NOTE

Anomalous Friction in Slurry Flows

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Experiments conducted with water slurries of 1 mm particles of specific gravity 1.59 in a laboratory pipeline 0.105 m in diameter have provided evidence of a change in the friction mechanism at velocities above 3 m/s. These flows were stratified and at low velocities the frictional pressure gradients were in satisfactory agreement with the predictions of the conventional two-layer model. However at higher velocities the friction is substantially lower than predicted. Measurements of concentration and velocity distributions within the pipe show that no major change in flow regime occurs concurrently with the change in the friction mechanism. It appears that the effect is due to a change in the nature of the particle–wall interaction, of a type which suggests that an inward-acting force affects the particles adjacent to the wall.

Des expériences menées avec des suspensions aqueuses de particules de 1 mm d'une densité de 1,59 dans un pipeline de laboratoire de 0,105 m de diamètre ont permis d'illustrer un changement dans le mécanisme de frottement à des vitesses supérieures à 3 m/s. Ces écoulements sont stratifiés, et à de faibles vitesses, les gradients de pression de frottement montrent un accord satisfaisant avec les prédictions du modèle à deux couches classiques. Toutefois, à de plus grandes vitesses, le frottement est substantiellement plus faible que prédit. Des mesures de distributions de concentrations et de vitesses dans la conduite montrent qu'aucun changement majeur n'est survenu dans le régime d'écoulement simultanément au changement dans le mécanisme de frottement. Il apparaît que l'effet est dû à un changement de la nature de l'interaction particules-paroi, d'une façon qui laisse supposer qu'une force agissant de l'intérieur influe sur les particules adjacentes à la paroi.

Keywords: stratified flows, high velocities, repulsive force, slurry flows.

Of all the parameters governing pipeline friction for slurry flows, particle diameter has long been recognized as being of paramount importance. Very fine particles, with diameters less than about 10 μm, are usually flocculated and the interaction of these flocs provides the structure which inhibits settling and leads to non-Newtonian behaviour. Particles which are fine but too large to flocculate produce slurry friction which is velocity dependent in a manner resembling that of pure fluids (kinetic friction). At low and moderate concentrations (less than about 30% solids by volume) kinetic friction depends upon slurry density and the viscosity of the carrier liquid.

Large particles, with settling velocities which are greater than the velocity fluctuations of turbulent flow, display friction which is insensitive to bulk velocity and which resembles the Coulomb friction of solids in sliding contact. The mechanistic model which has been proposed for these coarse-particle flows (Wilson, 1970, 1976) has been shown to be reliable in numerous subsequent investigations.

Many industrial slurries contain particles with diameters small enough to be suspended in part by fluid turbulence and Wilson's coarse-particle model has been adapted to deal with these slurries (Shook et al., 1986; Gillies and Shook, 1991, 2000). The kinetic and Coulomb mechanisms are assumed to be responsible for the total friction and since the dependence of each mechanism on pipe diameter is well understood, scale-up of laboratory test results to large pipelines should be reliable.

The model is based upon idealizations of the concentration and velocity distributions within the pipe so that two superimposed regions (layers) are defined. The frictional contributions of these two layers are evaluated using the kinetic and Coulomb mechanisms. The relative importance of the two mechanisms has been deduced from experiments employing a wide range of particle diameters, pipe diameters and fluid viscosities. Because the model is intended for use with particles of intermediate size and because large quantities of solids are required for experimentation when large pipes are used, most of the laboratory data in the literature referring to narrow particle size distributions were obtained with sand slurries.

Sand is a convenient material for use in experimental work, being relatively inexpensive and resistant to abrasive degradation. Its density is close to that of many minerals but is considerably greater than that of coal, which is usually handled in slurry form in cleaning plants. Although many experimental tests have been conducted with coal slurries and some of this data has been incorporated in the two-layer model, the friable character of many Canadian coals has made many test results difficult to interpret quantitatively. The present investigation was undertaken to examine a material with a density close to that of run-of-mine coal (Bakelite) and which was resistant to abrasive degradation. To complement the experimental results, tests were also undertaken using a sand of similar size in the same pipeline.

