also occurs in oil-water coal slurries.

CHAPTER III

EQUIPMENT AND EXPERIMENTAL PROCEDURE

This chapter outlines the experimental methods used in the study. First, the experimental apparatus is described, then the preparation of the slurry is outlined; finally, the experimental procedure is presented.

Initially, the viscosity of coal-water and coal-oil mixtures were measured under a variety of conditions, using a Brookfield viscometer. Because the data from laminar flow measurements indicated that, under some conditions, the results were not consistent and repeatable, data were also gathered from slurries flowing in a pipe. The viscometer data were used only in cases where the experimental error could be discarded as negligible. Drag reduction was observed to take place under both laminar and turbulent flow conditions, when the slurries were treated with chemical additives. The drag reduction theory discussed in the next chapter is supported by visual experiments. Photographs, taken through a microscope, show the structure formed between coal particles. In addition, a series of pictures showing the settling process of the particles was also obtained and are presented in the next chapter.

The Brookfield Rheometer Data

Slurry viscosities, under laminar flow conditions, were measured using a Brookfield Rheometer (Model RVT-RL-108) equipped with a pneumatic transmitter. This rheometer, manufactured by The Brookfield Engineering Laboratories, Inc., is a rotational viscometer consists of a rotating

cylinder (called a spindle) which is immersed in the liquid to be tested. The laboratory installation of the rheometer is shown in Figure III-1. In operation, the spindle experiences a viscous drag or resistance force which is a function of the spindle's rotational speed and the cohesiveness of the liquid. Shown schematically in Figure III-2, the rheometer consists of a cylinder of radius R_s in a cylindrical container of radius R_c . The liquid covers the spindle to a height h . The spindle rotates with an angular velocity Ω . The resistance to the external force applied on the spindle is the resistance to flow produced by the liquid. The external torque is measured and the shear stress is derived from the opposing torque in the fluid. The shear rate depends upon the geometric dimensions of the apparatus and the angular velocity of the spindle. The coefficient of viscosity is a simple function of the shear stress and shear rate.

The derivation of the basic equations to calculate the viscosity begins with the equation of continuity in cylindrical coordinates:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (\rho r V_r)}{\partial r} + \frac{1}{r} \frac{\partial (\rho V_\phi)}{\partial \phi} + \frac{\partial (r V_z)}{\partial z} = 0$$

The following assumption are used to simplify the equation of motion:

1. the liquid is incompressible,
2. the motion of the liquid is laminar,
3. the velocity of the liquid is a function only of radius,
4. the motion is in a steady state,

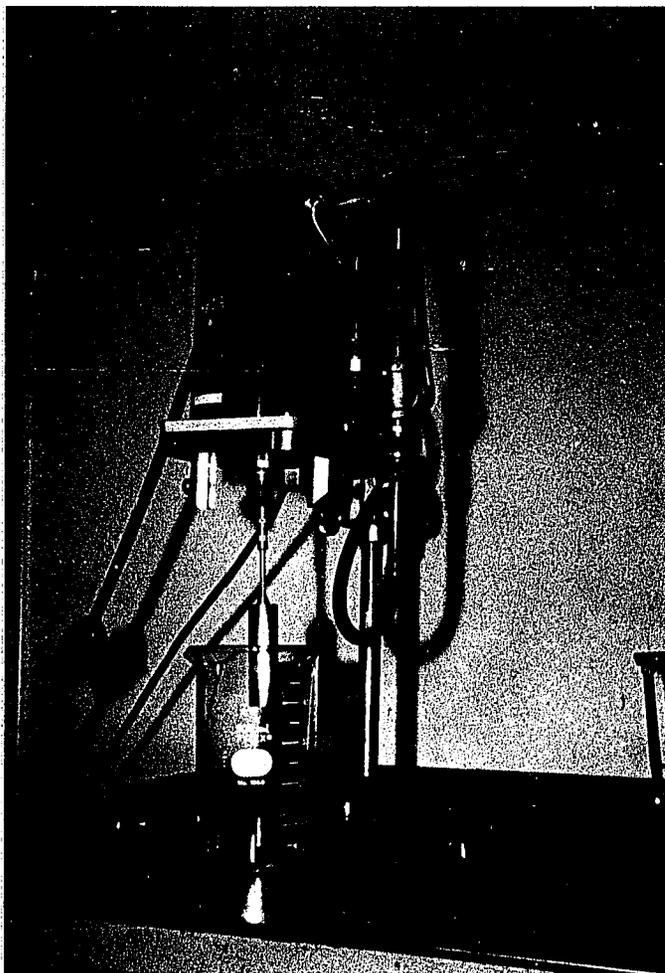


Figure III-1: Photograph of the Brookfield Rheometer

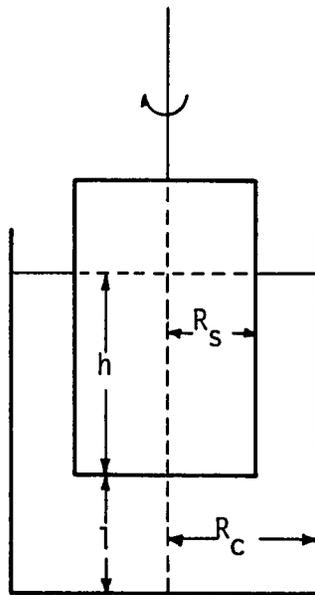


Figure III-2: Schematic diagram of a concentric cylinder viscometer

5. there is no slippage at the wall, and that the
6. the system is isothermal.

The equation of motion becomes:

$$\frac{1}{r^2} \frac{d(rS_r \phi)}{dr} = 0$$

where S is the shear stress.

Integrating the above equation we can calculate the torque

$$T = 2\pi R_s^2 h S$$

The shear stress calculated from the torque measured by the viscometer is:

$$S = \frac{M}{2\pi R_s^2 L}$$

S = Shear stress in dyne/cm²

M = The torque measured by the viscometer. Maximum torque for RVT models is 7187 dyne-centimeter.

R_s = Spindle radius in centimeter

h = Spindle height in centimeters.

The shear rate is given by the following equation:

$$\dot{\gamma} = -\frac{dv}{dr} = \frac{2\Omega}{r} \frac{R_s^2 R_c^2}{R_c^2 - R_s^2}$$

r = Distance from axis of rotation at which the rate of shear is being calculated; in our case r = R_c

The shear rate equation simplifies to:

$$\dot{\gamma} = 2\Omega \frac{R_s^2}{R_c^2 - R_s^2}$$

The torque is sensed by a pressure gauge and transformed into an electrical signal which can be read with a voltage measuring device. The details of the apparatus are described in the Instruction Manual of the Brookfield Rheolog.

The fundamental equation of motion, and an explanation of the theoretical approach of coaxial cylindrical viscometer, is presented in the classic book "Transport Phenomena" by R. B. Bird, W. E. Stuart, and E. N. Lightfoot (1960). The most complete and practical book on basic rheological theories is "Viscosity and Flow Measurements" by J. R. Van Wazer et al. (1963). It also provides a detailed description of commercially available viscometers.

The suspension samples used in the viscometer were prepared just before the experiments were performed. The coal was weighed and mixed with a known volume of water or fuel in a kitchen blender for two minutes at low speed and then for two minutes at high speed. The suspension viscosity measurements were made in a 600 ml beaker. In order to insure total immersion of the spindle, the sample volume was at least 500 ml. The distance L between the bottom of the beaker and the bottom of the spindle was kept constant in all measurements. As the suspension viscosity depends on the temperature of the carrier fluid, the temperature was maintained at a constant $26\text{ }^{\circ}\text{C} \pm 0.5\text{ }^{\circ}\text{C}$.

The samples were homogenized in the blender for periods of 30 seconds to one minute before each measurement. Each sample was then poured into the 600 ml beaker and the viscosity was measured within 10 seconds, before settling could occur. The spindle was then cleaned and

dried. After the initial viscosity measurement, the sample was returned to the blender, homogenized and another reading was made. In this way, the viscosities of coal suspensions at various concentrations were measured.

Three different types of coal were used:

Utah Bituminous,

Beulah Lignite and

Texas Lignite.

The chemical analysis and the size distribution of these coal types are given in Appendix A. The analysis was made for Dr. J. L. Wendt at the University of Arizona, to whom we extend our gratitude for the use of his data.

The liquids used to prepare the sample were:

Tap water,

Kerosene,

Fuel No. 2,

Fuel No. 5, and

Methanol.

In general, no difficulties were encountered except for the fact that the methanol evaporated very quickly, making the results somewhat unreliable.

The chemical additives used to examine the effect of electrolyte concentration on highly loaded coal suspensions were:

1. hydrochloric acid (33%) and
2. sodium hydroxide (concentrated), prepared from pellets.

As only a few drops of these additives were used in each sample, the

amounts were not measured. The pH of the sample was measured by a Corning Model 3 pH meter equipped with a glass membrane electrode. Some chemists might question the practice of measuring the pH of hydrocarbon fuels, as ionic dissociation does not occur in these liquids. However, the liquid hydrocarbons used in these experiments are obtained from commercial sources and they contain a certain amount of water. In addition, surface ions from the coal particles diffuse into the aqueous phase and are detectable by the pH meter. In these experiments, the pH value was taken only as an indication of the electrolyte concentration in the samples.

Slurries Flowing in a Pipe

Experiments on slurry flow in an actual pipeline are necessary in order to measure the energy requirements of the system. To estimate the power dissipated in the suspension, the pressure gradient was measured along a straight horizontal section of one inch galvanized pipe between two points separated by a distance of 1298 cm (approximately 43 feet). This length was chosen to minimize experimental error, and was the maximum length available within the constraints of the laboratory's dimensions. To prevent turbulence caused by changing flow direction, the pipe was extended at least two feet beyond each of the measuring points. A schematic diagram of the system is presented in Figure III-3.

The pressure was initially measured by a differential pressure gauge, connected to the system through water-filled reinforced plastic tubing. Any air trapped in the line was purged, but this process produced plugging in the tubing as the slurry entered the tubes and

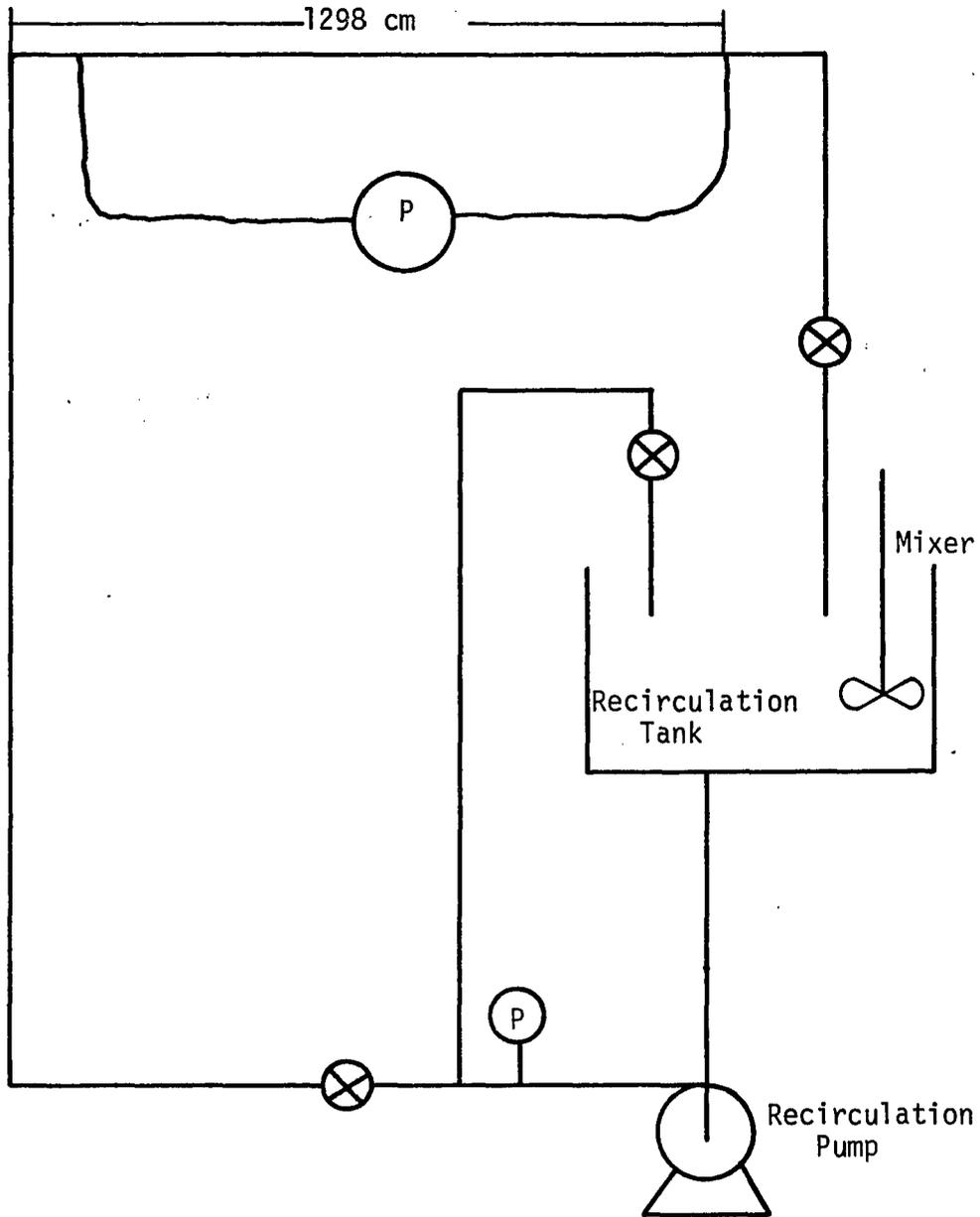


Figure III-3: Schematic diagram of the recirculation system to measure pressure drop of coal slurries.

particle settling. This interrupted the experiments until the tubes could be unplugged. Slurries of up to 15% solids were measured in this manner. In order to measure the properties of more concentrated suspensions, a special pressure transmitter was installed. The gauge was still a Meriam Instrument differential gauge with a range of 0 - 360 inches of water, calibrated in two-inch increments. The transmitter consisted of aluminum tubing, filled with silicone fluid. A pressure sensitive diaphragm separated the silicone fluid from the slurry. The pressure transmitter and gauge were pre-calibrated by Meriam Instruments, as high sophistication is required for the procedure.

