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STUDIES OF EFFECTIVENESS PARAMETERS ON SLURRY TRANSFER

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Abstract

Solid-liquid suspension is used for solid handling and also some of reactions in the chemical and petrochemical plants are occurred in heterogenic phase. Therefore, evaluation of slurry rheology is important and must be considered slurry behavior in pipeline or channel. For this purpose, an experimental analysis of slurry flow in pipe is investigated and effectiveness parameters such as particle size, critical velocity and dilution ratio in different system are evaluated. Then, a computer program is written for velocity and pressure drop calculation.

Key words: *slurry, pressure drop, pipeline, simulation*

Theoretical Background

The pressure drop of slurry flow in a pipeline varies with flow velocity. However, unlike a pure liquid flow, it is not monotonic, as shown in Figure 1. At sufficiently high velocity, all solids are suspended and their distributions are vertically homogeneous. As the velocity decreases below a certain point, U_1 (see Fig.1), all of the solids are still suspended, but their distribution becomes vertically heterogeneous. As the velocity further decreases to the critical velocity U_2, some solids start to move (e.g., sliding, hopping, jumping) along the pipe bottom as a “bed load.” At this point, the pressure drop usually becomes the minimum.

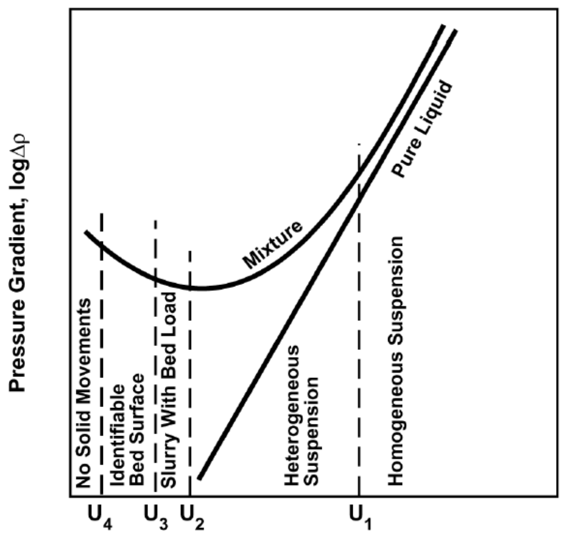

Figure 1. Pressure Drop Variation versus Velocity

As the velocity decreases further, fewer solids move as the suspended load, and more solids are transported as the bed load. At further reduced velocity, U_3, the bed load starts to generate the bed form. The bed form further increases the apparent pipe fraction factor, resulting in increased pressure drop. Finally, at further reduced velocity U_4, all solids stop moving. Thus, at critical velocity, U_2, the slurry operation is optimized and requires minimum pump pressure. However, once some solids start to move as bed load, more pressure is required to move them. The danger of plugging the pipeline arises if the pump does not have enough extra pressure to overcome this added pressure drop requirement or if the pipeline strength cannot accommodate this additional pressure requirement. Thus, to avoid potential pipeline plugging, waste transfer through the pipeline must be operated above the critical velocity, U_2.

There have been many slurry pipeline transport models developed to calculate the critical velocity and the pressure drop since Durand first developed a model based on experiments with closely sized, coarse particles carried by water. Wasp's model is "probably the best method at present". Wasp's contribution to slurry pipeline transport assessment was to introduce explicitly the concept of two-phase flow to the slurry pipeline transport. Based on coal slurry data accumulated over 13 years of experiments and actual 102-mile pipeline transport, he proposed to separate the slurry flow into two components: a vertically homogeneous slurry flow called a "vehicle" and a vertically heterogeneous slurry flow called a "Durand" flow. We now briefly describe his model, which predicts the critical velocity and the pressure drop[1].

The slurry pipe flow must be above the critical velocity based on the following conditions:

- It must be above U2 (see Fig. 1) to have all solids suspended (no bed load, as discussed above)
- It must be turbulent (for a pipe flow, Reynolds number of above 2,100 ~ 2,400)
- It must overcome the yield strength of the slurry, if any.

Wasp proposed the following model to calculate the minimum velocity required to suspend all solids by expanding the Durand model to better represent the solid concentrations and the mean particle size for more widely varied particle sizes:

$$U_c = 3.116\, C_V^{0.186} \left[2gD \left(\frac{\rho_S - \rho_L}{\rho_L} \right) \right]^{\frac{1}{2}} \left(\frac{d}{D} \right)^{\frac{1}{6}} \qquad (1)$$

Where:

CV = total solid volume fraction, D = pipe diameter, d = particle diameter (weighted mean diameter for mixed sizes), g = gravitational acceleration, UC = critical velocity

ρ_L and ρ_s = liquid and solid densities, respectively.

