Some Pumping Characteristics of Coal Char Slurries

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As part of the program sponsored by the Office of Coal Research for increasing coal markets, Project COED (Char Oil Energy Development) is aimed at 1) developing an economic process for upgrading coal energy by converting coal to an oil, a gas, and a fuel char, and 2) decreasing the delivered cost of coal energy (1). One possible method for lowering the delivered cost of coal energy is to transport the char in a slurry to market. The pumping of solid fuels in a slurry is not new. Consolidation Coal Company demonstrated the feasibility of pumping coal-water slurries in a 108-mile coal pipeline (2). Char from a COED plant could be conveyed either in a water or oil slurry. Alternately, the char could be pumped in a water slurry with intermittent slugs of COED oil. The objective of this study was to obtain preliminary data in order to evaluate the technical feasibility of transporting char in a pipeline as a slurry.

The viscosity of char slurries was measured to determine the effects of char loading and size distribution. This survey was followed by extensive testing in an experimental pipeline.

Slurry Material

Water and two different oils--mineral oil and a petroleum recycle oil--were used as slurry media. The latter oil was used because it was similar to the product oil from a COED plant. The viscosities of the two oils were 36 and 8 cp at 100°F.

The char used for the slurries was obtained from pyrolysis of Utah A-seam coal in a multistage fluidized-bed process developed under Project COED (1). Its properties are listed in Table I.

Initial Viscosity Measurements

A rotating-spindle viscometer, Brookfield Model RVT, was used in these studies. The depth to which the spindle was inserted into the slurry, the time required for the measurement, and the temperature of the slurry were duplicated for each test. Slurry viscosities were determined at 100°F.

For char loadings higher than 25 weight percent, the viscosities of the two char-oil slurries were nearly the same, although the viscosities of the pure slurry media differed by a factor of 3.5 (Figure 1). The viscosities for the water slurries were lower at the same solids concentration.

The size consist of the char has a large effect on the observed viscosity of the slurry. Size consists for eight slurries are shown in Table II. The size distributions have two distinct peaks. One occurs between 16 and 100 mesh, and the other below 325 mesh. The average particle size was changed by varying the relative size of these two peaks. Test No. 8 is different from the others in that a large proportion of plus 16-mesh char is present with little material between 48 and 325 mesh. This slurry had a viscosity of 184 cp, while the slurry in Test No. 4, which had the same average particle size, had a viscosity of 288 cp. Thus, a size distribution containing large and small particles, but no intermediate ones, may be desirable. This confirms the conclusions of Moreland (3) and Reichl (4).

Tests made on a 50 percent char-water slurry indicated that a minimum viscosity occurs when about one half of the char is minus 325-mesh material.

Some results of tests made employing different rotational speeds of the viscometer are given in Table III. These indicated that concentrated slurries exhibit non-Newtonian behavior. Further aspects of this non-Newtonian behavior will be discussed later.

Experimental Pipeline

A sketch of the pipeline used for testing the pumpability of char slurries is shown in Figure 2. The major components are:

1. A centrifugal pump with an open impeller and a 15 hp motor.
2. A 150-gallon slurry tank with an attached mixer for agitation.
3. A 55-gallon weigh drum for determining volumetric flow rates.
4. About 100 feet of 1-inch schedule 40 pipe arranged for recycle to the weigh tank or slurry tank.
5. Pressure-measuring devices consisting of diaphragm pressure seals, 6-inch dial gauges, and mercury manometers.

Known weights of char and slurry media were charged to the slurry tank and allowed to mix at least one hour before taking measurements to allow for absorption of the media in the pores of the char. Flow rates in the test section were controlled by by-passing a portion of the flow from the pump back to the slurry tank. Flow rates were determined by diverting the flow from the test section to a weigh tank. Average linear velocities ranged from 1 to 20 feet per second.

The pressure drop was measured over a 20-foot section with dial gauges and manometers. Pressure drops varied from 1 to 10 psi over the 20-foot section.

Pipeline Results

Figure 3 shows the effect of char concentration on pressure drop for char-mineral oil slurries at two linear velocities. Similar curves were obtained with char-water slurries. At low char loadings, the pressure drop increased only slightly over that of the liquid. After a certain loading was reached, however, the pressure drop rose very rapidly with further increases in char loading. The two oil slurries could no longer be pumped above a solids loading of 44 weight percent.