The SRC Two-Layer Model

A complete description of this model has been given elsewhere (Gillies and Shook, 2000) but to interpret the present series of experiments some of the salient features merit repetition. According to this model, the effect of bulk velocity upon friction is due to the contribution of the kinetic friction, and to the fact that the ability of the flow to suspend the particles depends primarily upon the relative magnitudes of the turbulent velocity fluctuations and the particle settling velocity.

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The kinetic wall shear stress is calculated from the velocity of the layer V_i using a Fanning equation:

$$\tau_{ki} = 0.5\ (f_1\ \rho_i + f_s\ \rho_s)\ V_i^2 \tag{1}$$

The friction factor f_1 is calculated from the relative pipe roughness and a Reynolds number which uses the density of the slurry and the viscosity of the carrier fluid: $f_1 = f_1[(DV\rho_i/\mu_L), k/D]$.

The particle friction factor f_s is a function of solids concentration (Gillies and Shook, 2000):

$$f_s = 0.00002\ \lambda^2 \tag{2}$$

where

$$\lambda = [(C_{max}/C)^{1/3} - 1]^{-1}$$

The immersed weight of the particles causes Coulombic friction, which Wilson has called "contact load friction". The fraction of the total solids content which contributes contact load friction is approximately (Gillies and Shook, 2000):

$$C_c/C_r = \exp(-0.0212\ V/v_\infty) \tag{3}$$

If the particles are larger than 5 to 10% of the pipe diameter Equation (3) underpredicts the contact load fraction, probably because the scale of the turbulence begins to inhibit turbulent suspension.

Recent research with slurries of high solids concentrations has suggested a modified version of Equation (3) at values of the Reynolds number Re_m less than about 192 000 (Gillies and Shook, 2000). A tentative alternative to Equation (3) at low Reynolds numbers has been suggested:

$$C_c/C_r = \exp(-.0001013\ Re_m^{0.25}\ V/v_\infty) \tag{3A}$$

In calculating the Coulomb friction contribution the following assumptions are employed:

1) particles suspended by fluid turbulence are assumed to combine with the fluid to contribute to a buoyant effect which reduces the friction of the contact load particles;
2) in the absence of experimental measurements, the coefficient of Coulomb friction for the contact load particles is considered to be 0.5; and
3) for particles with narrow size distributions the limiting concentration C_{max} is taken as 0.63.

Experimental Procedure

The experiments were conducted using the closed-loop pipeline described elsewhere (Gillies and Shook, 2000). The pipeline was fabricated from mild steel, with internal diameter 0.1047 m. The essential features of the loop are:

a) axial concentration variations were minimized by using a constant pipe diameter and long radius bends;
b) temperature was maintained constant at either 15°C or 48°C using the heat exchanger;
c) rust and scale were removed from the pipe wall before the tests by recirculating an abrasive sand slurry before testing. Water flow tests showed that the roughness was reduced to 2 μm; and
d) slurries were prepared by adding weighed quantities of solids to the loop whose volume was known.

Velocities were measured with calibrated magnetic flux flowmeters. Pressure drops were measured with calibrated variable reluctance pressure transducers whose voltage output was read with a digital computer. Solids concentration distributions in the vertical plane were measured using a traversing gamma ray density gauge. The integrated concentration distribution provided a verification of the mean solids concentration mentioned above.

Local velocities were measured with the electrical resistivity probe described elsewhere (Shook and Roco, 1991). In combination with the concentration distributions the velocity distributions provide an indication of the flow regime for the slurry.

The size distributions of the solid particles were determined frequently to monitor the extent of abrasive degradation. The values shown in Figure 1 were obtained after the tests shown and bracket the series of tests. The first experiment was the 10% slurry run and the final experiment was that at 40%; the change in particle size over the series can be seen to be minimal.