A mixture of the carefully weighed coal and liquids was prepared with a high speed, Ultra Turrax, Model SD 45 homogenizer made by Junke and Kunkel, Germany. The slurry was prepared in a 50 gallon tank from 70 liters of water and 60 kg of coal. The mixture was then allowed to stand for 12 hours to allow the escape of air trapped among the fine coal particles.

The outlet from the bottom of the tank passed through a Price centrifugal pump (Model SP 15-50SS) with a 1/2 hp motor. The pump is equipped with a ceramic seal which had to be replaced once during the study.

A return line fed into the top of the tank. The pressure of the system was regulated by valves. The volume of the mixture flowing through the pipe was measured at the outlet of the return line. The standard procedure was to measure the time required to fill a 10 liter container. Usually, between 3 and 5 measurements were taken for each

pressure drop. The results were within a 1 second margin of error (less than 3% in the worst case). When large fluctuations were observed, 5 measurements were made. The most deviant measurements were discarded and the remaining three were averaged. At low pressure drop, when the gauge began to drift or fluctuate, the measurements were discontinued.

Measurements of slurries containing low solid concentrations were performed first, at various flow rates. When the flow curve was complete, the concentration was increased by the addition of a known amount of coal. The suspension was again homogenized for 2 to 3 hours, cooled to room temperature and remeasured. A liquid volume of at least 60 liters was maintained to insure submersion of the homogenizer. The temperature was maintained at 27 ± 1 °C.

The effects of various chemical additives were tested in suspensions of high solid concentrations. For each additive to be tested, a new suspension was prepared and standardized for pressure drop versus flow velocity. Measured quantities of additives were then mixed with the suspensions and a new set of measurements taken.

The electrolytes used in this series were hydrochloric acid and sodium hydroxide as was the case in the rheometer experiments.

Visual Experiments

Two important visual observations were made on the suspensions: the settling rate of the suspended coal particles was monitored and photomicrographs were made of the suspensions. In order to observe the particle settling rate, samples containing equal amounts of Utah bituminous coal and tap water were prepared in glass test tubes. Samples

containing several drops of HCl or NaOH were compared with suspension standards. The samples were agitated on a vortex mixer for about 5 minutes, allowed to settle and were then resuspended. Photographs were then taken at given time intervals in order to visually determine the settling rate.

Photomicrographs of dry coal and of suspensions of coal-water, coal-water-acid and coal-water-base were also taken. A Zetopan Research Microscope, equipped with a Kam VBX photomicrographic camera was used. This equipment was manufactured by Optische Werke C. Reichert A. G., Austria. A magnification factor of x 160 was used. The pictures obtained through the microscope provided further information on the coal particle structures formed in suspension.

CHAPTER IV

EXPERIMENTAL RESULTS, DISCUSSION AND CONCLUSIONS

The results of the experimental work on the rheology of coal-water and coal-oil suspensions are presented in this chapter. The effects of chemical additives are observed and discussed. A theoretical explanation of the viscosity change due to the additives is also presented and visual experiments are provided to support the theory.

The Brookfield Rheometer Results

Rheological data of coal slurries were first collected using a Brookfield viscometer. The viscometer and the basic equations to calculate viscosity were described in the previous chapter. The sensitivity and the accuracy of the equipment were evaluated by measuring the viscosity of standard fluids. The standard fluids were glycerol reagent grade and UCON 50 HB. Their viscosity at 25°C is 750 cp and 1800 cp respectively. The accuracy of these measurements was satisfactory. The experimental error was 6 - 8 % consistently on the lower side for both fluids. Therefore, by comparing only measurements taken with the Brookfield viscometer we could assume that the experimental error is within the acceptable 3 - 5 %.

Viscosity measurements of COM and coal-water suspensions at various spindle speeds and at different solids concentrations were performed. The experimental error at low viscosities, in the range of 1 - 400 cp, calculated from average data was found to be unacceptably high

and the consistency of the results left to be desired. This is the range of viscosity for low and medium solids concentration. There were many reasons to our inability to measure the viscosity accurately in this range:

1. This is the lowest range measurable with this viscometer and the experimental error is large even for homogeneous liquids.
2. Fast settling of particles in the measuring vessel.
3. End effects resulting from the geometry of the viscometer.
4. Formation of a semi-solid crust on the surface of the spindle.
5. Evaporation of liquid during the experiment.

Therefore, this approach of investigating the rheology of coal suspensions was supplemented by data collected with a flowing system. The high concentration of coal in these experiments was chosen to provide viscosities within the optimum range of the viscometer and mainly because commercial pipeline operate in this range. Three types of coal were used in this experiment:

Utah bituminous
Texas lignite
Beulah lignite.

The chemical analysis of the coals was made available from an outside source and is given in Appendix A. The average particle size of Utah bituminous coal was approximately 45μ and similar size distribution was observed for the other types of coal. The particle size distribution of the coals are also presented in Appendix A. The superficial coal

density 1.33 was obtained by comparing weight of a known volume of water to the same volume of a suspension. Similar experiments performed in conjunction with vacuum extraction did not change the results significantly; the difference was about 3% which could be attributed to experimental error. The concentration of coal in COM and coal-water suspensions is given in Table IV-1.

TABLE IV-1:

Concentration of Coal in Suspensions Tested
with the Brookfield Viscometer

| Fluid | Fluid Volume in cm | Fluid Density | Coal Weight in grams | % Solids by weight | % Solids by volume |
|-----------|-----------------------|---------------|-------------------------|-----------------------|-----------------------|
| Water | 300 | 0.998 | 350 | 53.90 | 42.95 |
| Kerosene | 250 | 0.800 | 300 | 60.00 | 47.47 |
| Fuel no 2 | 250 | 0.853 | 250 | 53.96 | 42.35 |
| Fuel no 5 | 300 | 0.915 | 250 | 47.66 | 38.56 |
| Methanol | 300 | 0.798 | 200 | 45.52 | 33.42 |

The viscosities of the mixtures were measured immediately after they were prepared and after successive minute amounts of acid and base were added. The pH of each sample was measured as an indication of the amount of additive in the suspension. The spindle velocity was 3/4 rotation/seconds. The results of these experiments are summarized in Figures IV-1 a and b and tabulated in Appendix B. During the experiment it was noticed, that the viscosity of the suspension with fuel no 5 as the carrier fluid, changed with time. A constant value was reached, after

