EXPERIMENTAL INVESTIGATION OF SINGLE AND DOUBLE SPECIES SLURRY TRANSPORT IN A HORIZONTAL PIPELINE

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ABSTRACT

The U.S. Department of Energy (DOE) needs safe and efficient technologies for its tank waste retrieval, immobilization, and disposal activities. In the course of these activities, High-Level Waste (HLW) transfer lines have the potential to become plugged. In order to meet the DOE's needs for waste transfer technologies, Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET) is studying the mechanism and behavior of pipeline plugging. The project focuses on obtaining data and determining the conditions of slurry transport to avoid plugging of the waste slurry transfer pipeline system for high-level waste.

A laboratory-scale flow loop was designed and constructed at FIU-HCET. Recently, transport behavior of single- and double-species slurries has been studied. The single-species slurries were silica sand- and zircon sand-water mixtures. The double-species slurry was silica and zircon sand-water mixture. These two sands were selected because they have widely different densities. Thus, these sands can be representative of materials having density in the range of 2400 to 4300 kg/m^3. Both sands were sieved to the same particle size range of 75 to 150 μm. Rheology characterization of all slurries used in the tests was performed.

The relationship between the pressure drop in the straight horizontal sections of the flow loop and the mean slurry flow velocity was determined for different solids volume concentrations varying from 6.5 to 30%. The range of studied mean flow velocities was from 0.8 to 2.5 m/s. In addition, the process of bed formation, as the mean flow velocity was decreased,

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was observed visually using a CCD video camera equipped with a high magnification lens. Critical deposition velocity was determined visually and is indicated by the stoppage of the moving bed seen at the bottom of the transparent loop section. Two characteristic velocity values associated with settled bed motion were identified: one at which a sliding bed of solid particles begins to form on the bottom of the pipeline and the formed bed continues to move, the other one associated with the moving bed becoming stationary. Several empirical correlations available in the literature for critical velocity were used for comparison with the measured critical velocities. An existing empirical model that predicts the pressure gradient for a single-species slurry flow in a horizontal pipeline was used to describe the pressure drop data.

1. INTRODUCTION

As the waste tank clean-out and decommissioning program becomes active at DOE sites, the potential increases for waste transfer lines to become plugged and unable to transport waste from one tank to another or from the mixing tank to processing facilities. Some DOE sites, such as Savannah River, Hanford, and Oak Ridge, have already experienced plugged or blocked lines. Plugging may occur at additional sites at the onset of waste transfer. In order to meet DOE's needs for pipeline plugging prevention and unplugging technologies, Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET) has conducted both unplugging technologies demonstrations and lab-scale studies of pipeline plugging phenomena.

Laboratory research on the mechanism of pipe plugging phenomena is performed to determine pipeline operating conditions that will avoid pipeline plugging. The objective is to conduct systematic slurry transport experiments to understand the pipeline plugging mechanism caused by particle settling. The primary transport characteristics of interest are the pressure gradient in the pipeline versus flow velocity relationship and critical deposition velocity at which some solid particles settle out of the slurry and form a stationary bed of solids at the bottom of the pipeline. This paper presents baseline slurry transport data obtained in the horizontal pipeline flow loop for single- and double-species slurries and comparison to the prediction of Wasp's *et al.*[1] slurry transport model and critical velocity correlations available in the literature.

2. EXPERIMENTAL SET-UP

The FIU-HCET lab-scale flow loop consists of the 30-gallon slurry tank, 30-gallon water tank, Moyno 1000 progressive cavity positive displacement pump, and 30-meter 1-in O.D. pipelines. The schematic diagram of the loop is shown in Figure 1. In the slurry tank, a mixer powered by an electric motor is installed to agitate the slurry mixture to obtain homogeneous solids distribution in the tank. The rotation rate of the mixer is monitored by the ACT-2A electronic tachometer from Monarch Instruments. The loop is equipped with MAG 1100 MAGFLOW electromagnetic flow meter from EMCO, Model 1151GP gage pressure transmitters[a] at the loop inlet and outlet, and Model 1151DP differential pressure transmitters[a] in the horizontal sections of the loop. The gage pressure transmitters have a measuring accuracy of 0.1 psi. The differential pressure transmitters have a measuring accuracy of 0.3 in-H_2O. The electromagnetic flow meter has a measuring accuracy of 0.16 l/min.

