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TRANSPORTATION OF COARSE COAL IN A FINE MEDIUM

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Abstract—Transportation of coarse coal, up to a size of 7 mm, in a fine-coal slurry medium with a particle size $< 150\,\mu$m has been studied up to 58% by wt of the overall concentration in a 50 mm dia pipeline. A model has been established for calculating the yield stress with respect to the addition of coarse particles to a fine-particle slurry by analysing the laminar slurry flow. For the turbulent flow, an equation has been developed to predict the pressure drop accurately.

Key Words: rheology, pressure drop of coarse in fines, yield stress

1. INTRODUCTION

The technology of transporting slurries with a particle dia < 1 mm is well-established. However, it suffers from certain problems with respect to dewatering of the slurry, pipeline abrasion and the settling of particles due to shutdown of pipelines. In recent years these problems have been largely overcome with the development of the stabilized flow concept. In stabilized flow, the slurry consists of a heterogeneous mixture of coarse particulate solids in a fine-particle slurry medium of compatible or the same material. These slurries are stable and can be allowed to remain stationary in vessels over a long period. Further, the slurry of fine particles behaves as a pseudo-fluid, having yield stress which supports the coarse particles in the slurry and prevents them from settling. A review of the literature suggests that Elliott & Gliddon (1970) were the first to study the transportation of large-size coal, up to 13 mm in size, in a fine-coal water suspension. Thereafter, studies were also reported by Lawler *et al.* (1978) on stabilized flow. Extensive studies on coarse coal in a fine-coal slurry medium were published by Duckworth *et al.* (1983, 1986). They reported studies with stabilized slurries up to 67% by wt of solids in a carrier fluid containing 33% by wt of ground coal of $-200\,\mu$m in size, with the rest being coarse coal. Besides coal, similar techniques have been adopted in the mining industries for the hydraulic transport of backfill and fly-ash in heavy media (Verkerk 1984). Although flow under stabilized conditions has great potential as a transportation alternative, to date, the open literature in this field is very limited. Moreover, the studies conducted so far were restricted to low-ash coal slurries. Since the coals in India for thermal use have a high ash content, in the range of 30–40%, and higher ash coals have higher yield stresses, a specific study on these types of coal was undertaken.

2. EXPERIMENTAL

2.1. Test Slurry

A review of the literature suggests that a stabilized coal slurry should have a coal particle size distribution which can ensure the maximum packing density (Elliott & Gliddon 1970). It has been further suggested (Duckworth *et al.* 1983, 1986) that the fine medium of the stabilized slurry should have a high yield stress so as to support the coarse particles. For the present study the fines will have a chosen particle size $< 150\,\mu$m, which is somewhat coarse compared to the sizes used by other investigators (Lawler *et al.* 1978; Rigby *et al.* 1982; Duckworth *et al.* 1983). Since the coal used has a high ash content, the fine slurry medium achieves the necessary yield stress to support the coarse particles. The sieve analysis of the fines is shown in table 1; the sub-sieve analysis results ($<45\,\mu$m), obtained experimentally by Anderson's pipette method, are also listed. The specific gravity of the test coal sample is 1.74 and its ash content is 37%.

Table 1. Particle size distribution of fine coal

Particle size (μm)	Cumulative undersize (%)
150	100.0
75	66.0
45	52.0
30	40.5
20	32.4
15	13.3
10	1.3

Table 2. Particle size distribution of coarse coal

Particle size (μm)	Cumulative undersize (%)
7000	100.0
5000	94.5
3353	80.8
1003	55.6
300	2.3

In the experiments, two different concentrations by weight of fine slurry were used. Since preliminary studies indicated that a fine slurry below 35% by wt concentration would be unstable and settling, the fine-slurry concentrations were chosen to be 39 and 49% by wt. After the addition of the coarse fractions to the fine slurry, the total solid concentrations remained in the range of 55–58%.