At low char loadings, the pressure drop obeyed the relationship:

$$\frac{\Delta P}{L} = k\,\bar{V}^{a} \qquad (1)$$

The exponent was 1.72 for the two oil slurries, and 1.92 for the water slurries. This relation held for concentrations up to 25, 30, and 40 weight percent for the mineral oil, recycle oil, and water slurries, respectively, and for velocities as low as 3 ft./sec. The experimental data illustrating this relationship are shown in Figure 4. At higher concentrations the pressure drop was dependent on a smaller power of the velocity. This is an indication of the transition region between laminar and turbulent flow. However, dilute slurries could not be pumped in the laminar regime and concentrated slurries could not be pumped in the fully turbulent regime with the existing experimental equipment.

The effect of particle size on pressure drop was determined for char-water slurries. The addition of large amounts of minus 325-mesh char caused a marked decrease in the pressure drop, compared to that of a slurry with equal total solids loading but no fine material. Slurries with solids concentrations up to 50 percent were easily pumped. The quantitative effect of this fine material is shown in Figure 5 for two velocities at a total solids loading of 50 percent.

Discussion

An attempt was made to correlate the pipeline data on a friction factor-Reynolds number plot using the viscosity determined on the Brookfield viscometer. Such a correlation would be expected to exist, provided that the slurry can be described in terms of the properties of an equivalent fluid. The general shape of these plots were characteristic of the well known correlations for Newtonian fluids. The transition from laminar to turbulent flow was readily apparent. However, the quantitative results were not satisfactory. The transition to turbulent flow occurred at a Reynolds number of 1200 for char-mineral oil slurries and at a value of 600 for char-water slurries. In addition, the laminar data for the char-water slurries were not correlated by a single line. There was a definite trend towards higher friction factors with decreasing particle size (increasing minus 325-mesh). Hence, the effect of the size distribution was not completely accounted for by the equivalent Newtonian fluid properties of viscosity and density. This confirmed the non-Newtonian behavior indicated by the viscometer results.

A possible non-Newtonian model is the two-parameter Bingham fluid (5). This model gives the following relation between the shear stress and the shear rate:

$$\tau = -\eta \frac{du}{dr} + \tau_y \qquad \tau > \tau_y \qquad (2a)$$

$$\frac{du}{dr} = 0 \qquad \tau < \tau_y \qquad (2b)$$

This equation can be integrated (5) for pipe flow to give

$$q = (\bar{V}S) = \frac{\pi \Delta P R^4}{8 \eta L} \left[1 - \frac{4}{3}\frac{\tau_y}{\tau_w} + \frac{1}{3} \left(\frac{\tau_y}{\tau_w}\right)^4 \right] \quad (3)$$

If the yield stress is small compared to the wall stress, the last term in the brackets may be neglected. Rearrangement and the insertion of $(\Delta P/L)\ R/2$ for the wall shear transforms Equation (3) into

$$\frac{\Delta P}{L} = 8 \left[\frac{\eta \bar{V}}{R^2} + \frac{\tau_y}{3R} \right] \quad (4)$$

The laminar data for char-water slurries are in agreement with this model. Pressure drop-velocity data were fitted to Equation (4). The resulting values of yield stress and plasticity are tabulated in Table IV.

The failure of the friction factor-Reynolds number plot to correlate the data can now be explained. The dimensional analysis leading to this correlation was based on only one rheological parameter, the Newtonian viscosity. If the two Bingham parameters are taken into consideration, a third dimensionless group is required (6, 7, 8). This is the Hedstrom number:

$$N_{He} = \frac{\rho \tau_y D}{\eta^2} \quad (5)$$

The Reynolds number is now based on the plasticity instead of the Brookfield viscosity:

$$N'_{Re} = \frac{\rho \bar{V} D}{\eta} \quad (6)$$

The data for char-water slurries in laminar flow were plotted using these dimensionless parameters in Figure 6. One set of data for char-oil slurries and a set for coal-oil slurries (9) are included. This correlation indicates that the Hedstrom number is about 1000, which is consistent with the value calculated from experimental yield stresses.