[a] Rosemount Inc., 8200 Market Boulevard, Chanhassen, MN 55317, USA. www.rosemount.com

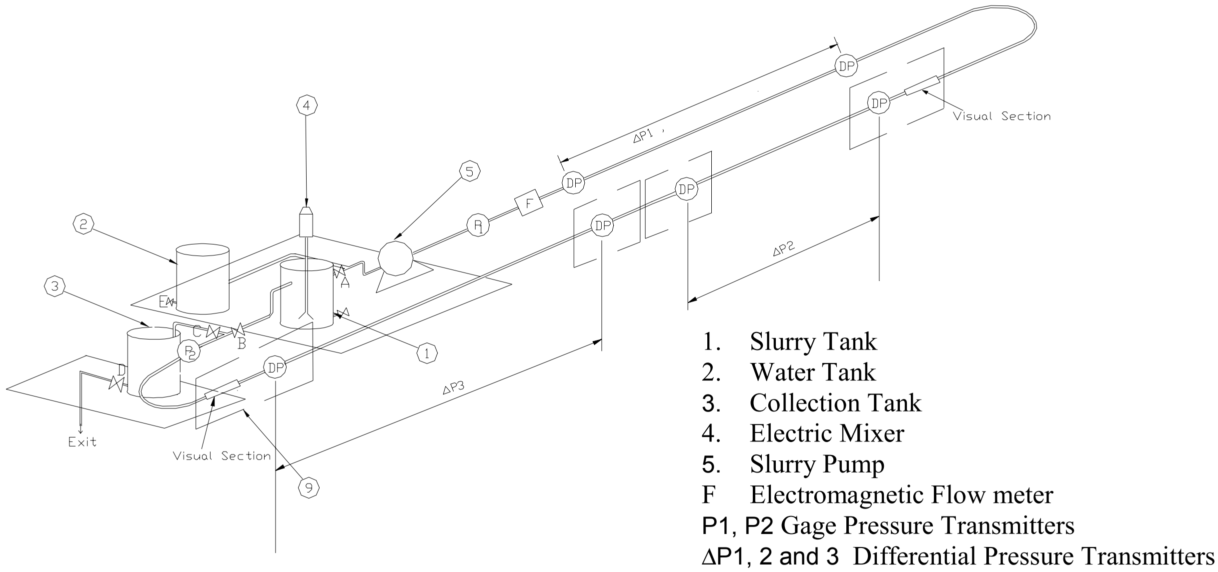

Figure 1. Schematic diagram of the flow loop.

Two kinds of sand, namely, silica and zircon, with great variation in specific gravity were chosen to prepare single- and double-species slurries for obtaining baseline data on slurry transport characteristics. The silica and zircon sand have densities of 2380 and 4223 kg/m^3, respectively, and their particle size range was the same from 75 mm to 150 mm.

The experimental procedure for pressure gradient versus flow velocity measurements was based on the common practice of slurry transport experiments in flow loops. The flow rate was controlled with the change of pump rotation frequency. The flow rates were set and numbered from maximum to minimum as 1, 2, 3, 4, 5, ……. During the experiments, the maximum flow rate was tested first, and then the odd-numbered flow rates were tested. The next step was going back to test second flow rate and the remaining even-numbered flow rates. Thus, any hysteresis in the data could be detected. For every flow rate, the pump was run at a fixed flow rate until all parameters reached steady state. Then the flow rate and pressure data were collected with the LabView-controlled data acquisition system. Fifty readings from the flow meter and each pressure transmitter were collected, and the average value was obtained.

The mean slurry velocity at which some solid particles settle out of the slurry and form a stationary bed of solids at the bottom of the pipeline is a very important transport parameter. Slurry transport at velocities equal to or less than this critical deposition velocity is considered dangerous because the flow regime is unsteady and plugging may occur due to gradual accumulations of solids in the pipeline. Thus, it is important to identify critical deposition velocity and transport slurry at a velocity higher than the critical one.

For critical velocity measurements, the following procedure was used. A CCD video camera was placed under the transparent section of the flow loop pipeline and focused on the bottom of the pipe. The slurry pump was run at a fixed flow rate (corresponding to a fully suspended flow) until all parameters reached steady state. Then the flow rate was decreased stepwise until a moving solids bed was observed through the video camera; this flow rate was measured with the data acquisition system. Each time the flow rate was decreased, the system was allowed to reach the quasi-steady state before proceeding to the next flow rate. After the flow rate for a moving solids bed was measured, the pump speed was decreased again until a stationary solids bed was observed. The flow rate for a stationary solids bed was measured, and the pump speed was increased to a fully suspended flow value to clear the solids accumulated in the pipeline.

3. WASP'S MODEL FOR PRESSURE GRADIENT IN A HORIZONTAL PIPELINE

Wasp *et al.*[1] developed an empirical method for calculating the pressure gradient in a horizontal pipeline as the sum of the gradients due to the symmetrically suspended material and to the asymmetrically suspended and sliding material. Wasp *et al.* pointed out that with a reasonable range of particle sizes present in a slurry, the smallest particles will normally be in the symmetric concentration flow pattern, the intermediate and large particles will be in the asymmetric pattern, and the largest may slide on the bottom of a pipe. Wasp's method provides a systematic means of interpolating between the two flow pattern extremes of homogeneous flow and asymmetric suspension and sliding bed flow, thus obtaining the results for usual mixed-size slurries. The central feature of the Wasp's model is determination of split between the homogeneous and heterogeneous portions of the slurry. This is done using the method proposed by Ismail[2]:

$$\log\frac{C}{C_A} = -1.8\frac{W_t}{0.4\cdot U^*} \tag{1}$$

where $\frac{C}{C_A}$ is the ratio of solids volume concentrations at 0.08 D from pipe top and at the pipe center, W_t is terminal settling velocity of solids, and $U^* = V\sqrt{\frac{f}{2}}$ is the friction velocity. Then the pressure gradient due to homogeneously suspended solids is determined by single-phase methods assuming Newtonian behavior. Pressure gradient due to asymmetrically suspended solids is determined by the empirical correlation of Durand[3]:

$$\Delta p_{asym} = 150\cdot\Delta p_w\cdot C_{\text{v}}\cdot\left[\frac{g\cdot D\cdot(\rho_s/\rho_l - 1)}{V^2\cdot\sqrt{C_D}}\right] \tag{2}$$

where C_{v} is the solids volume concentration in the slurry, D is a pipe internal diameter, ρ_s and ρ_l are density of solids and of carrier fluid respectively, V is the average flow velocity, and C_D is the drag coefficient of the particles. Finally, total pressure gradient is taken as the sum of pressure gradients due to the symmetrically suspended material and that due to the asymmetrically suspended one. The work of Wasp *et al.* is of great practical significance since it is based on, and confirmed by, extensive tests on large diameter commercial pipelines transporting coal-water slurries.

Since this method was developed for single-component slurries, it was decided to first test it for single-component sand-water slurries and then try to apply it for a double-species slurry with some modification. For each sand-water slurry, calculations were performed with three different correlations for slurry viscosity. One correlation was that of Thomas[4] (equation 3), the second is that of Landel[5] (equation 4), and the third correlation is that for slurry consistency obtained from rheology measurements. These three correlations were used to see which one would result in the best predictions of the pressure gradients by Wasp's model.

$$\mu_{sl} = \mu_w\cdot\left(1 + 2.5\cdot C_{\text{v}} + 10.05\cdot C_{\text{v}}^2 + 0.00273\cdot\exp(16.6\cdot C_{\text{v}})\right) \tag{3}$$

$$\mu_{sl} = \mu_w \cdot \left(1 - \frac{C_v}{(C_v)_{max}}\right)^{-2.5} \quad (4)$$

where μ_w is the viscosity of suspending medium (in this case, water), C_v is solids volume concentration in the slurry, and $(C_v)_{max}$ is maximum obtainable solids volume concentration.

To apply Wasp's model for double-species slurry, physical properties data of the slurry were adapted to fit the model. The weighted average method was used to calculate the average density of solids in the slurry and average densities of particles in different size ranges.

4. PRESSURE GRADIENTS

4.1. SILICA SAND-WATER SLURRY

Experimental pressure gradient curves for silica sand-water slurry are compared with Wasp's model predictions in Figure 2. Solids volume concentrations C_v are 6.5, 9.9, 18.9, and 28% (14.2, 20.9, 35.7, 48 wt%, respectively by weight), and average flow velocities are in the range of 0.4 to 2.5 m/s. Results of silica sand-water slurry characterization are summarized in Table 1. Wasp's model very well predicts pressure gradients for low solids volume concentration and flow velocities above 1 m/s, when Landel's or Thomas's correlations for viscosity are used. Pressure gradient curves for Landel's and Thomas's correlations for viscosity almost coincide because these correlations give almost the same viscosity for low solids volume concentrations. For higher volume concentrations (20% and above), the model under-predicts the pressure drop as high as 15%, and the under-prediction increases with increasing solids volume concentration. When slurry consistency was used as viscosity, the model considerably over-predicted the pressure drops. This over-prediction decreases with the increase in solids volume concentration especially in the low flow velocity range.

Table 1. Silica sand-water slurry properties.

Solids density, kg/m^3		2381
Bulk solids density, kg/m^3		1571
Void fraction, %		21.3
Slurry density, kg/m^3	C_v = 9.9 %	1014
	C_v = 18.9 %	1418
	C_v = 28 %	1610
Rheology (τ, Pa; γ, 1/s)	C_v = 9.9 %	$\tau = 0.005923\ \gamma + 3.077$
	C_v = 18.9 %	$\tau = 0.006253\ \gamma + 3.23$
	C_v = 28 %	$\tau = 0.006632\ \gamma + 3.44$

4.2. ZIRCON SAND-WATER SLURRY

Experimental pressure gradient curves for zircon sand-water slurry are compared with Wasp's model predictions in Figure 3. Solids volume concentrations C_v are 6, 10, 20, and 27% (21.2, 31.9, 51.4, and 61 wt%, respectively by weight), and average flow velocities are the range of 0.4 to 2.5 m/s. Results of zircon sand-water slurry characterization are summarized in Table 2. Similar to the silica sand results, there is a good agreement of model predictions with experiments for low solids volume concentration of C_v = 6%, when Landel's or Thomas's correlations for slurry viscosity are used. Pressure gradient curves corresponding to these correlations practically coincide; a difference could only be noted on the plots for C_v = 20%. For higher solids concentrations, better prediction is obtained when slurry consistency is used as viscosity in the model. In general, using Landel's and Thomas's correlations results in under-prediction of the pressure drop, while using consistency results in over-prediction of the pressure drop.