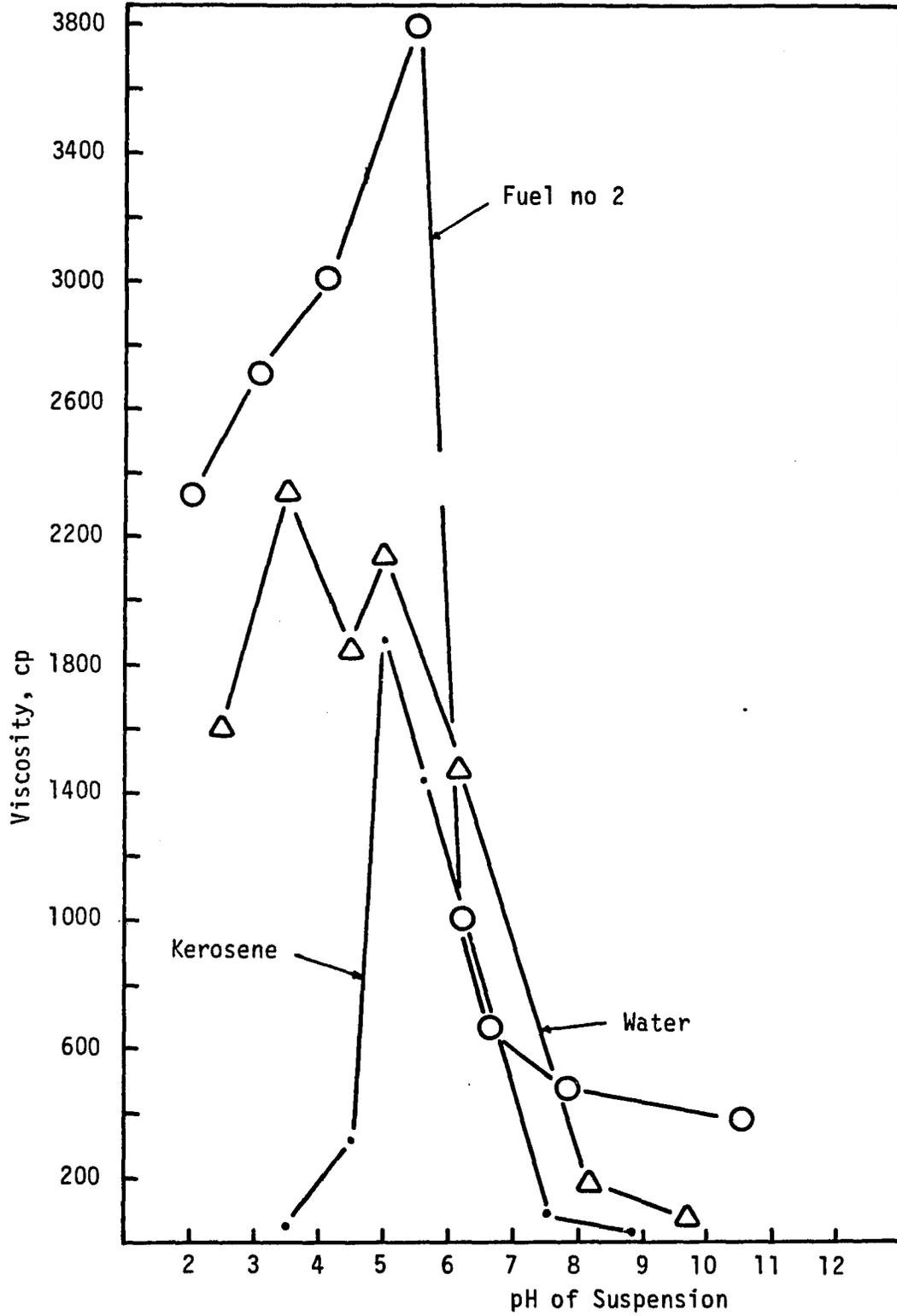


Figure IV-1a: Viscosity of coal slurries vs. pH

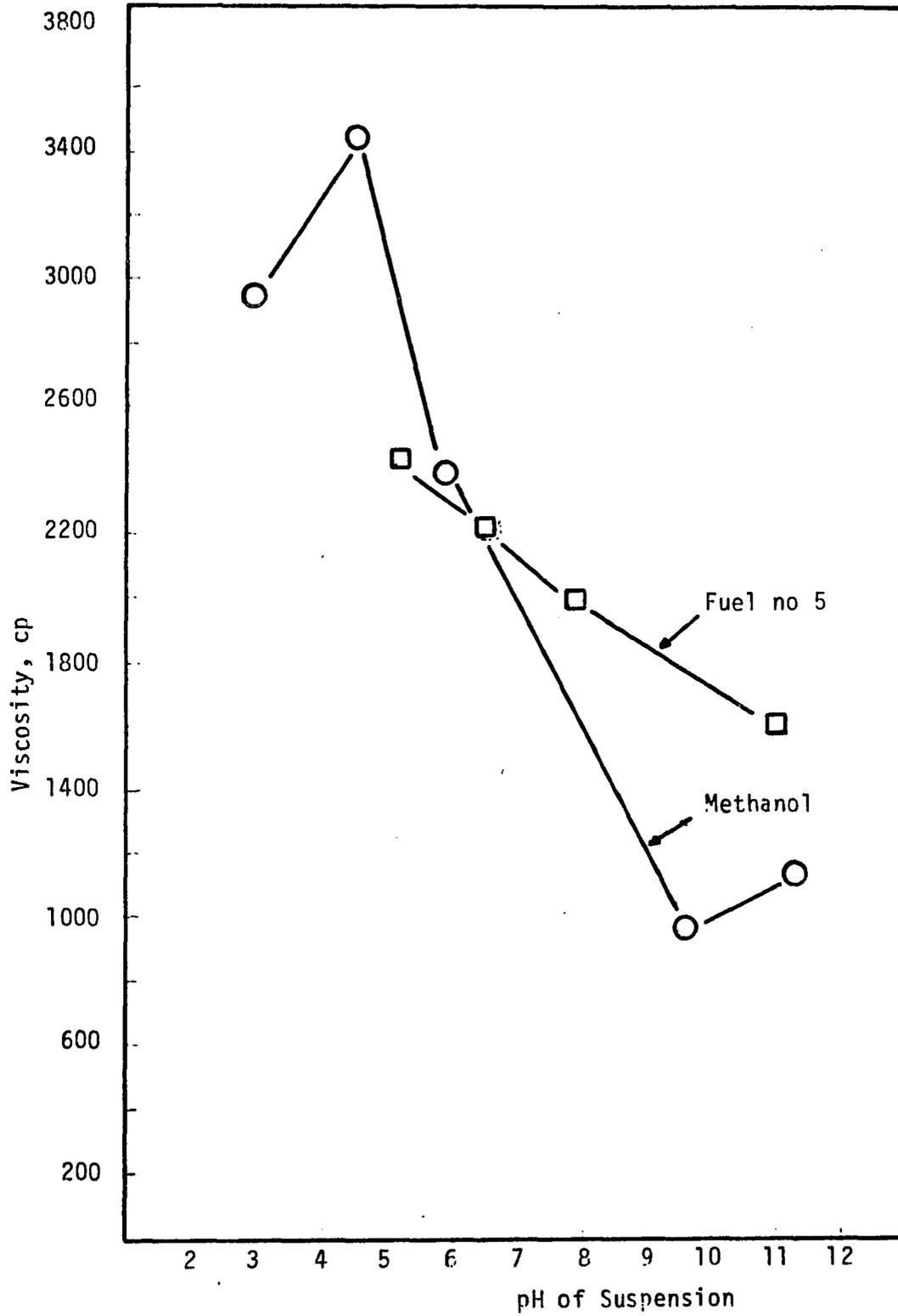


Figure IV-1b: Viscosity of coal-methanol and coal-fuel no 5 vs. pH

5 - 10 minutes of mixing. The experiments with methanol proved to be problematic, as the liquid evaporated very fast, leaving a crust of solids on the surface. It is, therefore, assumed that the experiments with methanol are less accurate than the others.

The results of the experiments as seen in Figures IV-1 a and b are not intended to compare the change in viscosity of the various coal suspensions, as the solids concentration is not constant and the viscosities of the carrier liquids vary, but to prove that the viscosity of CUMs and coal-water mixtures is a function of their pH, or in better words; the viscosity of coal suspensions can be significantly decreased by the addition of small amounts of base and could be increased when acid is added. The results of these experiments show that all suspensions exhibit a minimum viscosity around pH 8 - 10 and a maximum around pH 4.5 - 5.5. At pH higher than 10 the viscosity increases, and at pH lower than 4.5 it decreases.

During the experiments it was also noticed that the change in viscosity is completely reversible. Traces of acid are neutralized by base and vice-versa. As the phenomenon occur similarly in various organic fluids and in water, it seems reasonable to assume that it is a consequence resulting from a property of the coal. Experiments with Texas lignite and Beulah lignite prove this assumption. While Beulah lignite coal suspensions behave similarly to Utah bituminous, when treated with additives, while Texas lignite suspensions are less susceptible to changes in their viscosity. The experiments with Texas lignite show only a small change in the viscosity of its suspensions when

acid and base are added. Nevertheless the phenomenon is noticeable with all the types of coal tested.

The experiments employed to demonstrate reduction of drag by the addition of acid or base were crude and possibly subject to experimental error; however, the phenomena of drag reduction in suspensions of organic fluids and coal is obvious, and it has been not previously reported.

While the dependence on pH of flow properties of coal-water suspensions was reported earlier (1970) by Elliot and Gliddon, they did not discuss its significance. Elliot and Gliddon attributed this phenomenon to a reaction of clay (present in small amounts in coal), resulting in the formation of surfactants, which change the flow properties of the mixture. This hypothesis is not backed by any experiments or other proof, and seems to be highly improbable. The surfactants lower the pressure drop only in turbulent flow, while our experiments were conducted in laminar flow.

Another way to explain this phenomena is based on the porous structure of the coal. As the coal is porous and the addition of acid or base changes the surface tension of the suspensions, it seems possible that the alteration of the flow properties results from the adsorption of the fluid into the porous particles of coal. As the coal particle absorb more liquid, they become more buoyant, and simultaneously, there is less interparticular fluid. However, this hypothesis is also highly improbable. The change in the surface tension due to the additives is small, and the liquid able to enter into the pores would be negligible. Even if the liquid adsorbed would have significantly lowered the density

of the particles, the resulting reduction in viscosity would have been much lower than observed. Also, we should have noticed a difference between the hydrocarbon liquids and the water suspensions, but we do not. As this hypothesis cannot explain at all the increase in viscosity at high pH and the decrease at low pH, we had to look for another explanation.

The viscosity alteration due to electrolyte additives can be explained by taking into account the surface structure of the coal. The fact that the viscosity of slurries changes due to electrolytes addition only at high solids concentration and the similarity in the curves of the viscosity change versus pH in water and in organic liquids imply that this phenomenon is caused by electroviscous forces between the particles. It is known that coal surface is a mosaic of charged sites. The density of the sites depends on the coal type. This explains the difference in viscosity change due to electrolyte addition observed in suspensions of various types of coal.

Electrolytes in coal suspensions influence the attractive and the repulsive forces between the particles. Base added to coal suspensions is adsorbed on the coal surface and increase the alike potential charge. The repulsive forces between the particles are stronger and the particles try to stay as far apart from each other as possible to minimize the energy of the system. The particles form a network structure, which prevents them from settling on one hand, and increase the fluidity of the mixture on the other hand. When excess base is added, the coal surface reaches a saturation point, resulting in an increase of the attractive

forces between the particles. When acid is added to a coal suspension the attractive forces between the particles increase. Maximum viscosity is attained when the maximum attractive forces between particles are reached. Similar to base addition, when excess acid is added the repulsive forces are increased. The theory will be further discussed in details after more experiments are presented.

Suspension Flowing in a Pipe

In laminar flow liquids exhibit a different resistance to force exerted on them, than in turbulent flow. In laminar flow, layers of liquid past one another, and the friction between them comprise the overall viscosity of the liquid. In turbulent regime the bulk liquid flows in a plug flow pattern and the friction is reduced to a narrow layer adjacent to the wall. Thus, as the resistance to flow is not uniform throughout the whole medium, it is not a univalent function of the fluid characteristics. The effective viscosity calculated from measurements of energy dissipation in turbulent flow is always smaller than in laminar flow.

Homogeneous liquids in laminar regime are described mathematically by a simple equation of motion where the viscosity is either constant or has a simple mathematical dependency on other properties of the fluid. In turbulent flow the effective viscosity is not a simple function, thus the resistance to flow must be investigated at different shear rates. Therefore, in this report the coal suspension in turbulent flow were investigated at various conditions. Pressure drop was measured as a function of the volumetric flow rate at different solid

concentrations as described in the previous chapter.

A sample of the results is presented in Table IV-2; the remaining data are presented in Appendix B. Pressure drop of a 45 lb Utah Bituminous coal and 70 liter of water in suspension was measured at velocities from 132 cm/sec to 50 cm/sec. All measurements were taken at room temperature 27 ± 1 °C after at least one hour of vigorous mixing. The Reynolds number calculated for water at the same conditions, was in the range of 12,000 - 42,000. Other results are presented in Figure IV-2 where the pressure drop was measured with coal suspensions at solids concentration of 0 - 40%. The volumetric flow rates were measured from 100 cm³/sec to 700 cm³/sec, which translate to flow velocities range between 20 cm/sec to 140 cm/sec. The results are presented in figures rather than in tables as they are more concentrated and the comparison becomes more obvious.

From the results summarized in Figure IV-2 it is obvious that up to 27% solids concentration, the pressure drop is only slightly higher than that of pure water. At higher concentrations the pressure drop increases rapidly, such that at 36% solids concentration the pressure gradient is already several times that of pure water. Nevertheless at high velocity, the pressure gradient of suspensions with high solids concentration approach that of pure water as seen in cases of 29.3% and 31.7% solids concentrations.

TABLE IV-2:

Sample of Experimental Results
22.6% wt. Coal Suspension Flowing in 1" Pipe.

| Pressure Drop inches water | Time for 10 liter to flow in seconds | | | | | Flow Rate cm ³ /sec | Flow Velocity cm/sec |
|-------------------------------|---|-------|-------|-------|-------|-----------------------------------|-------------------------|
| | T1 | T2 | T3 | T4 | T5 | | |
| 62 | 15.1 | 14.9 | 15.0 | 15.9* | 14.7* | 671.14 | 132.42 |
| 57 | 16.6* | 15.7 | 15.1* | 15.5 | 15.5 | 642.40 | 126.78 |
| 55 | 15.5 | 15.7* | 15.3* | 15.4 | 15.4 | 647.95 | 127.87 |
| 50 | 16.5 | 16.2* | 16.8* | 16.5 | 16.4 | 607.29 | 119.85 |
| 46 | 16.8 | 17.1* | 16.9 | 16.5* | 16.8 | 594.06 | 117.24 |
| 42 | 17.4 | 17.3 | 17.2 | 17.5* | 17.2* | 578.03 | 114.08 |
| 40 | 18.3 | 17.6* | 18.0 | 18.4* | 18.3 | 549.45 | 108.44 |
| 36 | 19.2 | 19.2 | 19.3* | 19.1* | 19.1 | 521.74 | 102.97 |
| 32 | 20.1 | 20.1 | 20.5* | 20.0* | 20.1 | 497.51 | 98.19 |
| 30 | 20.5* | 21.1* | 21.0 | 20.8 | 20.9 | 478.47 | 94.43 |
| 28 | 21.3* | 21.7 | 21.8 | 21.8 | 21.9* | 459.42 | 90.67 |
| 25 | 22.7* | 22.6 | 22.5* | 22.6 | 22.6 | 442.48 | 87.32 |
| 22 | 24.8* | 24.8 | 24.4* | 24.6 | 24.7 | 404.86 | 79.90 |
| 17 | 26.3 | 26.5 | 26.2* | 26.4 | 26.7* | 387.79 | 74.75 |
| 13 | 29.4 | 29.6 | 29.7* | 29.6 | 29.3* | 338.60 | 66.82 |
| 9 | 33.2* | 32.2 | 32.9 | 32.3 | 32.2* | 307.69 | 60.72 |
| 5 | 39.8 | 40.6* | 40.5 | 40.0 | 39.7* | 249.38 | 49.21 |