Some assumptions were required to obtain the curve for the turbulent region in Figure 6. At high shear rates, corresponding to turbulent flow,

$$- \eta \frac{du}{dr} \gg \tau_y$$

and Equation (2a) can be approximated by

$$\tau = -\eta \frac{du}{dr} \tag{7}$$

The slurries in turbulent flow can now be treated like Newtonian fluids.

An equation of the Blassius (5) form

$$f = k'' (N'_{Re})^{b}$$

was assumed for turbulent flow. Forcing Equation (1) into this form yields:

$$f = k' (N'_{Re})^{(a-2)} \tag{8}$$

Data from Figure 4 were transformed from the coordinates of head loss versus velocity to those of f versus N'_{Re} by using Equation (8). The error introduced by these approximations was never more than 20 percent. The result is a reasonable representation of the turbulent regime in Figure 6.

The most significant aspect of this correlation is the predicted suppression of turbulence at high Hedstrom numbers. Since the Hedstrom number is proportional to the square of the pipe diameter, it becomes increasingly important when attempting scale-up.

Economics

From the predictions of the correlation in Figure 6 and the properties of the slurries studied, a preliminary estimate of pumping cost was obtained. Figure 7 shows the estimated cost on a cents per ton per mile basis as a function of pipe diameter. Only those costs which are dependent on pipe diameter are included. At the diameter corresponding to the minimum in the total cost curve, the pumping cost is 0.16 cents per ton per mile. This is comparable to the operating costs of other commercial slurry pipelines (2).

In the final economic evaluation, several other factors need to be considered. The costs in Figure 7 do not include terminal facilities. These include not only capital investment in pumping stations, but slurry preparation and separation facilities as well. The effect of the extra fine material, which must be added, on product value has not been determined.

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Nomenclature

a	Constant defined in Equation (1). Dimensionless
b	Constant
D	Pipe diameter, ft.
f	Fanning friction factor $= \frac{D}{4} \frac{\Delta P/Lg_c}{1/2\,\rho V^2}$ Dimensionless
k	Constant defined in Equation (1)
k'	Constant defined in Equation (8)
k''	Constant
L	Pipe length, ft.
N_{He}	Hedstrom number $= \frac{\rho \tau_y D^2}{\eta^2}$ Dimensionless
N'_{Re}	Modified Reynolds Number $= \frac{\rho \bar{V} D}{\eta}$ Dimensionless
ΔP	Pressure drop, psi
q	Volumetric flow rate, cu.ft./hr.
r	Radial distance, ft.
R	Pipe radius, ft.
S	Pipe cross sectional area, sq.ft.
$\underline{u}$	Linear velocity, ft.sec.$^{-1}$
$\bar{V}$	Average linear velocity, ft. sec.$^{-1}$
$\frac{du}{dr}$	Shear rate, sec.$^{-1}$
η	Plasticity defined by Equation (2a), lb_fsec.ft.$^{-2}$
ρ	Density, lb_mft.$^{-3}$
τ	Shear stress, lb_fft.$^{-2}$
τ_w	Shear stress at the wall $= \frac{P(R)}{L(2)}$ lb_fft.$^{-2}$
τ_y	Yield stress defined by Equation (2a) lb_fft.$^{-2}$

TABLE I

Physical Properties of Char

Properties	Before Pumping	After Pumping	
Slurry Medium		Mineral Oil	Recycle Oil
Density			
Bulk, lb./cu.ft.	27	34	-
Packed, lb./cu.ft.	31	41	-
Particle, g./cc.	0.79	-	-
Sieve Analysis, Tyler Mesh, cum. wt. %			
14	4	1	3
28	27	11	25
48	60	41	58
100	82	68	83
200	95	80	95
325	98	85	99
Average Particle Diameter, in.	0.009	0.005	0.009