For Turbulent flow, the acceptable slurry Reynolds number, Re_M must be

$$\mathrm{Re}_M = \frac{\rho_m U_C\, d}{\mu_m} \geq 2300 \qquad (2)$$

Where:

μ_M = slurry viscosity, ρ_M = slurry density and the slurry density may be estimated by:

$$\rho_m = (1 - C_V)\rho_L + C_V \rho_S \qquad (3)$$

The slurry viscosity may be estimated by several different equations. Einstein expressed the mixture viscosity of laminar slurry as

$$\mu_m = \mu_L\,(1 + 2.5 C_V) \qquad (4)$$

where μ_L is the liquid viscosity.

Equation (4) is not valid for solid concentrations much greater than 1%vol. There are many slurry viscosity formulas for more concentrated suspensions, including those of polynomial expressions of the form

$$\mu_m = \mu_L\,(1 + a_1 C_V + a_2 C_V^2 + a_3 C_V^3 + \cdots) \qquad (5)$$

where a_1, a_2, and a_3 are constants. Thomas developed the following more commonly used expression by modifying Einstein's formula:

$$\mu_m = \mu_L\,(1 + 2.5\, C_V + 10.05\, C_V^2 + 0.00273\, e^{16.6 C_V}) \qquad (6)$$

We use this Einstein formula modified by Thomas (6) in the Wasp model as a default. However, if slurry viscosity values for a specific application are available, it is better to use them than to use the slurry viscosity values obtained from various equations discussed above. If the slurry has yield strength, the pipe flow must overcome the yield strength. Thomas proposed the critical velocity to be Equation (7) with the pipeline Reynolds number set to 2100 to have transition to turbulence:

$$U_C = \sqrt{\frac{\mathrm{Re}_m}{6}}\sqrt{\frac{\tau_0}{\rho_m}} \tag{7}$$

where τ_0 is the slurry yield strength. Wasp et al. recommends the slurry (effective) viscosity to be

$$\mu_{eff} = \frac{\tau_0 D}{6 U_C} \tag{8}$$

Thus Equation (7) becomes

$$U_C = \sqrt{\frac{\tau_0}{\rho}} \tag{9}$$

If the slurry has no yield strength, τ_0 is zero. Thus, U_C also becomes zero. The actual critical velocity must be the largest U_C obtained from Equations (1), (2), and (9).

To handle the widely varying particle sizes present in real industrial slurry transport conditions, Wasp proposed to separate the slurry flow into “vehicle” (homogeneous) and “Durand” flow (heterogeneous) components. The overall pressure drop of the slurry flow is the sum of the pressure drops due to vehicle and “Durand” flow components:

$$\Delta P_{Total} = \Delta P_{Vehicle} + \Delta P_{Durand} \tag{10}$$

The Wasp model determines which portion of the slurry is in the “vehicle” and which is in the “Durand” flow portion via the following relationships:

$$C_{V,Vehicle} = C_{V,total}\left(\frac{C}{C_A}\right) \tag{11}$$

and

$$C_{V,Durand} = C_{V,total} - C_{V,Vehicle} \tag{12}$$

where C/CA is calculated with Equation (13) developed by Ismail:

$$\frac{C}{C_A} = 10^{\left(\frac{-1.8W}{\beta K U^*}\right)} \tag{13}$$

where the friction velocity is given by

$$U^* = U\sqrt{\frac{f}{2}} \tag{14}$$

and, C and CA = solid volume fractions at 8% of the diameter from the top of the pipe and at the middle, respectively, W = solid settling velocity ,ß = constant (=1)

. = Von Kerman constant (= 0.35 for a slurry flow),f = the friction factor.

For the “vehicle” component, Wasp’s model treats the slurry as if it is a liquid with density and viscosity accounting for the true carrying liquid and homogeneous portion of the solids. The pressure drop per unit pipe length due to the “vehicle” is thus calculated by

$$\frac{\Delta P_{vehicle}}{L} = 4\frac{f}{D}\frac{U^2}{2g} \tag{15}$$

The friction factor f can be obtained from the Moody diagram or, equivalently, in the turbulent regime, may be expressed as

$$\frac{1}{\sqrt{f}} = 4\log\frac{D}{2\varepsilon} + 3.48 - 4\log\left(1 + 9.35\frac{D}{2\varepsilon\ \mathrm{Re}\sqrt{f}}\right) \tag{16}$$

where: Re = Reynolds number of the vehicle, ε = pipe roughness.