* These results were not considered

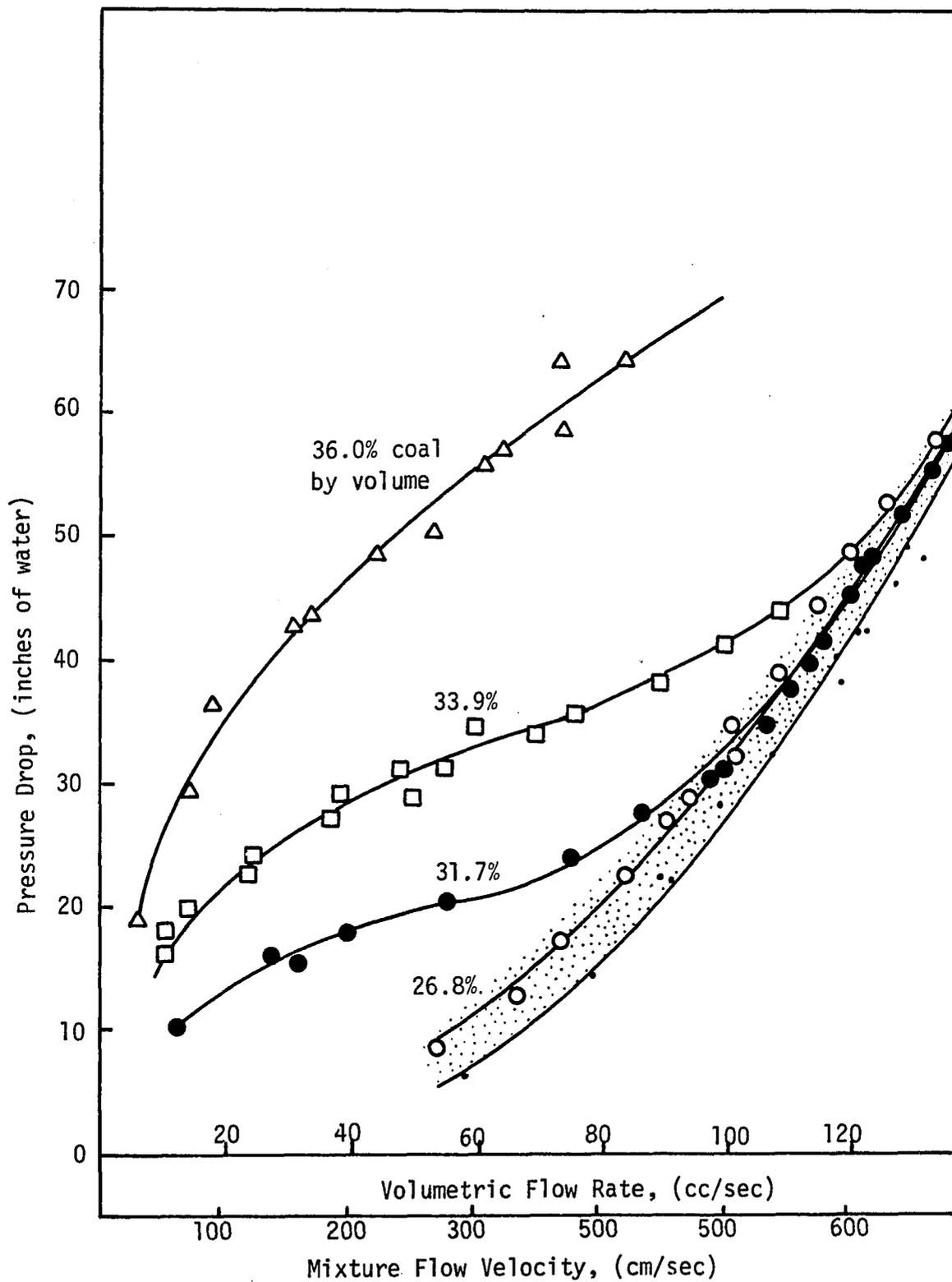


Figure IV-2: Pressure drop of coal- water slurries at different solid concentrations as a function of flow rate.

Processing this data and presenting them in Figure IV-3 as a graphic function between the shear stress and the volumetric flow rate, the relation between them becomes clearer. Again, up to 27% solids, the shear stress and the flow rate are similar to those of water. At high shear stress all suspensions approach the flow rate of pure water. As the velocity decreases, each concentration at a different loci departs from the water curve and the velocity drops rapidly as a linear function of the shear stress on a log-log plot. The shear stress at the wall, in our case, is of the form:

$$\tau_w = \frac{\Delta PR_o}{2L} + \tau_o$$

As we could not evaluate R_o and τ_o , we evaluated the shear stress at the wall as if the flow was laminar and Newtonian.

$$\tau_w = \frac{\Delta PR}{2L}$$

where R is the radius of the pipe.

Thomas (1961) had presented similar results in kaolin suspensions with concentrations of 6.9 - 15.4% of thorium oxide particles. Thomas assumed that the linear relationship on a log-log plot between the shear stress and the apparent shear rate results from laminar flow of the suspensions. At high flow rates when the curves become parallel to the water curve, the suspensions flow becomes turbulent. The transition loci between laminar flow and turbulent flow in the same system depends only on the solid concentration and the magnitude of the shear stress.

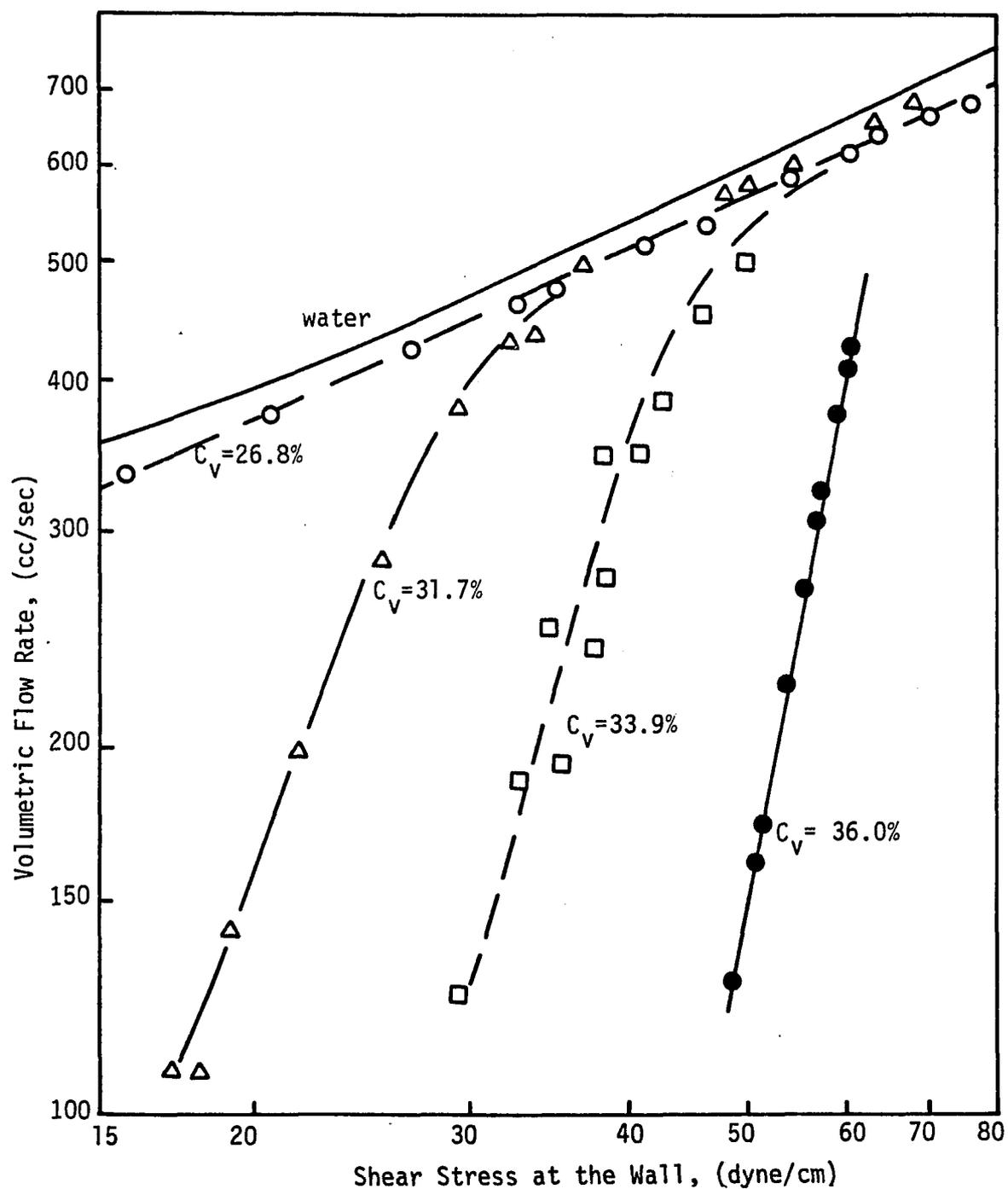


Figure IV-3: Volumetric flow rate of coal-water slurries versus shear stress at different coal concentration.

This conclusion reached by Thomas is proved also by our experimental results.

Chemical Additives

The effects of additives on the rheology of suspensions, visible in the viscometer tests were investigated also in the suspension flowing system. A suspension of 95 lb coal and 70 liters water was prepared in the recirculation tank, and measurements of pressure drop at different flow rates were taken. Addition of 65 grams Sodium Hydroxide pellets raised the pH from 6.6 to 9.4 - 9.5 reducing the pressure gradient substantially. Titrating the solution with 100 cc 33% Hydrochloric Acid neutralized all the base added, reducing the pH to 6.9. Additional 50 cc portions of acid lowered the pH by 0.4 - 0.2. The results of this experiment are presented graphically in Figure IV-4. The results show an obvious increase in the pressure drop as the acidity of the suspension increases.

Presenting the results as the relation between flow rate and the shear stress at the wall (the power exerted on the suspension) in Figure IV-5, the relation between them becomes clearer. All suspensions approach the flow rate of water at high shear stress. At lower shear stress the curves depart from the water line rapidly, each suspension at a different place, depending on its pH. As the pH decreases the departure from the water curve occurs at larger shear stress, in a similar fashion with the increase in solids concentration in the previous experiments. In this region the relation between flow rate and shear stress is linear on a log-log plot, which hints that in this region the flow might be laminar.