Table 2. Zircon sand-water slurry properties.

Solids density, kg/m^3		4223
Bulk solids density, kg/m^3		2714
Void fraction, %		35.8
Slurry density, kg/m^3	C_v = 6 %	1194
	C_v = 10 %	1322
	C_v = 20 %	1639
	C_v = 27 %	1840
Rheology (τ, Pa; γ, 1/s)	C_v = 6 %	$\tau = 0.0041\,\gamma + 1.86$
	C_v = 10 %	$\tau = 0.0044\,\gamma + 2.01$
	C_v = 20 %	$\tau = 0.0056\,\gamma + 2.50$
	C_v = 27 %	$\tau = 0.0066\,\gamma + 2.81$

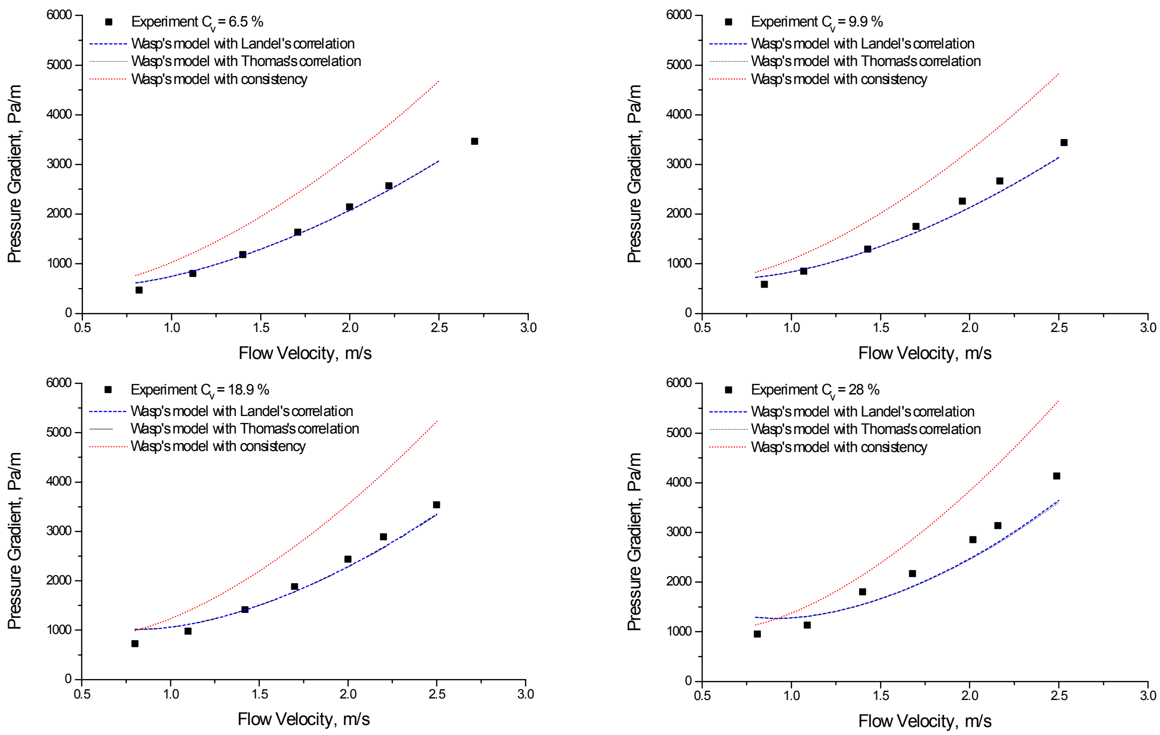

Figure 2. Comparison of Wasp model predictions and experimental results for silica sand-water slurry: a) C_v = 6.5%; b) C_v = 9.9%; c) C_v = 18.9%; d) C_v = 28%.