Experimental Results

Figure 2 presents the experimental pressure gradient as a function of bulk velocity and in-situ solids concentration at 15°C. Figure 3 displays the experimental data at 48°C and, for purposes of comparison, Figure 4 shows experimental data obtained in the same test loop with a sand (d_{50} = 0.63 mm) having a narrow particle size distribution. The lowest velocities reported for all the slurries are close to the deposition condition.

Inspection of Figures 2 and 3 shows that they are qualitatively similar. At low velocities the slurry pressure gradients are much higher than the corresponding values for water. At velocities just above the deposition condition, the friction losses increase with velocity as the solids-rich region near the bottom of the pipe dilates. With further increases in velocity the pressure gradient increases more slowly and at high velocities, the friction losses for the slurry actually converge towards the water friction results.

This effect is quite different from that of the sand slurries shown in Figure 4, whose behaviour may be regarded as typical of coarse particles with (solids/fluid) density ratios greater than 2 or thereabouts. For coarse sand slurries, the friction loss loci remain nearly parallel to that of the carrier fluid. The conventional explanation for this behaviour is that as the velocity

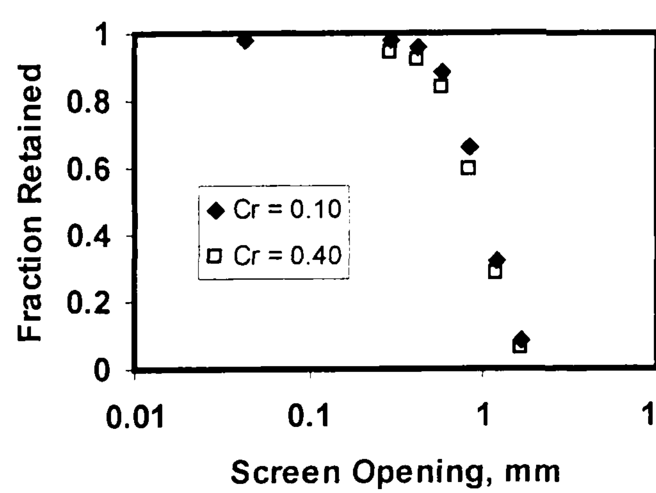

Figure 1. Particle size distributions.

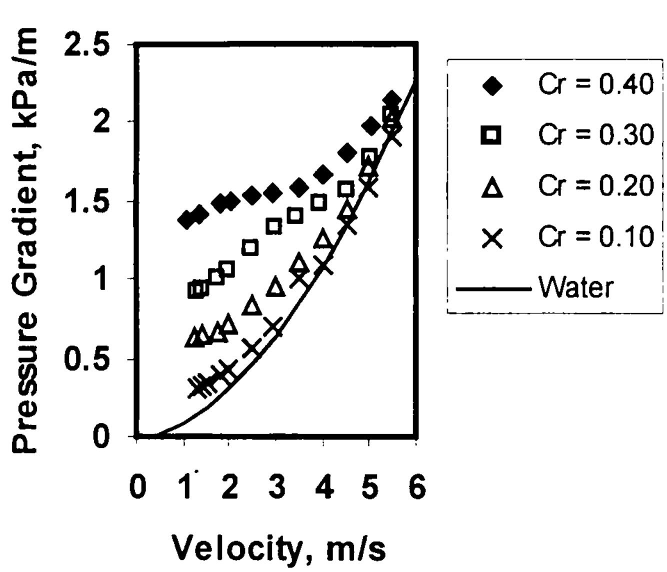

Figure 2. Pressure gradient as a function of mean velocity and solids concentration at 15°C.