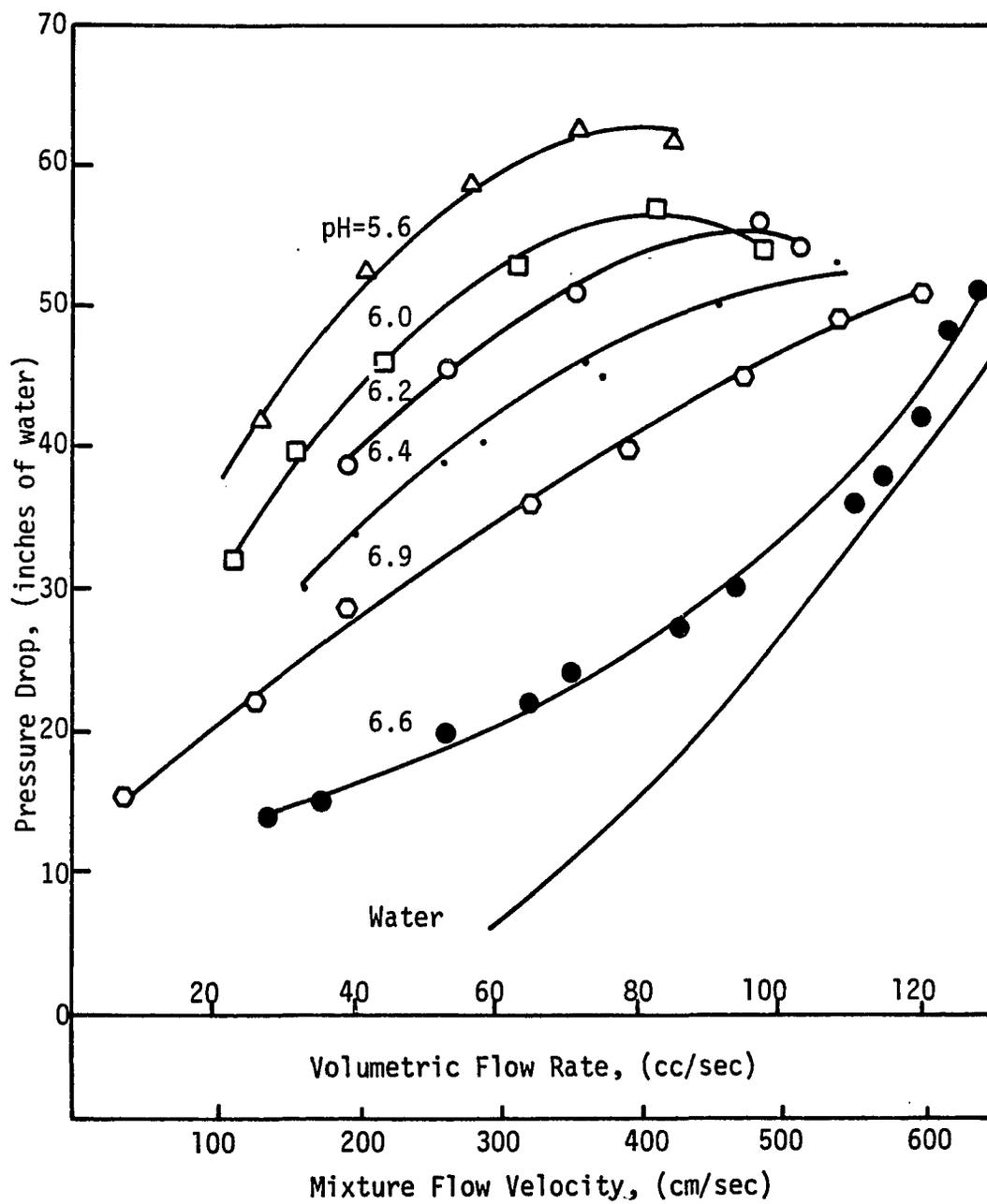
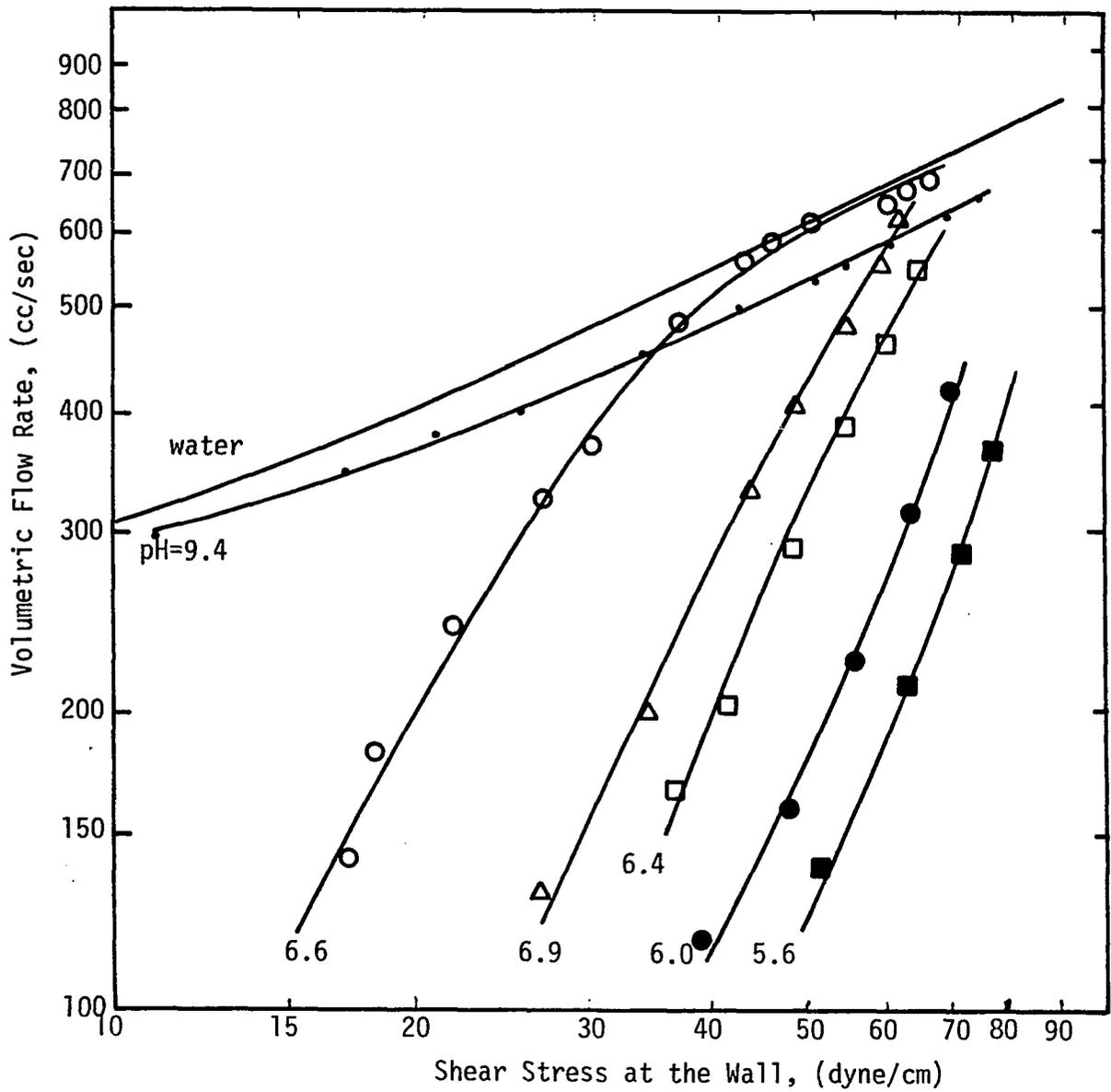


Figure IV-4: Pressure gradient of coal-water slurry at different pH after addition of acid.

Figure IV-5: Volumetric flow rate of coal-water slurries versus shear stress after addition of acid.



As the pH increases even at low shear stresses the curves become more parallel to that of water, meaning a turbulent flow. The phenomena will be further explained after the next experiment is presented.

The effect of addition of sodium hydroxide (NaOH) to a 41.57% solids - coal water suspension was investigated in the same apparatus. The suspension was prepared from 60 liters water and 125 lb coal in the recirculation tank. Small amounts of base were added and the pressure drop was measured at velocities of 10 - 135 cm/sec. The standard suspension has a pH of 6.6. A concentrated solution prepared from 125 grams of sodium hydroxide pellets was added to the slurry in 7 equal portions, resulting in a final pH of 8.1. Later, amounts of 25 grams of NaOH pellets were added and part of the results are summarized in Figure IV-6 and in Figure IV-7.

The pressure gradient along the pipeline as presented in Figure IV-6 increases first up to pH 7.3 - 7.5. At higher pH, the pressure gradient decreases until at pH 8.1, it becomes similar to that of the standard suspension. Significant reduction in the pressure drop occurs at higher pH, as seen in Figure IV-7. The pressure gradient reaches a minimum at the pH of 8.8, after which it begins increasing again. Not all the results were plotted to avoid crowding and confusion.

At slow velocities the reduction in pressure drop due to the base addition is 3 - 4 times compared to the standard solution. For example the standard suspension at 20 inches of water pressure drop has a flow rate of 15 cc/sec, while the same suspension at pH of 8.8 has a flow rate of 67 cc/sec. At high velocities all the pressure drop curves approach

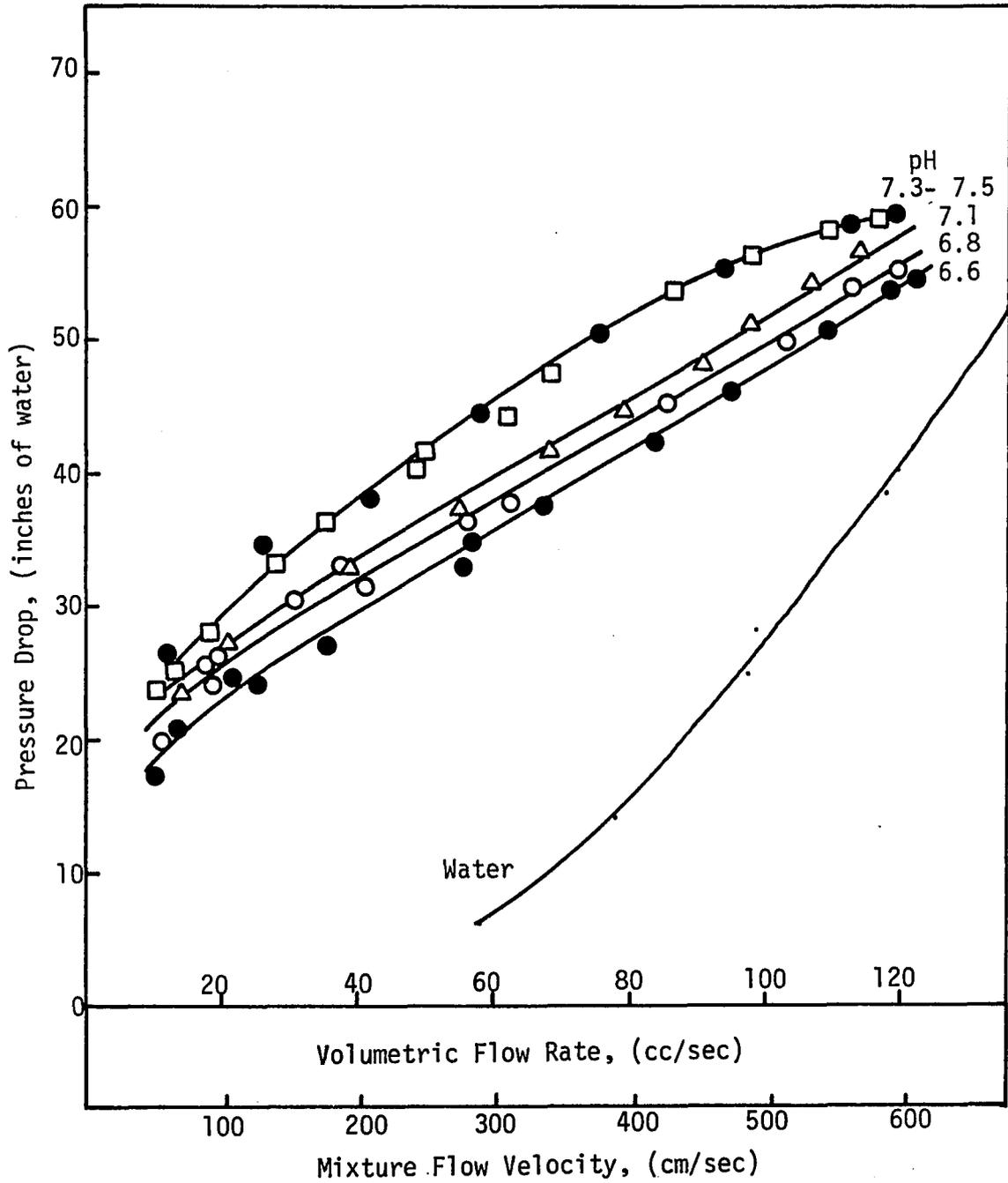


Figure IV-6: Pressure gradient of coal-water slurry after addition of base, up to pH of 7.3-7.5.

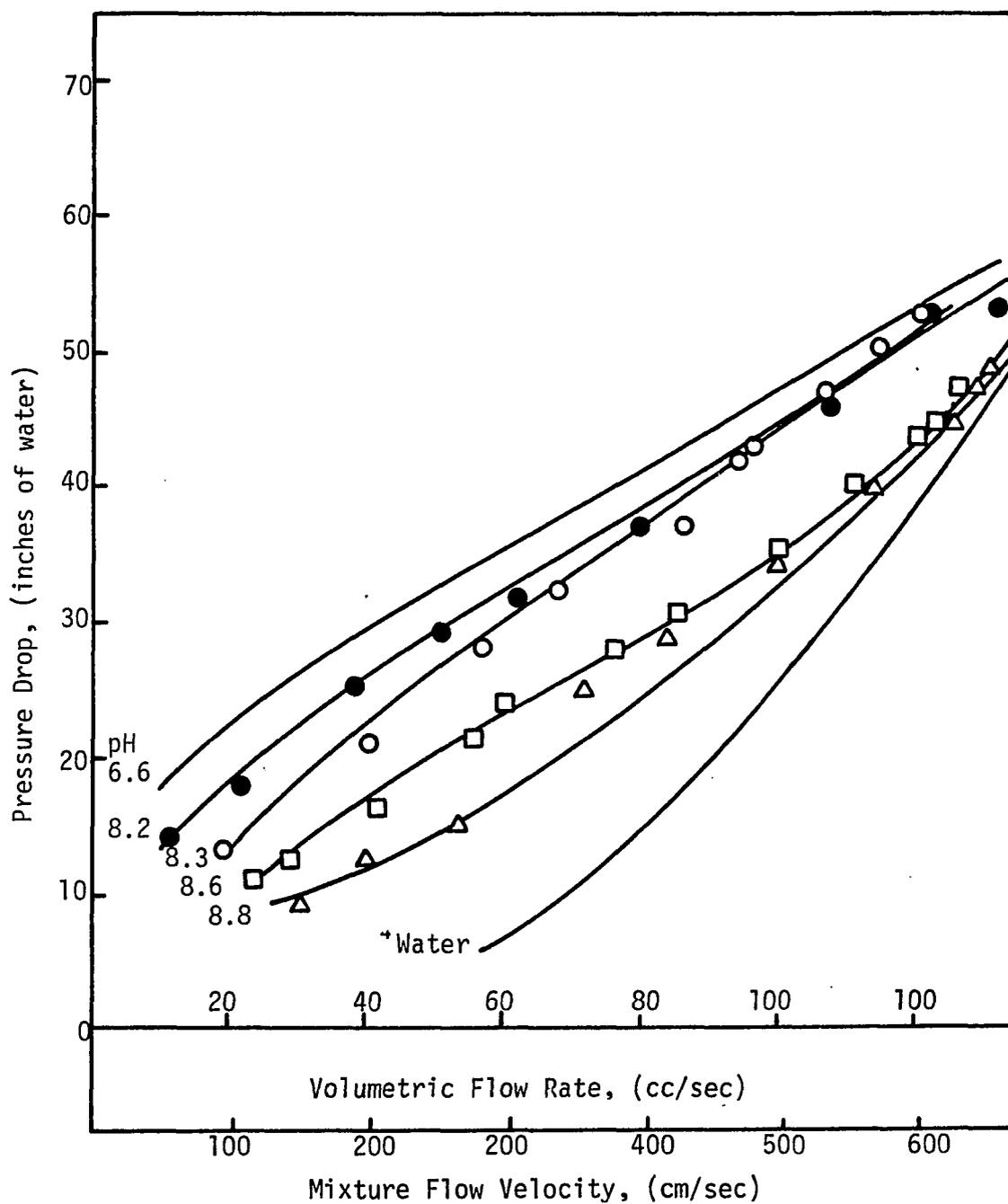


Figure IV-7: Pressure gradient of coal-water slurry after addition of base, at high pH.

the curve of pure water. The effect of drag reduction seems even more impressive when the flow rate is plotted versus the wall shear stress on a log-log plot in Figure IV-8.