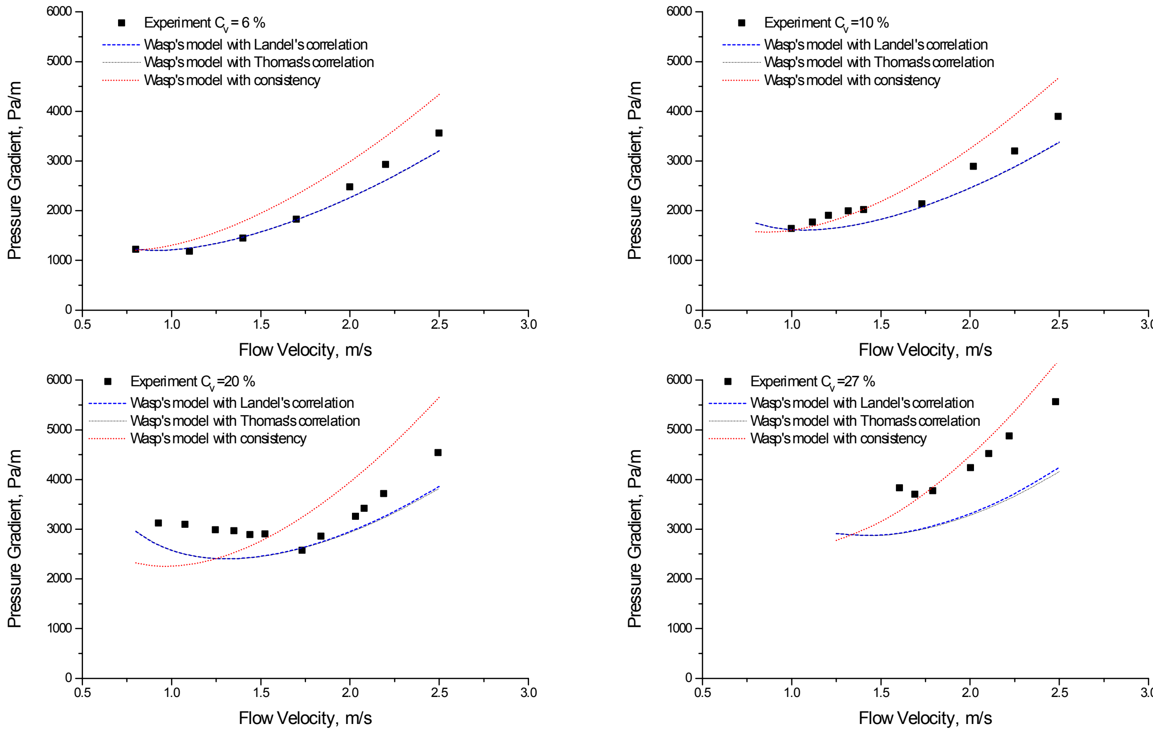

Figure 3. Comparison of Wasp model predictions and experimental results for zircon sand-water slurry: a) $C_v = 6\%$; b) $C_v = 10\%$; c) $C_v = 20\%$; d) $C_v = 27\%$.

4.3. DOUBLE-SPECIES SAND-WATER SLURRY

Experimental pressure gradient curves for double-species (zircon and silica) sand-water slurry are compared with Wasp's model predictions in Figure 4. Solids volume concentrations C_v are 6.1, 10, 20.7, and 30% (18.2, 25.8, 42.3, and 53.8 wt%, respectively by weight), and average flow velocities are in the range of 0.4 to 2.5 m/s. Results of double-species sand-water slurry characterization are summarized in Table 3. Best model predictions were obtained for low solids volume concentration of $C_v = 6.1\%$ using Landel's or Thomas's correlations for slurry viscosity. For higher solids concentrations, using Landel's or Thomas's correlations results in over-prediction of the pressure drop for low flow velocities and under-prediction of the pressure drop for high flow velocities. With these correlations, Wasp's model gives good pressure drop predictions for mean flow velocities in the range from 1.25 m/s to 1.75 m/s. When slurry consistency is used as viscosity in the model, predicted pressure drops are always higher than experimentally observed ones. Over-prediction is higher for high flow velocities and reaches up to 20%.

Table 3. Double-species sand-water slurry properties.

Solids volume concentration, %	Solids density, kg/m^3	Bulk solids density, kg/m^3	Void fraction, %	Slurry density, kg/m^3	Rheology (τ, Pa; γ, 1/s)
6.1	3400	1897	48.1	1050	$\tau = 0.0039\ \gamma + 1.77$
10	3530	1910	46.7	1221	$\tau = 0.0057\ \gamma + 2.65$
20.7	3565	1987	42.3	1390	$\tau = 0.0059\ \gamma + 2.73$
30	3440	2115	38.5	1728	$\tau = 0.0065\ \gamma + 2.92$