The size of the coarse fraction in the stabilized slurry is determined with respect to the yield stress developed by the fine medium so that the coarse is supported by the medium under the condition of laminar flow. To achieve this, for a maximum coarse size, d_p, the condition of static equilibrium should be satisfied where the yield stress, τ_y, exceeds a limiting value, as proposed by Thomas (1978) and Duckworth *et al.* (1983, 1986):

Thomas: $$\tau_y \geqslant 0.092 d_p g(\rho_s - \rho_{mf}) \qquad [1]$$

and

Duckworth *et al.*: $$\tau_y \geqslant 0.1 d_p g(\rho_s - \rho_{mf}), \qquad [2]$$

where ρ_s and ρ_{mf} are the specific gravities of the solid and the fine medium, respectively. The yield stresses of the fine-slurry media of 39 and 49% concentration were determined from rheological tests using a Haake RV 100 rotational viscometer. Corresponding to the yield stresses, the maximum particle size of the coarse fraction was determined from [1] and [2] and was found to be in the range of 5–7 mm. The particle size distribution of the coarse fraction used in the experiments is given in table 2.

2.2. *Determination of Pressure Drop*

The setup used for conducting the experiments is shown in figure 1. The test loop is of 50-mm piping, where the pipe i.d. = 48.5 mm and the length is around 75 m. The loop is fitted with a centrifugal rubber-lined slurry pump having with a throughput of 30 m^3/h, driven by a 30 kW DC motor. The motor is thyristor controlled with fully continuous speed variations. The maximum discharge pressure of the pump is 45×10^4 N/m^2. The slurry storage tank is 3 m^3 in capacity and is fitted with a 5 kW agitator.

Slurries of different concentrations were prepared by mixing the required amount of solids and water under agitation. At the start, the fine-coal slurry was prepared and its flow characteristics were investigated. The coarse coal particles were added in steps to the fine-slurry medium to form the coarse–fine mixture slurries. The experiments were conducted with following sets of slurries:

Set A. A fine-slurry medium with 39% solids by wt ($\rho_{mf} = 1.15$) and coarse particles added to make the total weight concentration of solids up to 50% ($\rho_{mt} = 1.2$) and 55% ($\rho_{mt} = 1.226$).

Set B. A fine-slurry medium with 49% solids by wt ($\rho_{mf} = 1.193$) and coarse particles added to make the total weight concentration of solids up to 55% ($\rho_{mt} = 1.226$) and 58% ($\rho_{mt} = 1.25$).

Where ρ_{mf} is the specific gravity of the fine slurry and ρ_{mt} is the specific gravity of the slurry of fine + coarse particles.

Variations in the slurry flow rate were obtained by varying the pump speed. The slurry volumetric flow rates were measured by an electromagnetic flow meter and the pressure drop differentials for a distance of 10 m were recorded using a mercury manometer. The reproducibility of the data was ensured by repeating the experiments. The slurry pH was maintained between 6 and 7. Samples of the slurry from time to time were drawn for particle size distribution analysis and it was found that no significant change occurred in the size distribution.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show logarithmic plots of the head loss vs velocity for water + fines and water + fines + coarse for set A and set B slurries, respectively. From these plots, the laminar–turbulent transitions are clearly evident and the analysis was carried out separately for the laminar and turbulent regions.

3.1. Rheological Analysis in the Laminar Region

The pressure drop data for laminar slurry flow conditions were used for constructing the pseudo-shear diagrams. This was done following the Buckingham equation for laminar flow of Bingham plastic fluids, where the term $(\tau_y/\tau_w)^4/3$ is neglected, being $\ll 1$, and the equation reduces to the following form:

$$\tau_w = (4/3)\tau_y + \eta(8V/D), \qquad [3]$$

where τ_y is the yield stress (Pa), η is the plastic viscosity (Pa s) and τ_w is the wall shear stress (Pa), equal to $D\,\Delta P/4L$; ΔP is the pressure drop of slurry flowing in a straight pipe of diameter D (m) and length L (m) and V (m/s) is the flow velocity.