The results in Figure IV-8 show that the flow rate decreases when the Sodium Hydroxide is added, up to pH 7.3 - 7.5. A significant increase in flow rate is obtained as the suspension approaches pH 8.8 after which the flow rate decreases again. As the pH approaches 8.8 the curves approach the curve of pure water, therefore we must assume that the flow becomes more turbulent while at lower pH the suspension flows in a laminar regime. The laminar flow regime is hinted in this graph also by the linear relation between the shear stress and the flow rate on the log-log plot. From the above results, the logical conclusion is that the additives work as turbulence suppressor and enhancer which causes the change in the pressure gradient.

As explained before, small particles in suspension have a tendency to aggregate due to the van der Waals attractive forces between them. Particles in suspensions are frequently stabilized by layers of solvent molecules which cover the surface of the particles and prevent aggregation. Dispersions are stabilized also by repulsive interactions between similarly charged electrical double layers surrounding the particles. These electrical charges can result from the surface configuration of the particles or the characteristics of the fluid. Thus, the coal particles surface, which consists of a mosaic of negative and positive sites, but is mainly hydrophilic can easily attract the water molecules. The ratio between the positive and the negative sites depend

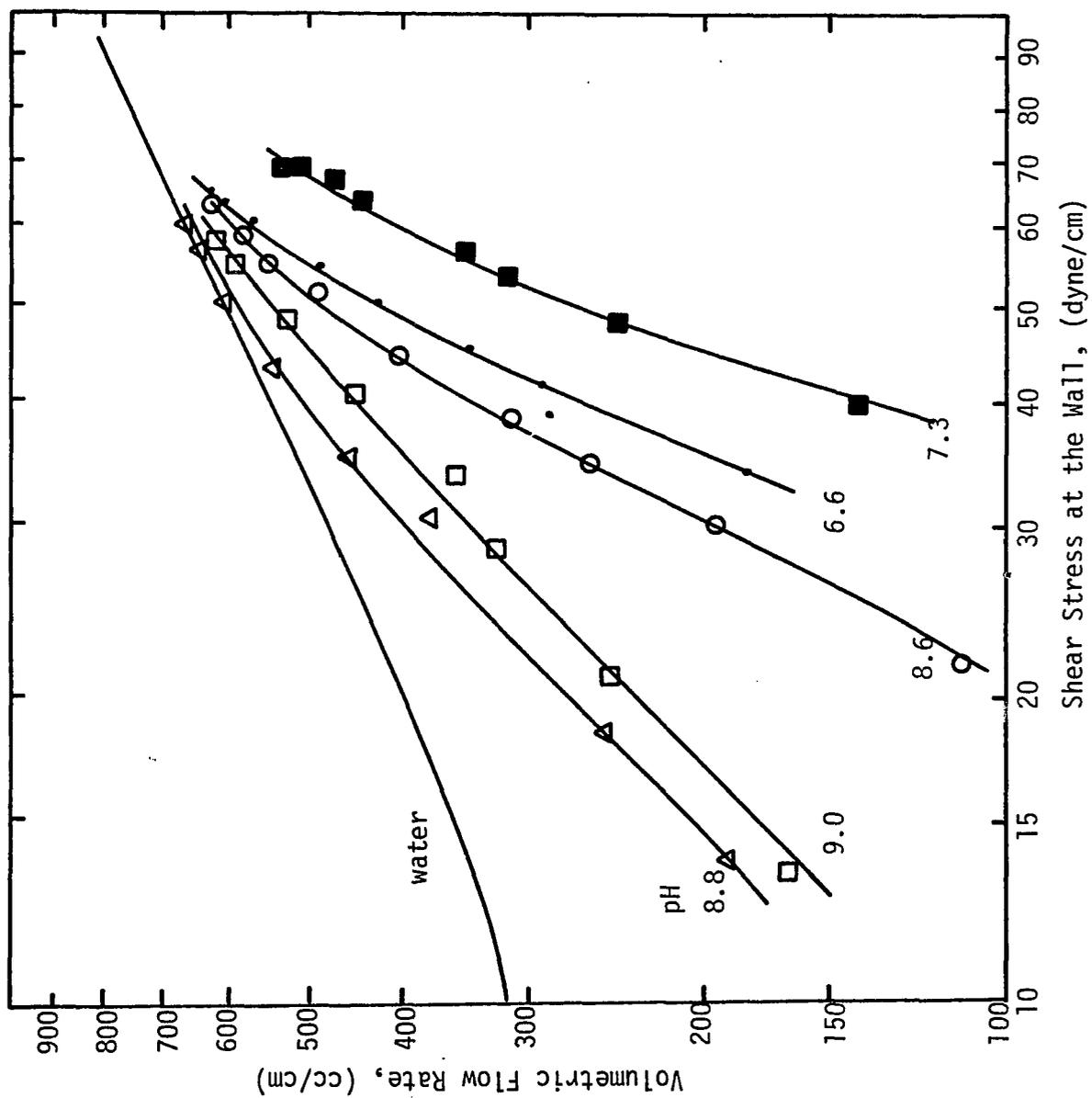


Figure IV-8: Volumetric flow rate of coal-water slurries versus shear stress after addition of base.

on the amount of impurities the coal contains and on the type of coal. Depending on the concentration ratio of charged sites, fluids may be attracted to the active sites, thus preventing the aggregation of the coal particles.

The effect of a surfactant on the stability of a dispersion, according to the DLVO theory is limited to its effects on the surface potential of the dispersed particles, the effective Hamaker constant and the ionic strength of the dispersing fluid. The main effect of a ionic surfactant is on the surface potential of the dispersed particles. The addition of an ionic surfactant to a dispersion with similarly charged particles increases the stability of the dispersion, whereas its addition to an oppositely charged particles destabilized the dispersion. Furthermore, the adsorption of the surfactant may change the contact angle of the particles with the dispersing liquid. A decrease in the contact angle may increase the dispersability and vice versa.

The stabilization of suspensions can be increased or decreased by relatively small amounts of ions that hydrate easily. The addition of electrolytes can cause the compression of the electrically charged double layers surrounding the particles. This would lower the energy barrier to coagulation, and as in our case the addition of acid would promote the particles' settling. Alternatively, a small amount of base could stabilize the coal suspension by specific adsorption on the particle surface. In addition to the charge concentration and the zeta potential of the particles other parameters which could influence the suspension stability are the size and the shape of the dispersed particles, the

distance between them, their surface potential, and the ionic strength and the dielectric constant of the dispersing liquid.

The total potential energy of interaction between particles include the scalar summation of the attractive van der Waals forces and the repulsive forces. The total potential energy of interaction is a function of the distance from the particle surface. This function depends on the ratio of the particle size to the thickness of the electrical double layer, the electrolyte concentration and the surface potential. When the electrolyte is adsorbed onto the particle surface the potential at the Stern layer increases as in the case of base addition. The repulsion between the particles is increased and a minimum in the total energy of the system is achieved by the formation of a network between the particles.

The network formation between the particles suppresses turbulence, causing at the same time a plug flow, thus reducing the power required to transport the slurry. This effect is observed only at high solids concentrations when the interactions between the particles become important. Therefore, by reducing the power wasted on turbulence, the flow of coal suspensions will show an anomaly in their expected behavior and at the same shear stress could show similar flow rate to that of the pure liquid, or even lower (at high shear stress).

The formation of a network between the particles in slurries was observed by visual experiments through a microscope. Standard coal slurries and dispersions treated with acid and with base were prepared on microscope slides, and their configuration was noticed. The base treated

coal slurry formed a network of particle throughout the whole sample, while in the acid treated sample the coal particles tended to agglomerate. The standard suspension appears to behave similarly to the acid treated sample, but the agglomeration rate is slower. The samples were photographed through the microscope and the pictures are presented in Figures IV-9 - IV-11.

The formation of the network between the coal particles is proven also by visual experiments on the rate of settling of coal slurries samples. The samples of standard coal slurry and acid and base treated dispersions were prepared as described in the previous chapter. The settling rate of the coal particles was noticed to differ significantly. The sample treated with acid began settling immediately, while the base treated sample did not begin to agglomerate until much later. The standard suspension began settling after the acid treated sample, but a long time before the base treated suspension. This experiment proves also that the coal particles could be induced to remain dispersed in a liquid, opposing the gravity force, by an ionic surfactant. The surfactant, in this case a base is adsorbed onto the coal particles and promotes the formation of a network configuration throughout the dispersion. Thus, the total energy of the system achieves a minimum by increasing the stability of the dispersion. The settling rate of the coal slurry is visible in Figures IV-12 through IV-16.

Conclusions

Although rheological studies of dispersions have been conducted for years, the multitude of parameters governing the flow, the diversity

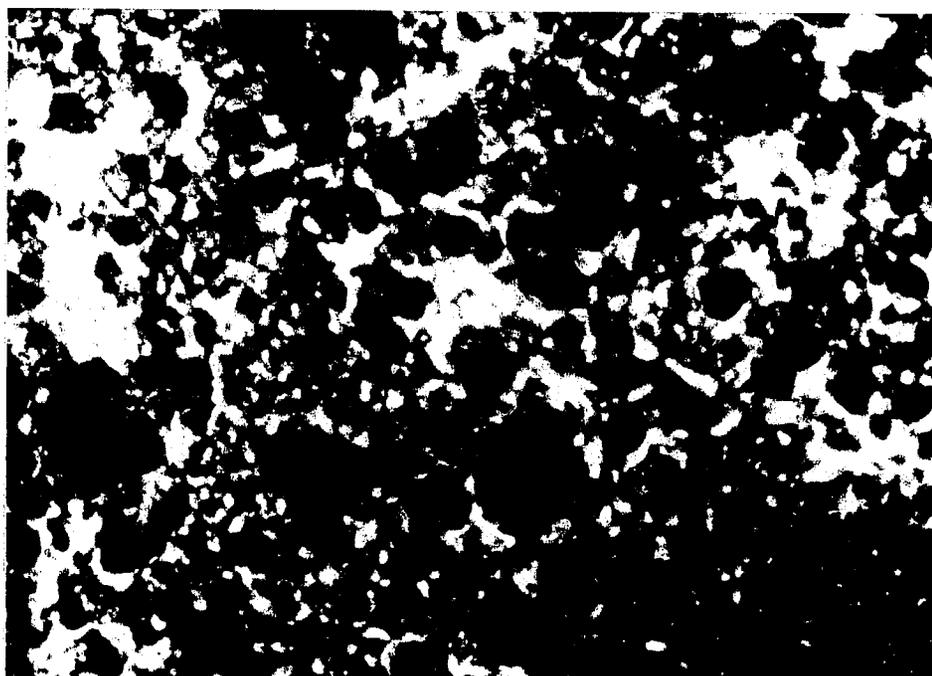


Figure IV-9: Photomicrograph of acid treated coal-water suspension (magnification 160)

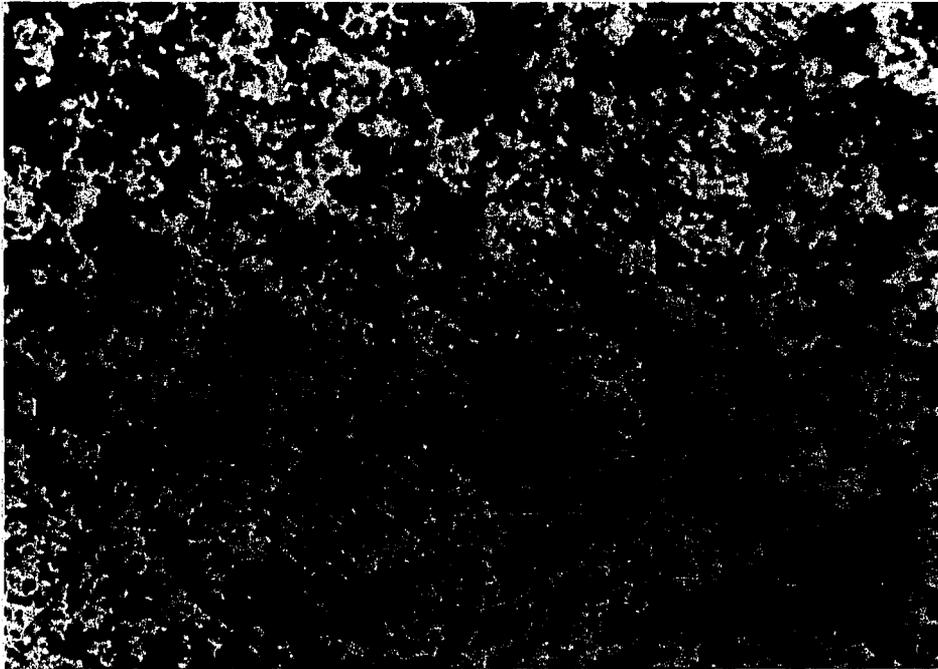


Figure IV-10: Photomicrograph of base treated coal-water suspension (magnification 160)