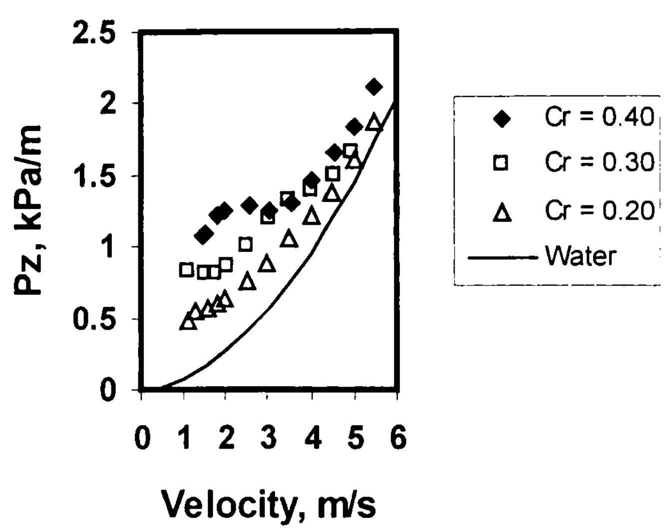

Figure 3. Pressure gradient as a function of mean velocity and solids concentration at 48°C.

increases, the contact load fraction and its associated friction decrease (Equations 3 and 3A) while the density ρ_1 increases. The increased kinetic friction (Equation 1) compensates to some extent for the reduced Coulomb friction so that the friction loci remain approximately parallel, although a shallow minimum in the friction loci often occurs. If the contact load fraction is very low, kinetic friction is dominant and the loci will diverge. However, there is no obvious reason for the curves to converge.

A possible inference from the convergence of the pressure gradient loci in Figures 2 and 3 is that the slurries become "homogeneous" at high velocities in a manner which somehow suppresses the divergence in the friction loci. Information bearing on this hypothesis was provided by concentration distributions which were measured at $V = 2.5$ m/s and $V = 4.5$ m/s. The data in Figures 2 and 3 show that these two velocities bracket the range of velocities at which a change in the frictional behaviour occurs. Figure 5 shows the chord-averaged solids concentration as a function of vertical position for $C_r = 0.40$ at 48°C. The measurements obtained at 15°C were very similar to those in Figure 5.

Although the higher velocity does reduce the concentration variation within the slurries to some extent, they retain their stratified nature. The stratified character of the slurry can also be seen in the particle velocities which were measured in the vertical plane through the pipe axis and which are presented in Figure 6. Similar velocity distributions were measured at the lower temperature. The flows are evidently highly asymmetric; the principal difference is that the loci are displaced by an amount approximately equal to the difference in the bulk velocities. A consequence of this displacement is that the velocities of the particles closest to the pipe wall are much higher at $V = 4.5$ m/s than at $V = 2.5$ m/s.

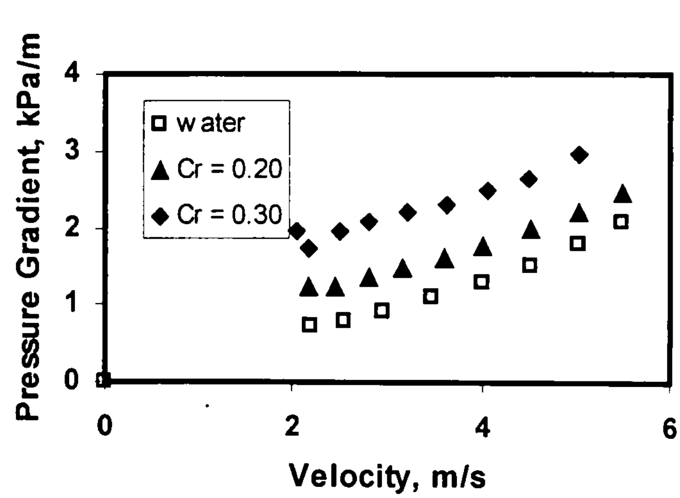

Figure 4. Pressure gradient vs. bulk velocity for coarse sand ($d_{50} = 0.64$ mm) slurries. at 15°C.