TABLE II

Effect of Minus 325-Mesh Char Content on the Viscosity of a Char-Oil Slurry

Test No.	Char Size Consist, wt. % on Tyler Screen: 16	28	48	100	200	325	Minus 325	Average Particle Diameter, in.	Viscosity of a 44 wt. % Char-Oil Slurry at 100°F., cp.
1	5.6	21.2	36.8	23.4	10.8	1.3	0.9	0.00739	616
2	5.1	19.3	33.4	21.2	9.8	1.2	10.0	0.00447	344
3	6.0	19.0	30.0	14.0	9.0	4.0	17.0	0.00344	328
4	4.5	17.1	29.7	18.9	8.7	1.1	20.0	0.00323	288
5	4.0	15.0	26.0	16.5	7.6	0.9	30.0	0.00252	250
6	3.4	12.8	22.3	14.2	6.5	0.8	40.0	0.00205	180
7	0.3	11.0	26.4	17.6	10.6	6.6	27.5	0.00245	202
8	31.0	20.5	12.0	6.1	2.6	1.1	26.5	0.00310	184

TABLE III

Viscosity of a 40 Weight Percent Char-Water Slurry at Different Rotational Speeds of Viscometer

Rotational Speed, rpm	Apparent Viscosity Measured With a Brookfield RVT Viscometer Using Spindle No. 2
100	132
50	260
20	455

TABLE IV

Rheological Parameters

Nominal Total Solids Concentration, wt. %	Minus 325-Mesh Char Concentration, wt. % of total solids	Yield Stress, τ_y $lb_f/sq.ft. \times 10^2$	Plasticity or Limiting Viscosity, η $lb_f.sec./sq.ft. \times 10^4$	Measured Total Solids Concentration, wt. %
50 char in water	47.5	4.13	5.84	50.4
	41.9	6.42	5.85	51.6
	36.9	2.53	8.02	47.4
	34.8	7.01	7.67	48.9
	28.6	5.27	10.52	52.3
45 char in water	28.6	5.49	6.55	45.4
38 char in recycle oil	-	(-6.96)	21.8	-
55 coal in oil	-	0.276	11.88	-

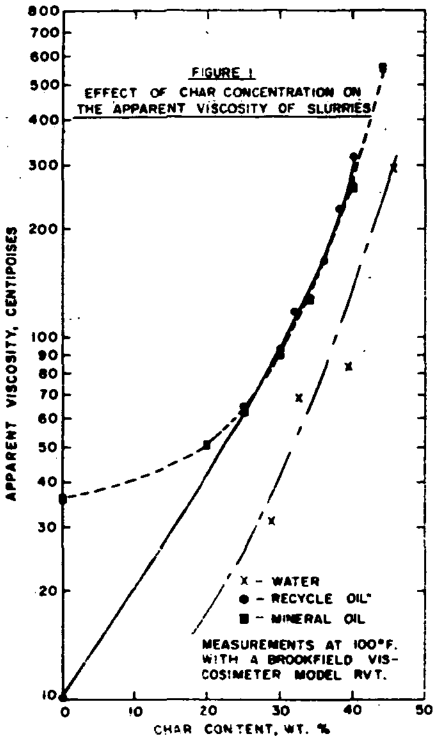
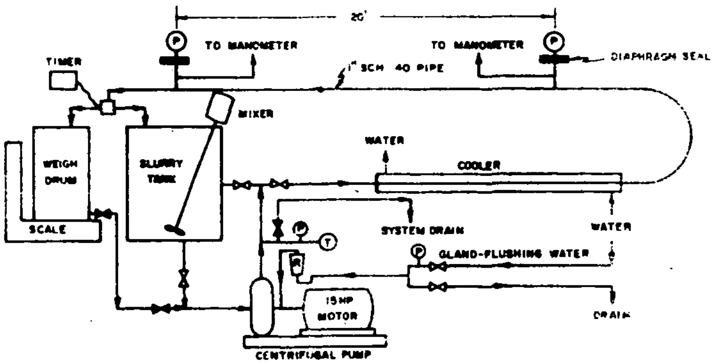