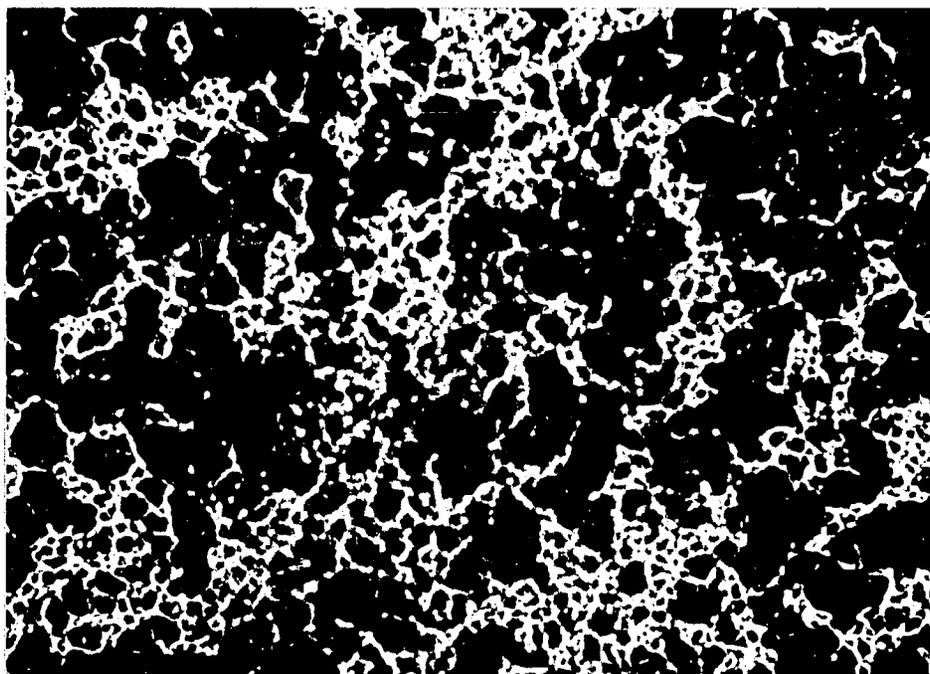


Figure IV-11: Photomicrograph of standard coal-water suspension (magnification 160)



Figure IV-12: Photograph of coal-water suspension settling in glass beaker (1 hour after mixing)



Figure IV-13: Photograph of coal-water suspension settling in glass beaker (2 hours after mixing)



Figure IV-14: Photograph of coal-water suspension settling in glass beaker (3 hours after mixing)



Figure IV-15: Photograph of coal-water suspension settling in glass beaker (4 hours after mixing)



Figure IV-16: Photograph of coal-water suspension settling in glass beaker (6 hours after mixing)

in the behavior of various couples of solids and liquids, and the great importance of impurities even in minute amounts on the rheological properties of suspensions limited the research to a few simple systems. The rheological behavior of coal slurries has been limited to scale-up operations required for the design of coal slurry pipelines. Related research on drag reduction was conducted successfully by the petroleum industry, but in general the drag reduction research on coal water and on coal oil dispersions has been scarce.

This study intended to investigate rheological properties of coal-water and coal-oil slurries. The results of the study are summarized as follows:

1. The viscosity of coal slurries is slightly higher than the viscosity of the carrier fluid up to solids concentration of 25 - 27% (average particle size - 45μ).
2. At higher concentration of coal the viscosity of the slurries increases rapidly.
3. At high shear stress, the flow rate of coal slurries approaches the flow rate of the carrier fluid.
4. At low shear stress, the flow rate versus shear stress curve departs from the curve of the pure fluid, and for each solids concentration a new curve is formed. These curves drop rapidly parallel to each other.
5. Although other research proved that the flow of slurries is a plug flow, the turbulence of the dispersions is reduced and behaves similarly to laminar flow systems.

6. Surfactants such as strong bases and strong acids have a great influence on the coal slurries behavior at high solids concentration. The base lowers significantly the pressure drop at the same flow rate while the acid increases the pressure drop.
7. Visual experiments prove that base promotes the formation of a network of particles, increasing the stability of the dispersion. It is believed that the network configuration reduces turbulence, thus reducing the power required for transporting the slurry.
8. Acid promotes the aggregation of coal particles, faster than regular slurries.
9. It is believed that both the acid and the base are adsorbed onto the coal surface and change its surface potential. The change in zeta potential of the particles is responsible for the alterations in the rheological properties of coal slurries.

The understanding of coal slurries rheology should be further pursued by more sophisticated research. Systems which can monitor the movement of particles independently from the flow of the liquid, the investigation of the transition zone between true laminar flow and plug flow with reduced turbulence, and testing of various types of coal would give a more comprehensive understanding of coal slurry rheology. Additional research on the surface chemistry of coal treated with surfactants and especially the zeta potential of particles could

enlighten the phenomenon of surfactant influence on rheology of dispersions.

As the use of coal is expected to increase more rapidly than in the past, to partially replace the depleting petroleum, it is important to offer the market the alternative of coal as a fuel, which can be handled cleanly, inexpensively, and without major changes in today's technology; coal slurries could be part of the answer.

APPENDIX A
ADDITIONAL INFORMATION

TABLE 1
ANALYSIS OF COALS

Analysis of Three Coals

| | (Weight Percent) | | |
|----------------------|------------------|-----------------------------|------------|
| | Utah Bit. | Beulah Lig. (low sodium) | Texas Lig. |
| Proximate | | | |
| Volatile Matter | 40.6 | ---- | 29.5 |
| Fixed Carbon | 44.3 | ---- | 25.6 |
| Moisture | 5.6 | 20.0 | 26.7 |
| Ash | 9.4 | 10.8 | 18.2 |
| Ultimate (dry basis) | | | |
| Carbon | 70.0 | 60.9 | 52.2 |
| Hydrogen | 5.1 | 3.0 | 3.4 |
| Sulfur | 1.0 | 3.4 | 3.2 |
| Nitrogen | 1.2 | 0.9 | 0.8 |
| Oxygen | 12.7 | 16.5 | 15.5 |
| Ash | 10.0 | 15.3 | 24.8 |
| HHV (Btu/lb) | 11650 | 10160 | 8979 |

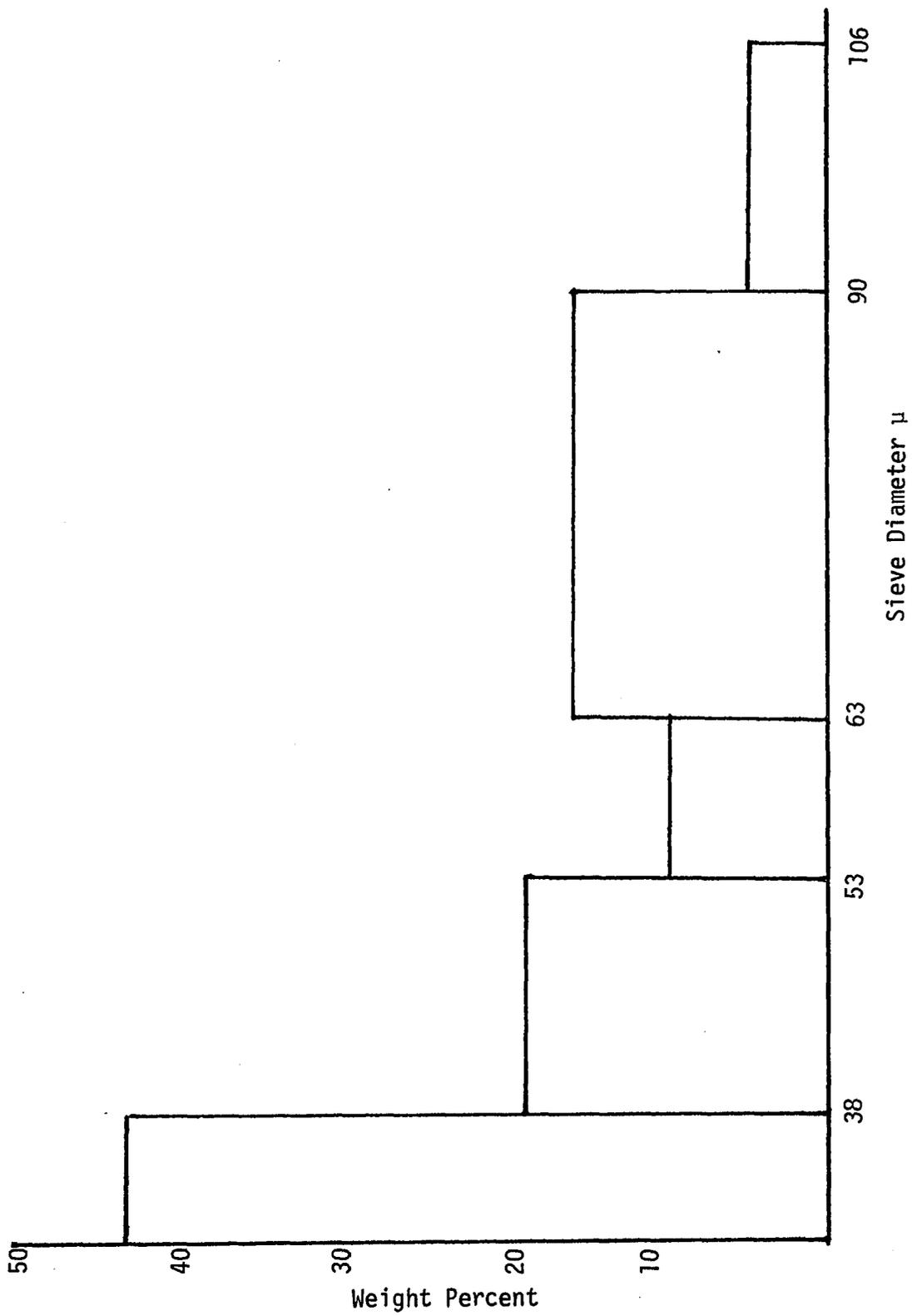


Figure A 1: Particle size distribution of Utah Bituminous coal

APPENDIX B
SUMMARY OF SELECTED DATA

TABLE 1

VISCOSITY CHANGE IN COAL-WATER SUSPENSIONS DUE
TO ACID AND BASE ADDITION

Coal: Utah Bituminous
Concentration: 53.9% by weight
47.5% by volume
Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|-----|----------------|
| 6.6 | 1180 |
| 6.1 | 1478 |
| 8.2 | 185 |
| 9.6 | 75 |
| 5.0 | 2145 |
| 4.5 | 1850 |
| 3.0 | 2330 |

TABLE 2

VISCOSITY CHANGE IN KEROSENE-COAL SUSPENSIONS
DUE TO ACID AND BASE ADDITION

Coal: Utah Bituminous
Concentration: 60.0% by weight
42.95 by volume
Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|-----|----------------|
| 5.6 | 1338 |
| 7.5 | 89 |
| 8.8 | 44 |
| 5.0 | 1873 |
| 4.5 | 312 |
| 3.5 | 44 |

TABLE 3
 VISCOSITY CHANGE IN FUEL NO 2-COAL SUSPENSIONS
 DUE TO ADDITION OF ACID AND BASE

Coal: Utah Bituminous
 Concentration: 53.9% by weight
 42.3% by volume
 Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|------|----------------|
| 6.2 | 999 |
| 6.6 | 666 |
| 7.8 | 480 |
| 10.5 | 370 |
| 5.5 | 3807 |
| 4.1 | 2997 |
| 3 | 2702 |
| 2 | 2330 |

TABLE 4
 VISCOSITY CHANGE IN FUEL NO 5-COAL SUSPENSIONS
 DUE TO ACID AND BASE ADDITION

Coal: Utah Bituminous
 Concentration: 47.7% by weight
 38.6% by volume
 Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|-----|----------------|
| 5.2 | 2441 |
| 6.4 | 2234 |
| 7.8 | 1998 |
| 11 | 1591 |