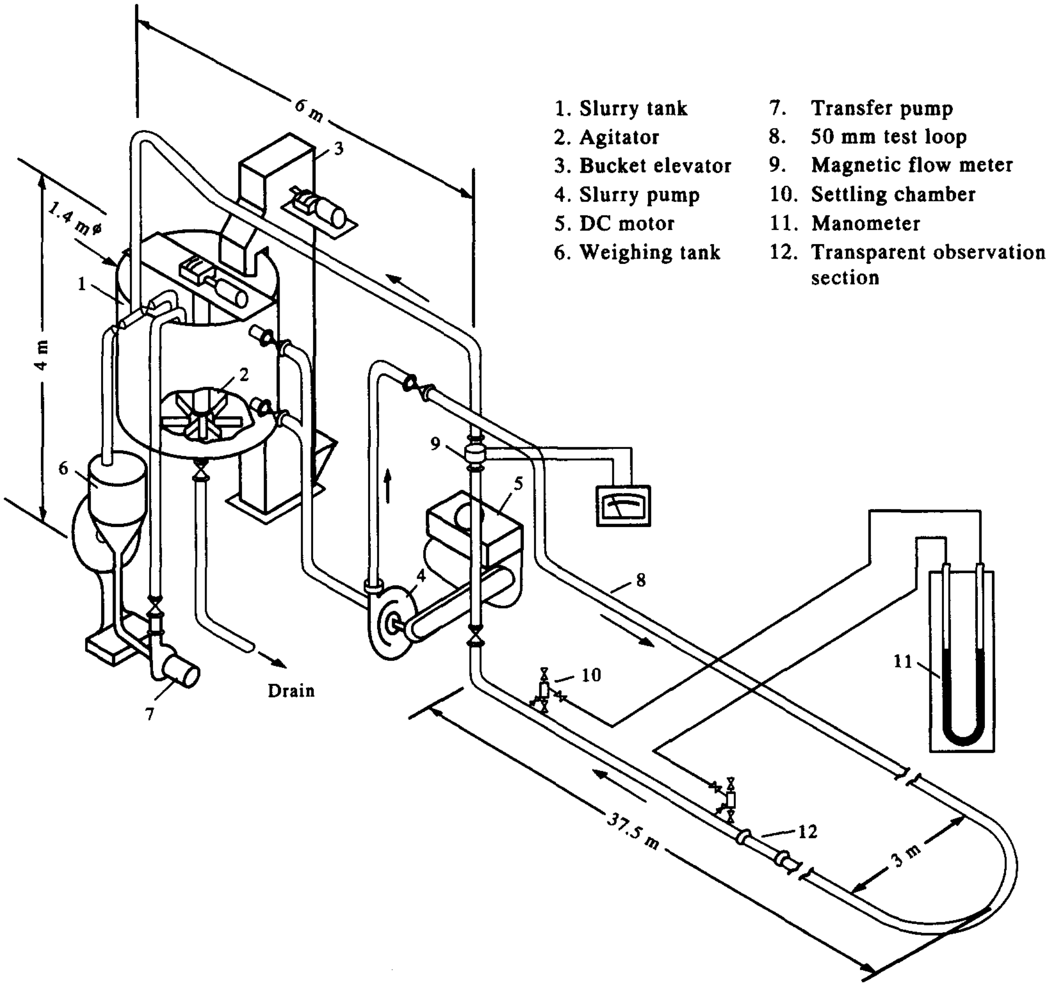

Figure 1. Experimental setup with the 50 mm nominal diameter pipeline test loop.

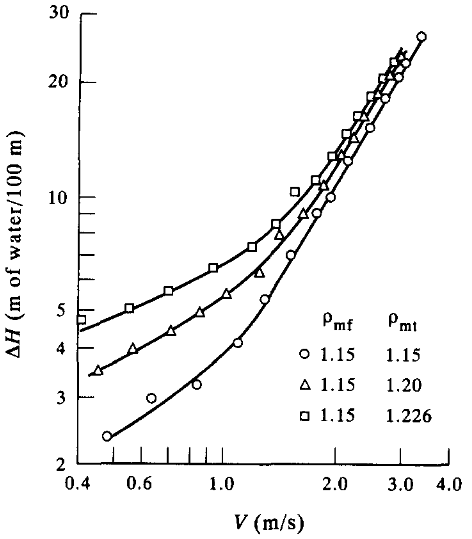

Figure 2. Variation of head loss, ΔH, with velocity for set A coal slurries with a fine medium of 39% by wt concentration.