The Wasp model uses the Durand formula for calculating the pressure drop due to the “Durand” (heterogeneous) slurry flow component. This is expressed as

$$\frac{\Delta P_{Durand}}{L} = 82\left(\frac{\Delta P_{water}}{L}\right) C_{V,Durand} \left(\frac{g\,D\left(\frac{\rho_S}{\rho_L} - 1\right)}{U^2 \;\sqrt{C_D}} \right)^{1.5} \tag{17}$$

Where: C_D = Drag coefficient, $C_{V,Durand}$ = Volume fraction of solids in the Durand (heterogeneous) portion of the slurry flow.

The pressure drop of a water flow, ΔP_{Water}, can be obtained in the same manner as $\Delta P_{vehicle}$ with Equation (5).

These calculations are iterated until there is no measurable change for the calculated friction factor and resultant pressure drop[2-5].

Experimental tests

The pressure drop section of the test loop is pertinent to the current investigation. This straight, horizontal pipe section, measuring 6 m between the pressure transducers, was constructed of 4-inch diameter, schedule-40 stainless steel. The pressure differential was measured with a Rosemount 3051CD transmitter with a remote seal assembly with 0.25 inches of water accuracy.

The instrument validation facility is a slurry test loop capable of pumping slurry of varied physical properties at various flow rates. The slurry characteristics of the test cases considered are given in Table I.

Table (I): Slurry Loop Test Conditions

No.	Liquid flow rate	Solid flow rate	Viscosity	Solid Density	Liquid Density	Average solid particle size
	kg/hr	kg/hr	cp	gr/cm^3	gr/cm^3	mm
1	75	4.5	0.4	2	0.69	0.3627
2	6188.7	6.96	1.12	0.96	0.69	0.0966
3	11957.5	17936.5	1.05	1.5	1	0.321
4	389.2	109.7	1.47	2.24	1.59	0.04
5	3.15	0.00855	0.4	2	0.69	0.3627

Samples 1 and 5 are slurry from polypropylene plant, that solid particle of catalyst (Ziegler-Natta) is suspended in liquid phase (hexane). Sample 3 is High density polypropylene in Hexane. Samples 3,4 are Coal –Water and Silica-Iodide Potassium solution, respectively.

Discussion and results

We evaluated the slurry transferring in a pilot plant study .The Wasp slurry pipeline transport model was used for this assessment. We validated the Wasp model with experimental data and applied the Wasp model to calculate the critical velocity and expected pressure drop to determine.

The evaluation was subject to the following this restrictions:

- The slurry velocity must be greater than the critical velocity at above which all solids are suspended during the transfer.
- The slurry flow must be turbulent.

Experimental test is done for pressure drop determination and effectiveness parameter on slurry transfer is studied. If particle sizes solid increase, then pressure loss will be increased (fig.2).

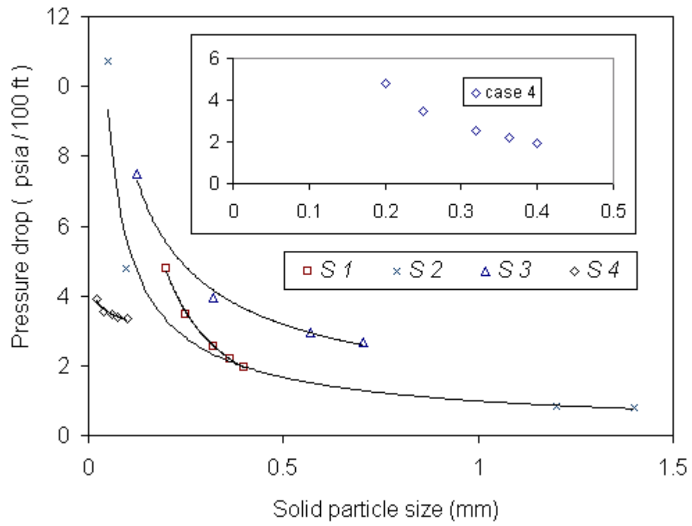

Figure 2. Pressure drop curve versus solid particle size

In some cases, it is need the slurry to dilution for transferring through the pipeline.

The dilution rate can be calculated base on system specification. Figure 3 is shown pressure drop curve versus solid volume. For the cases in which the coarse particle size distribution was assigned, pressure fluctuations may occur as significant portions of the slurry flow may be transferred as Durand (heterogeneous) flow.