FIGURE 1

EFFECT OF CHAR CONCENTRATION ON THE APPARENT VISCOSITY OF SLURRIES

FIGURE 2

PIPELINE TEST SYSTEM



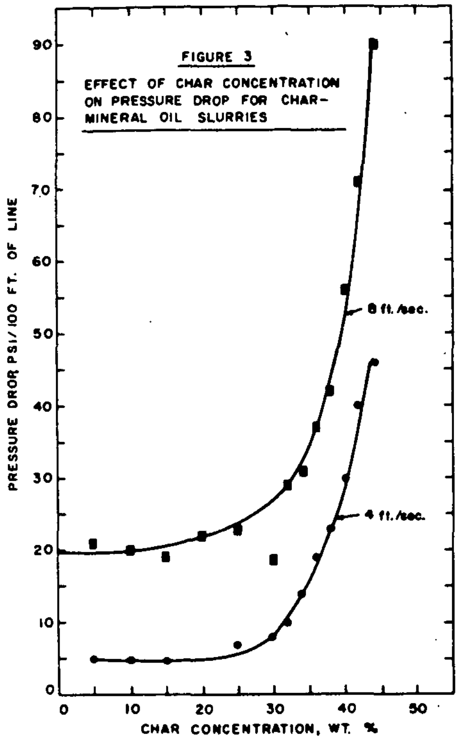


FIGURE 4

HEAD LOSS VERSUS VELOCITY FOR CHAR-WATER SLURRIES WITH SOLIDS CONCENTRATIONS FROM 21 TO 39 WEIGHT PERCENT

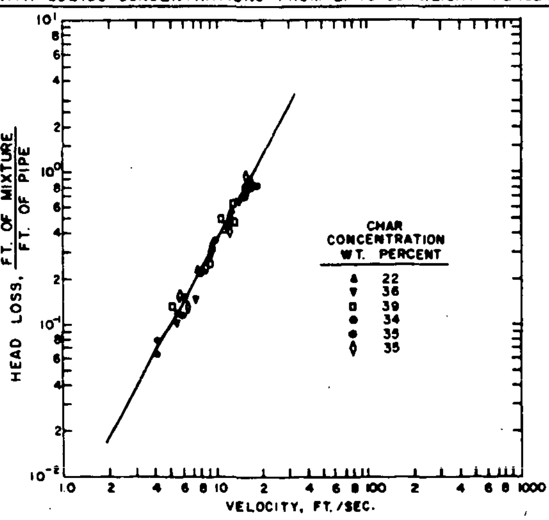


FIGURE 5

EFFECT OF CONTENT OF MINUS 325-MESH CHAR ON PRESSURE DROP FOR A 50-50 CHAR-WATER SLURRY

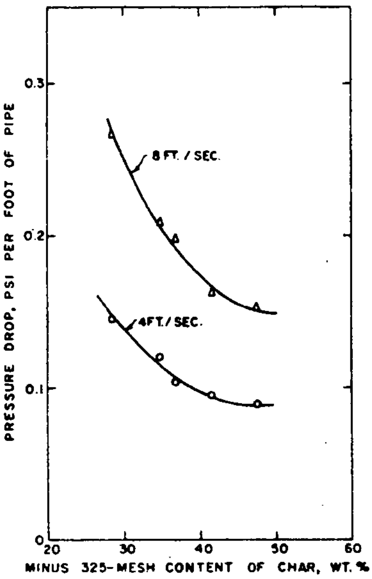


FIGURE 6

HEDSTROM NUMBER-REYNOLDS NUMBER-FRICTION FACTOR PLOT

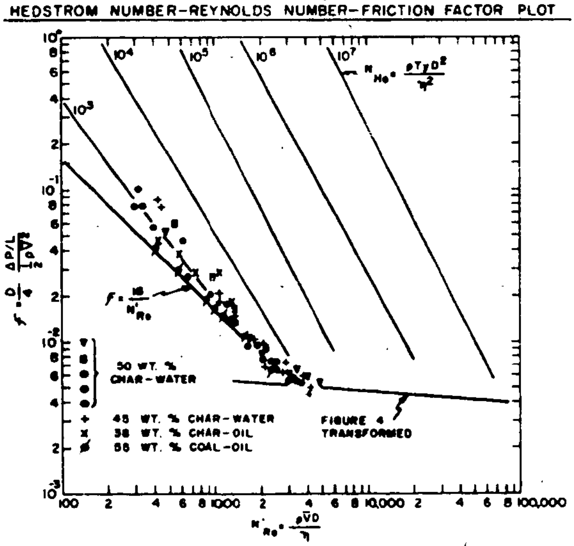


FIGURE 7

PIPE DIAMETER VERSUS COST OF PIPELINING FOR A CONSTANT THROUGHPUT OF 11,380 Cu. Ft./Hr.