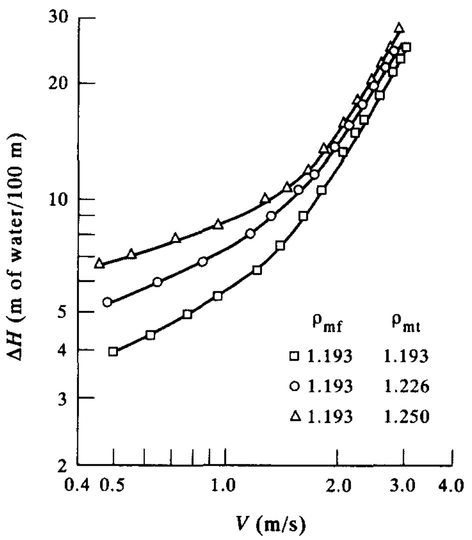

Figure 3. Variation of head loss, ΔH, with velocity for set B coal slurries with a fine medium of 49% by wt concentration.

Equation [3] provides a linear plot between τ_w and $8V/D$, the pseudo-shear rate. The intercept at the Y-axis equals $4\tau_y/3$ and the slope of the plot provides the value of η, the plastic viscosity. The pseudo-shear diagrams for set A and set B slurries, as shown in figures 4 and 5, substantiate the Bingham plastic nature of the slurries and also indicate the effect of coarse particle addition on fines. It can be seen from these figures that the yield stress successively increases with the addition of coarse particles, while the Bingham viscosity does not vary significantly.

For correlating the variations in the yield stresses due to coarse particle addition, two non-dimensional parameters for the yield stresses and the volumetric concentrations of the slurries are defined in terms of the ratios

$$\tau^* = \tau_{yt}/\tau_y \qquad [4]$$

and

$$S^* = C_{vt}/C_v, \qquad [5]$$

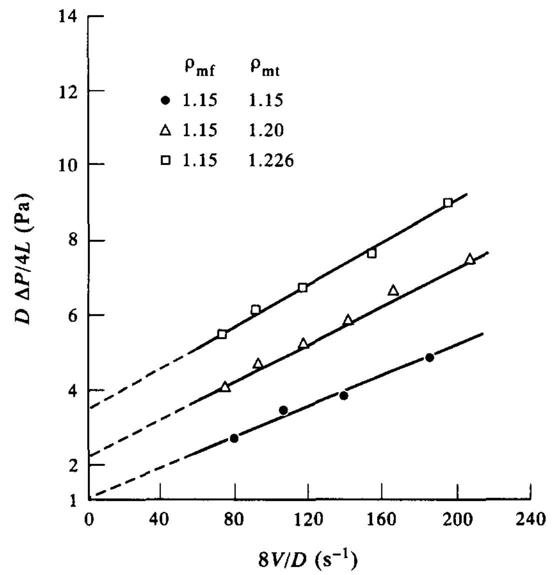

Figure 4. Variation of wall shear stress, $D\,\Delta P/4L$, with pseudo-shear rate, $8V/D$, for set A coal slurries in laminar flow.

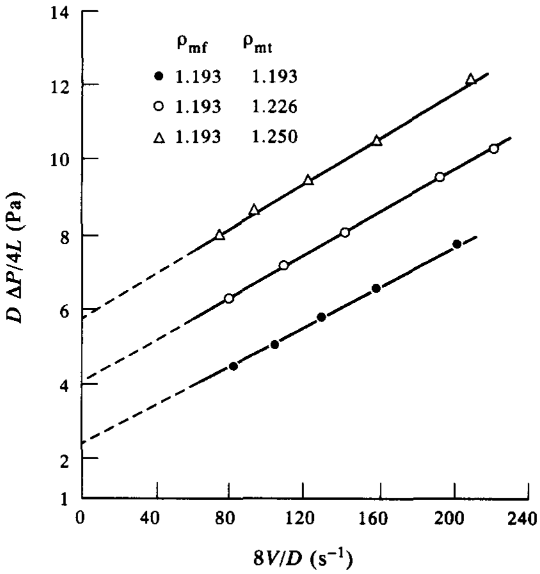

Figure 5. Variation of wall shear stress, $D\,\Delta P/4L$, with pseudo-shear rate, $8V/D$, for set B coal slurries in laminar flow.