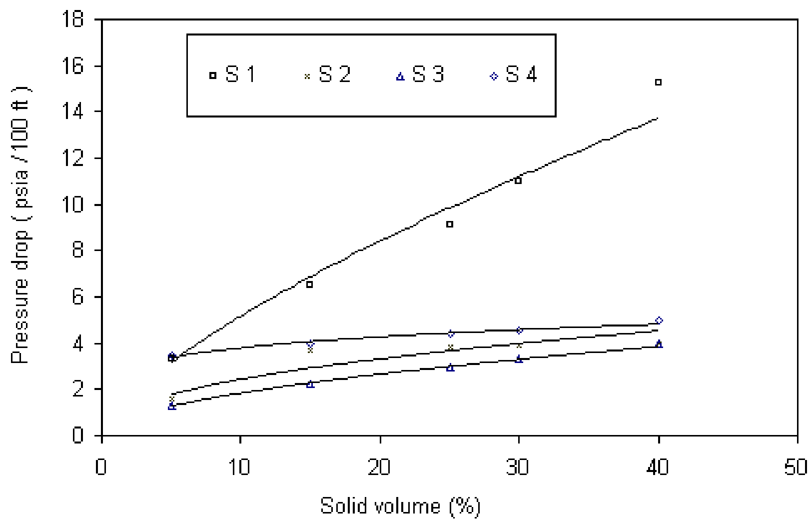

Figure 3. Pressure drop curve versus solid volume

Figures 4,5 are shown pressure drop versus relative density and pipe diameter, respectively.

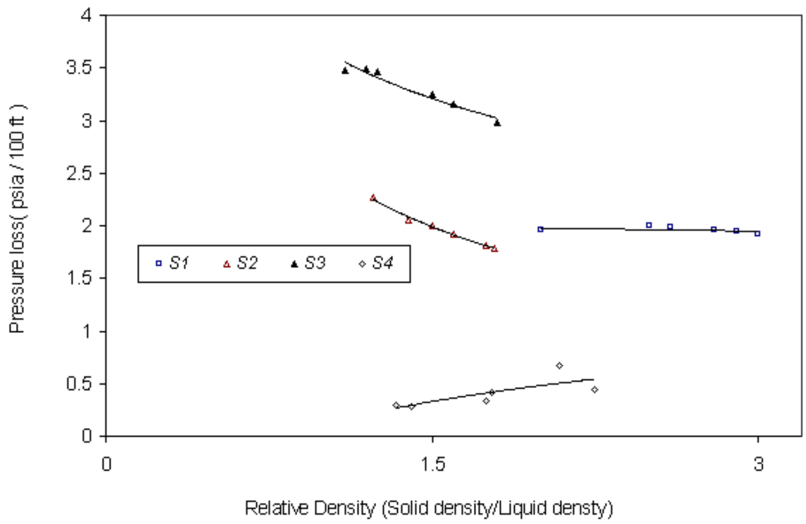

Figure 4. Pressure drop curve versus relative density

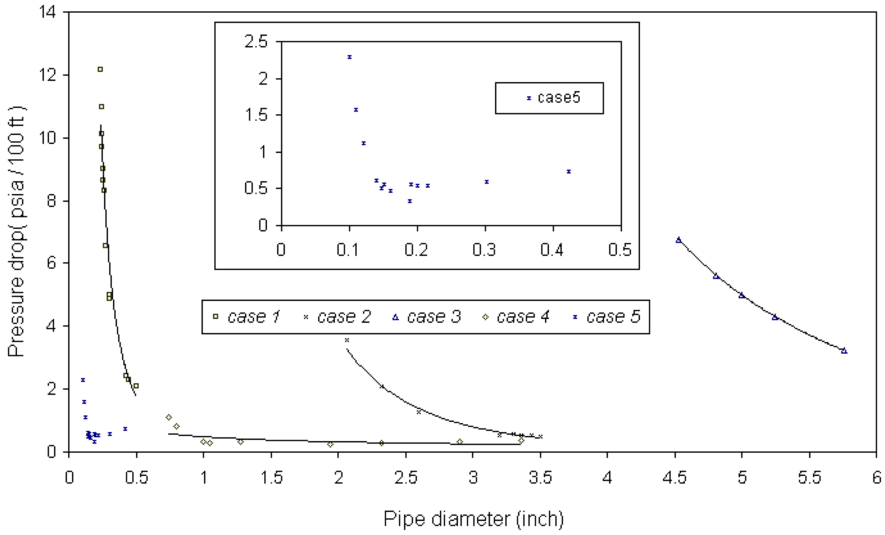

Figure 5. Pressure drop curve versus pipe diameter

For fine particle size cases, over 99% of the solids would be transferred as a vehicle (homogeneous flow), thus the pipeline pressure would remain steady.

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