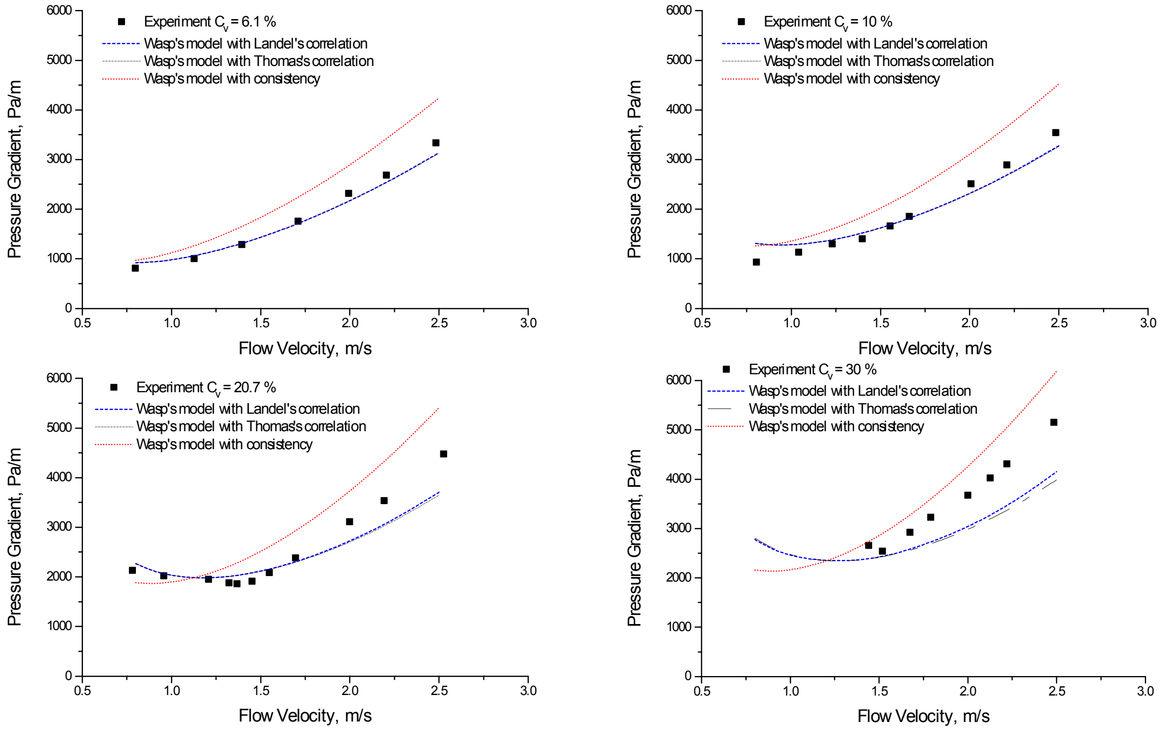

Figure 4. Comparison of Wasp model predictions and experimental results double-species sand-water slurry: a) $C_v = 6.1\%$; b) $C_v = 10\%$; c) $C_v = 20.7\%$; d) $C_v = 30\%$.

5. CRITICAL DEPOSITION VELOCITY

Several correlations for critical transport velocity available in the literature were examined to check how well they predict experimental data. One of the tested correlations is that of Durand[3]:

$$V_c = F_L \left[2gD \left(\frac{\rho_s - \rho_l}{\rho_l} \right) \right]^{0.5} \tag{5}$$

where F_L is a dimensionless factor that depends on particle size and concentration, D is pipe diameter, ρ_s is the density of transported solid particles, and ρ_l is the density of carrier fluid (in this case, water).

Dimensionless factor F_L can be determined from the plot shown in Figure 5. For typical experimental conditions of particle sizes below 150 µm and solids volume concentrations above 5%, the value of F_L is approximately the same and equals 0.95.

Using the above value in the equation (5) results in critical velocities for sand-water slurries presented in Figure 6. When compared with experimentally determined values, values from Durand's correlation under-predict the critical velocity by as much as 31% for silica sand, 41% for zircon sand, and 45% for double-species sand. Wasp *et al.*[1] pointed out that Durand's correlation does not fully describe the effect of solids density on critical velocity, giving best predictions for silica sand-water slurries. This is in agreement with our findings.

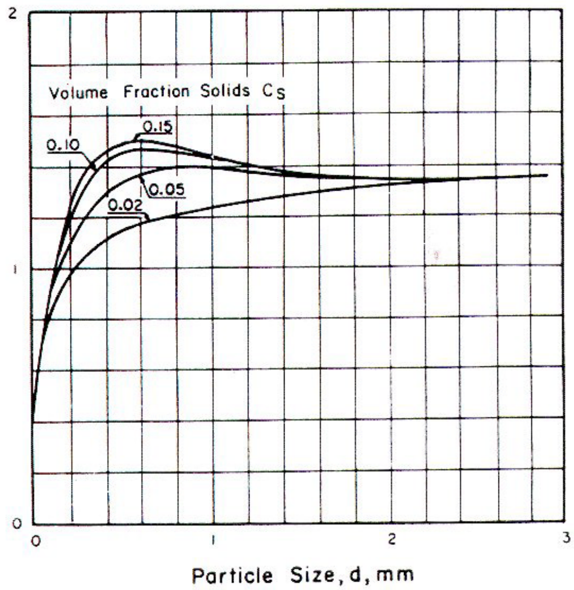

Figure 5. Dimensionless factor F_L for Durand's[3] correlation of critical velocity.

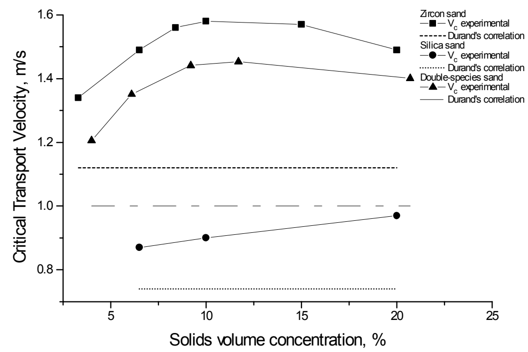

Figure 6. Comparison of critical velocities measured experimentally and predicted by Durand's[3] correlation.