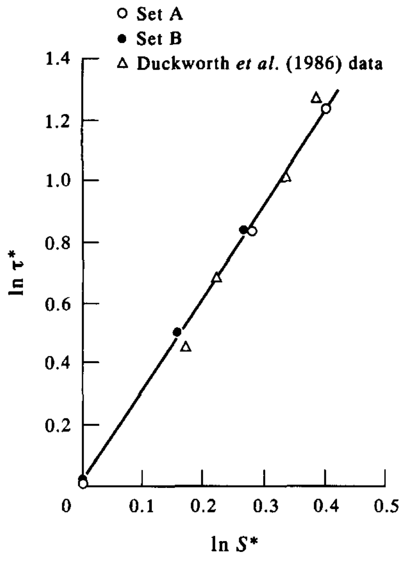

Figure 6. Correlation plot between the yield stress ratio, τ^*, and the volumetric concentration ratio, S^*, for coarse coal in a fine medium.

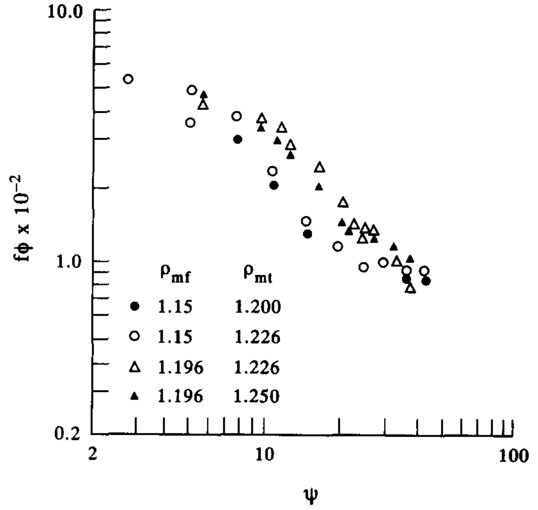

Figure 7. Plot of $f\phi$ vs ψ with the present experimental data following the method of Sakamoto *et al.* (1982).

where τ_y and τ_{yt} are the yield stresses due to the fines and the fine + coarse mixture, respectively, and C_v and C_{vt} are the respective volume concentrations.

The τ^* and S^* values for different fine + coarse mixtures are plotted in figure 6. The straight-line variation in logarithmic coordinates provides the following correlation:

$$\tau^* = (S^*)^3. \tag{6}$$

It can be seen from figure 6 that the above equation also correctly correlates the data of Duckworth *et al.* (1986) for stabilized coal slurries. The significance of this equation is that it can predict the increase in the yield stress due to the volumetric addition of coarse particles to a fine-coal slurry medium.

3.2. *Prediction of the Pressure Drop in Turbulent Flow*

The analysis of turbulent flow of a fine + coarse mixture of coal has been performed previously by Sakamoto *et al.* (1982); they correlated the pressure drop by the following empirical equation:

$$4f\phi = \alpha\psi^{-\beta}, \tag{7}$$

where α and β are experimentally determined parameters, f is the friction factor of the slurry and ϕ and ψ are the pressure drop parameter and the modified Froude number, respectively; defined as

$$\phi = \frac{i_t - i_{mf}}{C_{vt}\, i_{mf}} \tag{8}$$

and

$$\psi = \frac{V^2}{gD}\frac{\rho_{mf}}{(\rho_s - \rho_{mf})}, \tag{9}$$

where i_{mf} and i_t are the pressure drop due to the fines and due to the fine + coarse slurry, respectively, C_{vt} is the volumetric concentration of the total slurry and ρ_s and ρ_{mf} are the specific gravities of the solid material and fine slurry, respectively.

In the analysis of Sakamoto *et al.* (1982), when the parameters α and β are attributed constant values the correlation is found to be poor, as seen from their plots. A plot made with $f\phi$ vs ψ with the data of the present experiments also shows a wide scatter of values, as seen in figure 7. Moreover, figure 7 does not indicate that α and β can be functions of the total weight concentration of slurry, as conceived by Sakamoto *et al.* (1982) in their paper. Therefore, a modified approach has been taken by directly plotting ϕ vs ψ, as shown in figures 8 and 9, for set A and set B slurries, respectively.