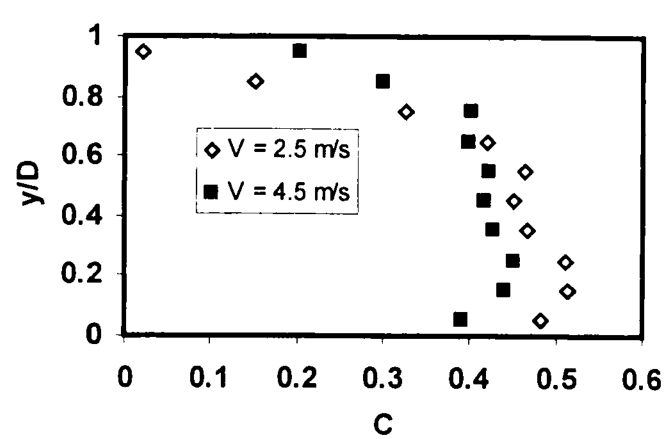

Figure 5. Solids concentration as a function of vertical position at 48°C, $C_r = 0.40$.

Discussion

Since the concentration and velocity distributions show that the slurries are still stratified when the friction converges towards that of the carrier fluid, it seems likely that the friction reduction is due to processes which occur very close to the wall. It seems plausible to regard the change in friction mechanism as being associated with a reduced probability of particle–wall contact produced by a lift force which repels the particles from the wall. The existence of a region of reduced concentration near the pipe wall at high velocities is not inconsistent with the chord-average concentration distributions shown in Figure 5.

To examine the plausibility of this hypothesis, the data obtained at $C_r = 0.40$ have been compared with predictions which use the SRC two layer model of Gillies and Shook (2000), assuming a coefficient of kinetic friction of 0.5. These results are shown in Figures 7 and 8. To show the effect of an "off-the-wall force", comparisons which assume $f_s = 0$ are also shown.

The calculations suggest that this type of change in friction mechanism could be responsible for the reduced experimental friction losses which were observed at high velocities. The cause of the phenomenon remains to be identified however.

The forces acting on a particles adjacent to the wall at a given level include the immersed weight of the contact load particles above the particle and a lubrication force which results from the fact that the surface of the particle adjacent to the wall is moving at a velocity higher than that of the fluid at the same position. In addition, particle rotation could produce an inward lift force. The "off-the-wall" force would be opposed by forces derived from particle–particle collisions, including those which transmit the immersed weight.

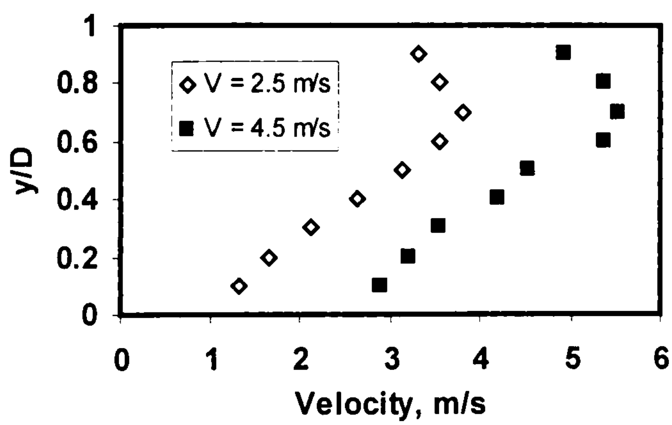

Figure 6. Velocity measured on the vertical axis at 48°C, $C_r = 0.30$.

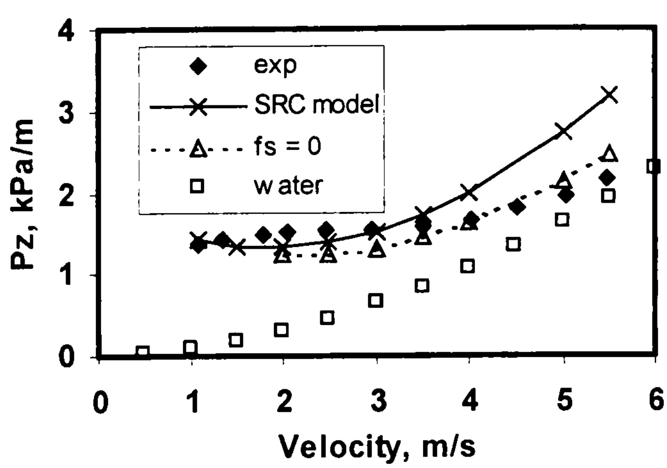

Figure 7. Model predictions at 15°C for $C_r = 0.40$.