Another tested correlation was developed by Sinclair[6] based on the experiments in small pipes (1/2 to 1 in) with closely sized sand, coal, and iron particles in the size range from 30 to 2000 μm. Sinclair showed that critical transport velocity depends on solids concentration, and it has a maximum at intermediate solids volume concentrations between 5 and 20%. He also found that for $d_{85}/D < 0.001$, critical velocity becomes independent of d/D ratio (here d is solid particle diameter, D is pipe inner diameter, and d_{85} is the particle diameter, such that 85% by weight of particles are less than d_{85}). For this case of $d_{85}/D < 0.001$, Sinclair developed correlation for maximum value of critical velocity (equation 6). He also presented the relationships for critical velocity normalized by its maximum value with solids volume concentration in the form of a graph, as shown in Figure 7.

$$\frac{(V_c)^2_{\max}}{g \cdot d_{85} \cdot (\rho_s/\rho_l - 1)^{0.8}} \approx 650 \qquad (6)$$

Comparison of critical transport velocity measured in these experiments with three types of sand and the critical velocity predicted by Sinclair's correlation is shown in Figure 8. Good agreement between the experiments and the correlation was found for zircon and double-species sand-water slurries with average difference about 5%. For silica sand-water slurry, Sinclair's correlation over-predicts the critical velocity by about 15% for C_v of 6.5 and 10%.

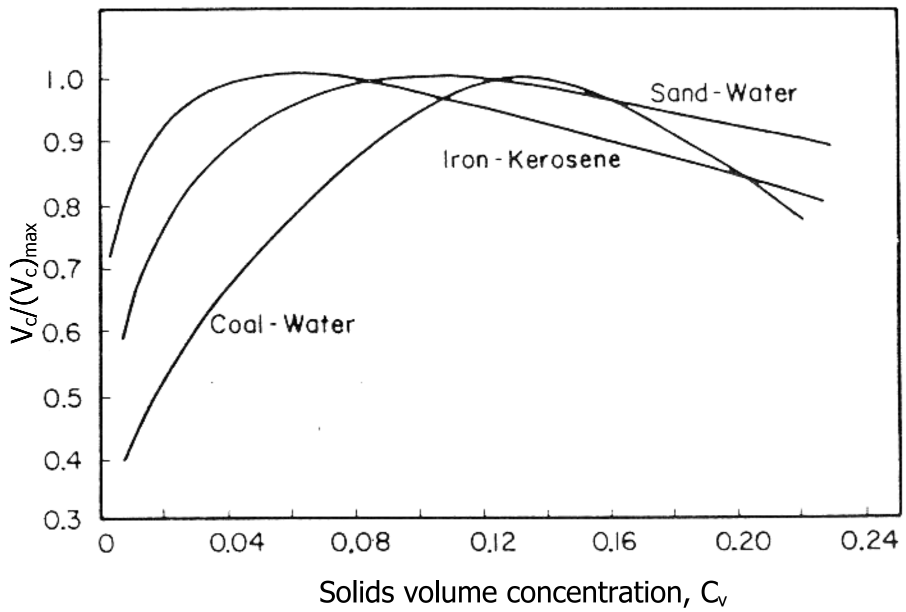

Figure 7. Dimensionless critical transport velocity dependence on solids volume concentration (Sinclair[6]).

The third tested correlation for critical velocity was developed by Thomas[7]. Thomas developed separate correlations for particle sizes above and below the thickness of the laminar sublayer defined as

$$\delta = \frac{5\mu}{\rho_l \cdot U_c^*} \tag{7}$$

where U^*_c is the friction velocity corresponding to the flow at critical velocity V_c, assuming a zero concentration of particles:

$$U_c^* = V_c\sqrt{\frac{f}{2}} \tag{8}$$ *

For $d/\delta < 1$, Thomas gives the following correlation for critical velocity:

$$\frac{W_t}{U_c^*} = 0.010 \cdot \left[\frac{d \cdot U_c^* \cdot \rho_l}{\mu}\right]^{2.71} \tag{9}$$

and for $d/\delta > 1$,

$$\frac{W_t}{U_c^*} = 4.90\left[\frac{d \cdot U_c^* \cdot \rho_l}{\mu}\right] \cdot \left[\frac{\mu}{D \cdot U_c^* \cdot \rho_l}\right]^{0.60} \cdot \left(\frac{\rho_s}{\rho_l} - 1\right)^{0.23} \tag{10}$$

where W_t is terminal settling velocity of solids in the carrier fluid (in this case, water), d is solids particle diameter, and D is the pipeline inner diameter.