TABLE 5
 VISCOSITY CHANGE IN METHANOL-COAL SUSPENSIONS DUE
 TO ACID AND BASE ADDITION

Coal: Utah Bituminous
 Concentration: 45.5% by weight
 33.4% by volume
 Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|------|----------------|
| 5.8 | 2404 |
| 9.6 | 961 |
| 11.2 | 1147 |
| 4.5 | 3440 |
| 3.0 | 2960 |

TABLE 6
 VISCOSITY OF TEXAS LIGNITE COAL-WATER SUSPENSIONS
 AFTER ACID AND BASE TREATMENT

Coal: Beulah Lignite
 Concentration: 50.0% by weight
 Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|-----|----------------|
| 4.2 | 4271 |
| 4.5 | 4603 |
| 5.0 | 3815 |
| 5.6 | 2654 |
| 5.8 | 2215 |
| 6.0 | 2073 |
| 6.4 | 2114 |
| 6.8 | 2156 |
| 7.2 | 1990 |
| 7.5 | 2944 |
| 7.9 | 3359 |

TABLE 7
VISCOSITY OF BEULAH LIGNITE COAL=WATER SUSPENSIONS
AFTER ACID AND BASE TREATMENT

Coal: Beulah Lignite
Concentration: 50.0% by weight
Equipment: Brookfield Rheometer

| pH | Viscosity (cp) |
|-----|----------------|
| 5.2 | 5307 |
| 5.4 | 4478 |
| 5.6 | 4478 |
| 5.8 | 3649 |
| 6.0 | 2737 |
| 6.4 | 2820 |
| 6.5 | 3566 |
| 6.9 | 3815 |
| 7.0 | 3607 |
| 7.3 | 3898 |
| 7.6 | 2819 |
| 7.8 | 1990 |
| 8.0 | 1451 |
| 8.3 | 1327 |
| 8.4 | 1161 |
| 8.6 | 1119 |
| 8.8 | 995 |
| 9.0 | 1285 |
| 9.1 | 1451 |
| 9.2 | 1576 |

TABLE 8
PRESSURE DROP OF WATER

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 76 | 798 | 158 |
| 74 | 773 | 153 |
| 72 | 781 | 154 |
| 69 | 769 | 152 |
| 65 | 754 | 149 |
| 62 | 719 | 142 |
| 60 | 721 | 142 |
| 59 | 718 | 142 |
| 58 | 694 | 137 |
| 57 | 693 | 137 |
| 54 | 665 | 131 |
| 53 | 664 | 131 |
| 49 | 652 | 129 |
| 47 | 636 | 125 |
| 46 | 645 | 127 |
| 42 | 612 | 120 |
| 40 | 596 | 118 |
| 38 | 562 | 111 |
| 36 | 552 | 109 |
| 34 | 536 | 106 |
| 31 | 526 | 104 |
| 29 | 523 | 103 |
| 28 | 511 | 101 |
| 27 | 490 | 97 |
| 24 | 469 | 93 |
| 22 | 455 | 89 |
| 20 | 425 | 84 |
| 17 | 405 | 80 |
| 13 | 367 | 72 |
| 10 | 329 | 65 |
| 6 | 288 | 57 |

TABLE 9

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 8.9% by weight
6.8% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 69 | 796 | 157 |
| 64 | 769 | 152 |
| 60 | 735 | 145 |
| 56 | 709 | 140 |
| 51 | 682 | 135 |
| 48 | 653 | 129 |
| 41 | 607 | 120 |
| 39 | 592 | 117 |
| 36 | 565 | 112 |
| 31 | 522 | 103 |
| 26 | 482 | 95 |
| 24 | 468 | 92 |
| 21 | 446 | 88 |
| 16 | 392 | 77 |
| 14 | 375 | 74 |
| 10 | 330 | 65 |
| 6 | 274 | 54 |

TABLE 10

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 13.9% by weight
10.9% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 58 | 721 | 142 |
| 55 | 693 | 136 |
| 52 | 676 | 133 |
| 46 | 626 | 124 |
| 42 | 593 | 117 |
| 39 | 579 | 114 |
| 35 | 560 | 110 |
| 30 | 514 | 102 |
| 27 | 460 | 91 |
| 24 | 440 | 87 |
| 21 | 430 | 84 |
| 17 | 401 | 73 |
| 14 | 362 | 71 |
| 11 | 354 | 70 |
| 6 | 289 | 57 |

TABLE 11

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 22.6% by weight
18.0% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 62 | 671 | 132 |
| 57 | 642 | 127 |
| 55 | 648 | 128 |
| 50 | 607 | 120 |
| 46 | 594 | 117 |
| 42 | 578 | 114 |
| 40 | 549 | 108 |
| 36 | 522 | 103 |
| 32 | 498 | 98 |
| 30 | 478 | 94 |
| 28 | 459 | 91 |
| 25 | 442 | 87 |
| 22 | 405 | 80 |
| 17 | 379 | 75 |
| 14 | 339 | 67 |
| 9 | 307 | 61 |
| 5 | 249 | 49 |

TABLE 12

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 26.3% by weight
21.2% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 58 | 670 | 132 |
| 55 | 637 | 126 |
| 51 | 610 | 120 |
| 45 | 568 | 112 |
| 41 | 559 | 110 |
| 36 | 527 | 104 |
| 32 | 496 | 98 |
| 29 | 467 | 92 |
| 27 | 448 | 88 |
| 24 | 435 | 86 |
| 21 | 412 | 81 |
| 17 | 384 | 76 |
| 14 | 350 | 69 |
| 10 | 304 | 60 |
| 6 | 283 | 56 |

TABLE 13

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 29.6% by weight
24.1% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 62 | 679 | 134 |
| 58 | 654 | 129 |
| 54 | 640 | 126 |
| 51 | 622 | 123 |
| 48 | 613 | 121 |
| 46 | 602 | 119 |
| 44 | 598 | 118 |
| 39 | 573 | 113 |
| 33 | 502 | 99 |
| 30 | 483 | 95 |
| 27 | 458 | 90 |
| 22 | 420 | 83 |
| 18 | 399 | 79 |
| 15 | 358 | 71 |
| 12 | 337 | 67 |
| 9 | 299 | 59 |
| 6 | 262 | 52 |

TABLE 14

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 32.7% by weight
26.8% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 62 | 677 | 134 |
| 57 | 655 | 129 |
| 54 | 628 | 124 |
| 49 | 605 | 119 |
| 45 | 582 | 115 |
| 38 | 536 | 106 |
| 34 | 516 | 102 |
| 29 | 475 | 94 |
| 27 | 457 | 90 |
| 22 | 427 | 84 |
| 17 | 375 | 74 |
| 13 | 339 | 67 |
| 7 | 290 | 57 |

TABLE 15

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 35.5% by weight
29.3% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 60 | 664 | 131 |
| 58 | 659 | 130 |
| 53 | 645 | 127 |
| 49 | 610 | 120 |
| 48 | 602 | 119 |
| 42 | 580 | 114 |
| 35 | 528 | 104 |
| 33 | 518 | 102 |
| 30 | 489 | 97 |
| 25 | 468 | 92 |
| 22 | 444 | 88 |
| 18 | 424 | 84 |
| 14 | 382 | 75 |

TABLE 16

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 38.1% by weight
31.7% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 56 | 677 | 134 |
| 52 | 654 | 129 |
| 48 | 622 | 123 |
| 45 | 613 | 121 |
| 41 | 588 | 116 |
| 39 | 579 | 114 |
| 37 | 575 | 113 |
| 31 | 501 | 99 |
| 30 | 463 | 97 |
| 27 | 434 | 86 |
| 24 | 381 | 75 |
| 21 | 285 | 56 |
| 18 | 198 | 39 |
| 16 | 142 | 28 |
| 14 | 109 | 22 |
| 11 | 61 | 12 |

TABLE 17

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 40.5% by weight
33.9% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 48 | 621 | 123 |
| 44 | 548 | 108 |
| 41 | 502 | 99 |
| 38 | 455 | 90 |
| 35 | 384 | 76 |
| 34 | 350 | 69 |
| 31 | 274 | 54 |
| 29 | 242 | 49 |
| 27 | 187 | 37 |
| 24 | 124 | 25 |
| 23 | 119 | 24 |
| 20 | 72 | 14 |
| 16 | 53 | 11 |

TABLE 18

PRESSURE DROP OF COAL-WATER SLURRY

Coal: Utah bituminous
Concentration: 42.7% by weight
35.9% by volume
Equipment: Recirculation system

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 64 | 426 | 84 |
| 59 | 374 | 74 |
| 57 | 322 | 64 |
| 55 | 310 | 61 |
| 50 | 268 | 53 |
| 48 | 225 | 44 |
| 44 | 172 | 34 |
| 42 | 159 | 31 |
| 36 | 93 | 18 |
| 30 | 75 | 15 |
| 20 | 33 | 7 |

TABLE 19
PRESSURE DROP OF A COAL-WATER SLURRY
TREATED WITH BASE OR ACID

Coal: Utah bituminous
Concentration: 38.1% by weight
31.7% by volume
Equipment: Recirculation system
pH: 6.7 (no additives)

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 55 | 670 | 132 |
| 52 | 656 | 130 |
| 48 | 633 | 125 |
| 42 | 609 | 120 |
| 38 | 581 | 115 |
| 35 | 564 | 111 |
| 30 | 482 | 95 |
| 28 | 437 | 86 |
| 25 | 360 | 71 |
| 22 | 327 | 64 |
| 20 | 269 | 53 |
| 16 | 193 | 38 |
| 15 | 182 | 36 |
| 14 | 142 | 28 |

TABLE 20
PRESSURE DROP OF A COAL-WATER SLURRY
TREATED WITH BASE OR ACID

Coal: Utah bituminous
Concentration: 38.1% by weight
31.7% by volume
Equipment: Recirculation system
pH: 9.4 (65 grams of NaOH)

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 61 | 644 | 127 |
| 57 | 611 | 121 |
| 50 | 575 | 114 |
| 42 | 528 | 104 |
| 35 | 488 | 96 |
| 28 | 443 | 87 |
| 21 | 393 | 78 |
| 18 | 377 | 74 |
| 14 | 348 | 69 |
| 9 | 299 | 59 |

TABLE 21
 PRESSURE DROP OF A COAL-WATER SLURRY
 TREATED WITH BASE OR ACID

Coal: Utah bituminous
 Concentration: 38.1% by weight
 31.7% by volume
 Equipment: Recirculation system
 pH: 6.0

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 54 | 501 | 99 |
| 56 | 468 | 92 |
| 57 | 418 | 82 |
| 52 | 316 | 62 |
| 46 | 222 | 44 |
| 39 | 159 | 31 |
| 32 | 117 | 23 |
| pH= 5.6 | | |
| 62 | 427 | 84 |
| 63 | 359 | 71 |
| 58 | 287 | 57 |
| 52 | 211 | 52 |
| 42 | 138 | 27 |

TABLE 21
 PRESSURE DROP OF A COAL-WATER SLURRY
 TREATED WITH BASE OR ACID

Coal: Utah bituminous
 Concentration: 48.6% by weight
 41.6% by volume
 Equipment: Recirculation system
 pH: 6.7 (no additives)

| Pressure Drop inches water | Flow Rate cc/sec | Velocity cm/sec |
|-------------------------------|---------------------|--------------------|
| 54 | 622 | 123 |
| 53 | 604 | 119 |
| 51 | 564 | 111 |
| 46 | 488 | 96 |
| 42 | 429 | 85 |
| 38 | 343 | 68 |
| 33 | 289 | 57 |
| 28 | 181 | 36 |
| 24 | 126 | 25 |
| 21 | 70 | 14 |
| 17 | 52 | 10 |
| pH= 8.2 | | |
| 52 | 621 | 123 |
| 49 | 574 | 113 |
| 46 | 544 | 107 |
| 43 | 490 | 97 |
| 37 | 407 | 80 |
| 32 | 316 | 62 |
| 29 | 262 | 52 |

TABLE 21 CONTINUE

| | | |
|---------|-----|-----|
| 25 | 196 | 39 |
| 18 | 111 | 22 |
| 14 | 59 | 12 |
| pH= 8.6 | | |
| 53 | 658 | 129 |
| 48 | 642 | 127 |
| 44 | 615 | 121 |
| 40 | 570 | 113 |
| 35 | 506 | 100 |
| 31 | 435 | 86 |
| 28 | 384 | 76 |
| 24 | 303 | 60 |
| 16 | 214 | 42 |
| 13 | 146 | 29 |
| 10 | 69 | 13 |
| pH= 8.8 | | |
| 50 | 662 | 131 |
| 47 | 647 | 128 |
| 42 | 616 | 122 |
| 36 | 541 | 107 |
| 29 | 453 | 89 |
| 26 | 369 | 73 |
| 16 | 251 | 50 |
| 12 | 190 | 38 |
| 6 | 119 | 23 |

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