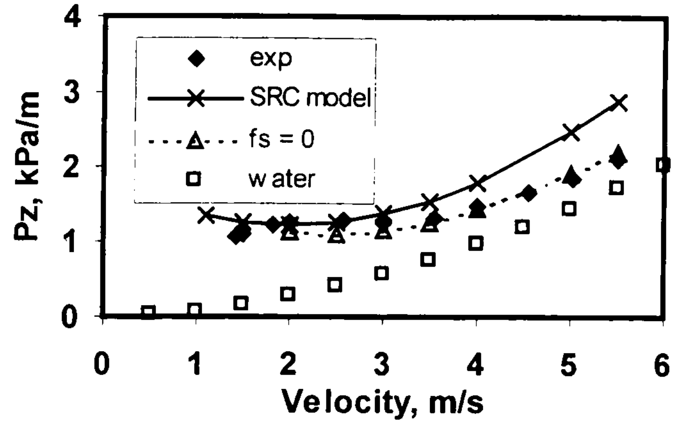

Figure 8. Model predictions at 48°C for $C_r = 0.40$.

Evidence of off-the-wall forces in slurries has been provided by concentration distribution measurements for vertical flows (McKibben,1992; Sumner, 1992) . These distributions revealed a region of depleted concentration at the pipe wall. Their experimental distributions have been used, together with a continuum model for slurry flow, to explain measured friction losses for vertical flows of particles of diameter 100 and 200 µm. These friction losses were lower than predictions made using $f_s = 0$ (Bartosik and Shook,1991).

The lubrication force on a single sphere moving parallel to a wall in a quiescent fluid is a function of relative velocity, fluid viscosity, particle diameter and the separation distance (Cameron, 1982). The present experiments show that the two-fold difference in fluid viscosity does not produce a corresponding change in the velocity required to initiate the phenomenon. This suggests that other mechanisms should be investigated.

Although it is not possible to produce a comprehensive theory from a single set of experiments, it seems clear that further study of the phenomenon is desirable. The effects of pipe diameter, particle diameter and particle density should be studied systematically so that the effects on kinetic friction and Coulomb friction can be established.

The experiments suggest that the SRC two layer model, including Equations (1), (2), (3) and (3A), is less reliable at high velocities for particles with density lower than that of sand. This deficiency may not be serious in practice since industrial slurry pipelines are usually designed to operate at low velocities near the deposition condition. However, to avoid overprediction of friction losses, prudent design practice for coal slurry pipelines should be based upon experimental measurements using the actual slurry until the cause of the anomalous low friction phenomenon is identified.

Conclusions

Experiments with slurries of narrowly sized coarse particles (d_{50} = 1 mm, S = 1.59) show that the SRC model was valid only at low velocities. At velocities above 3.5 m/s, a significant deviation occurred so that the friction converged towards that of the carrier fluid. The deviation appears to be due to particle repulsion from the wall and further systematic investigation of the phenomenon is desirable.

Nomenclature

C local (chord-averaged) solids concentration, volume fraction
C_c contact load solids concentration, volume fraction
C_r coarse particle (+74 μm) in-situ solids concentration, volume fraction
D pipe diameter, (m)
d_{50} median particle diameter, (m)
f Fanning friction factor
k wall roughness, (m)
P_z axial pressure gradient, (Pa/m)
Re_m Reynolds number of slurry flow
S density ratio, solids/fluid
v velocity at a point, (m/s)
v_∞ single particle terminal settling velocity, (m/s)
V mean velocity, (m/s)
y distance from bottom of pipe, (m)

Greek Symbols

λ linear solids concentration
μ viscosity, (Pa·s)
ρ density, (kg/m^3)

Subscripts

i denotes a particular layer, 1 = upper, 2 = lower
k denotes kinetic friction
L liquid carrier
m denotes a mean value for the mixture
s solids

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