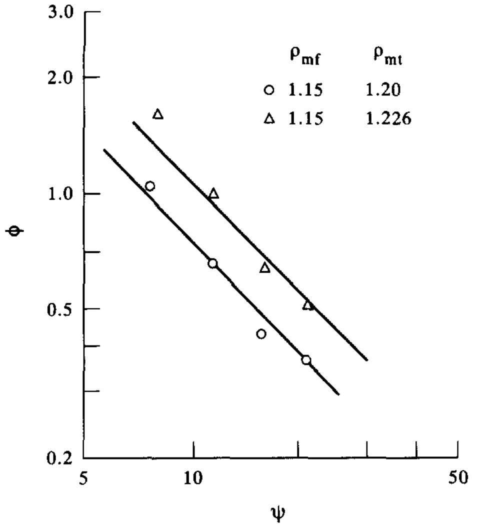

Figure 8. Plot of the pressure drop parameter, ϕ, vs the modified Froude number, ψ, for set A coal slurries.

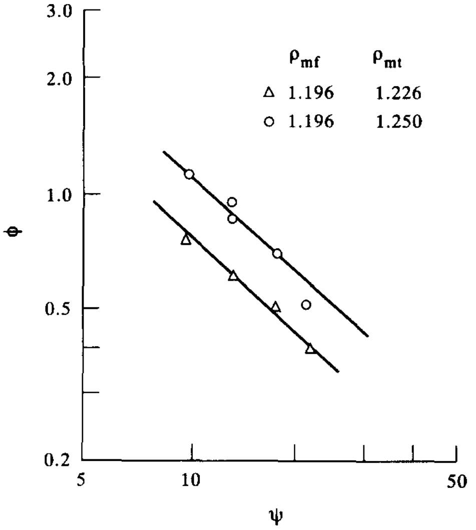

Figure 9. Plot of the pressure drop parameter, ϕ, vs the modified Froude number, ψ, for set B coal slurries.

The plots in figures 8 and 9 are found to depict the ϕ and ψ relationship in a better manner but the straight lines in the logarithmic scale are found to shift in parallel, which is possibly due to the different coarse fractions present in the fine slurry. To take this into account, a concentration function, K_c, has been introduced in the pressure drop parameter, ϕ, which is rewritten as

$$\phi_m = \frac{i_t - i_{mf}}{K_c C_{vt} i_{mf}}, \tag{10}$$

where K_c is defined as

$$K_c = \frac{\rho_{mt} - \rho_{mf}}{\rho_s - \rho_{mf}}. \tag{11}$$

When ϕ_m is plotted vs ψ on the logarithmic scale, as shown in figure 10, the relationship is represented by the following equation:

$$\phi_m = 1.685\psi^{0.815}. \tag{12}$$

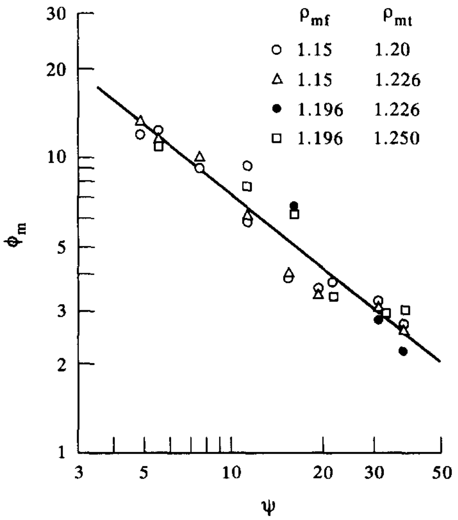

Figure 10. Correlation plot between the modified pressure drop parameter, ϕ_m, and the modified Froude number, ψ, for pipe flow of coarse coal in a fine medium.

4. CONCLUSIONS

The present study has ascertained the flow behaviour of coarse coal in a fine medium in laminar as well as turbulent flow. The rheology of the slurries, determined by analysis of the laminar flow data, indicate a Bingham plastic nature and satisfies the modified Buckingham equation. The increase in the yield stress due to coarse particle addition has been correlated and it is found that between a slurry of coarse + fine mixture and a fine-slurry medium the yield stress ratio varies as the cubic power of the ratio of the volumetric concentrations. It is also seen that the Bingham viscosity does not vary appreciably as a result of coarse particle addition. For the turbulent flow range, a modified pressure drop parameter, ϕ_m, has been defined, taking into consideration the addition of coarse particles to fines. When ϕ_m is plotted vs the modified Froude number, ψ, a straight-line variation in the logarithmic scale is obtained, resulting in a simplified pressure drop equation for turbulent slurry flow.

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