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* f is a friction factor, which for a turbulent flow can be calculated using equation proposed by Colebrook (1939):

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

Comparison of critical transport velocities predicted by Thomas's correlation and measured in our experiments is shown in Figure 9. The figure shows that Thomas's correlation considerably under-predicts critical velocities for zircon and double-species sand-water slurries; for silica sand-water slurry, the agreement between the correlation and experiments is better, but still the under-prediction is as high as 15%. Thus, similar to Durand's correlation, Thomas's correlation does not well describe the effect of solids density on the critical velocity.

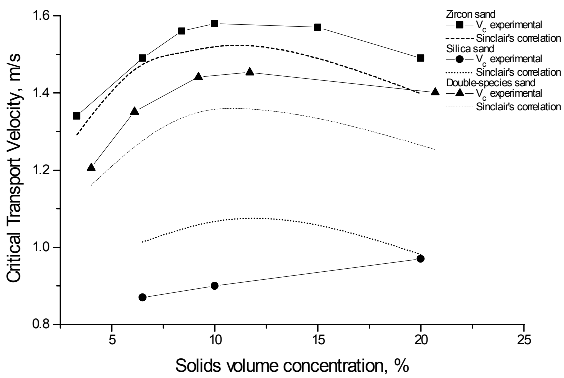

Figure 8. Comparison of critical velocities measured experimentally and predicted by Sinclair's[6] correlation.

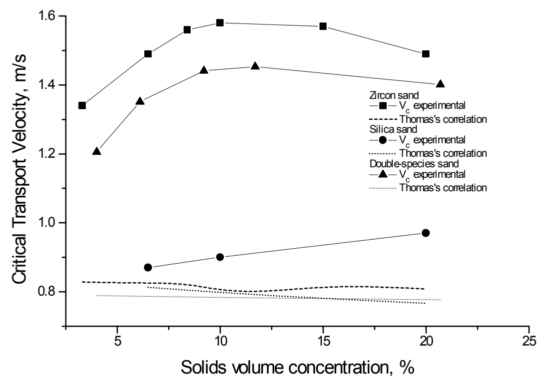

Figure 9. Comparison of critical velocities measured experimentally and predicted by Thomas's[7] correlation.

6. CONCLUSIONS

Baseline slurry transport data were obtained for simple single- and double-species sand-water slurries. Pressure gradient versus flow velocity relationships and critical transport velocities were measured for two kinds of sand (silica and zircon) with different specific gravities as well as for double-species sand composed of silica and zircon sands. It was found that pressure gradient in the pipeline increases with increasing solids volume concentration in the slurry for all tested slurries. For the same mean flow velocity, pressure gradient is higher for the sand with higher specific gravity. Slurry flow velocities at the formation of a moving bed and a stationary bed increase with increasing solids volume concentration as well as with increasing specific gravity of the transported sand.

Wasp *et al.*'s[1] empirical method for calculating the pressure gradients in horizontal pipelines was examined to see how well it can predict obtained experimental results. Acceptable agreement between predicted pressure gradients and experimentally measured ones was obtained for slurries with solids volume concentrations below 10% transported with mean flow velocities from 1 to 2.5 m/s. Such an agreement was obtained when Landel's[5] or Thomas's[4] correlation was used to estimate the slurry viscosity. Using experimentally measured slurry consistency as slurry viscosity resulted in over-prediction of the pressure gradients.

Using the weighted average method to adapt double- and multi-species slurries, physical properties for the Wasp's model designed for single-species slurries proved to be satisfactory. Further testing of the model with different multi-species slurries is necessary to have better confidence in applying the model for multi-species slurries. Thus, Wasp's model can be used for preliminary design or estimation purposes to predict the pressure gradients for slurries at low solids volume concentrations. The model could be used with Landel's or Thomas's correlation and with slurry consistency to approximate lower and upper boundaries of the expected pressure gradients.

Three correlations for critical transport velocity from the open literature were examined to compare their predictions with experimentally observed values. It was found that Durand's[3] and Thomas's[7] correlations do not describe well the effect of transported solids density on the critical velocity. Both these correlations give the best predictions for silica sand-water slurry, most likely because they were developed based on experimental data for this type of slurry. Sinclair's[6] correlation agreed reasonably well with zircon and double-species sand-water slurry data but did not work well for silica sand-water slurry. Compared to the other two correlations, Sinclair's correlation well described the effect of the solids density on the critical velocity. Even though Sinclair's correlation was developed for single-species slurries, it gave good predictions for double-species slurry, when weighted average solids density was used. Further evaluation of this correlation is necessary for more complex multi-species slurries. However, for evaluation and preliminary design purposes, this correlation is recommended over Durand's and Thomas's correlations.

NOMENCLATURE

C	concentration, %
C_D	drag coefficient, dimensionless
D	internal diameter of a pipeline, m
d	solid particle diameter, m
d_{85}	particle diameter, such that 85% by weight of particles are less than d_{85}, m
F_L	Durand's[3] dimensionless factor used in critical velocity correlation, dimensionless
f	friction factor, dimensionless
g	gravitational acceleration, m/s
Δp	pressure drop, Pa
Re	$= \frac{\rho V D}{\mu}$ Reynolds number, dimensionless
U^*	$= V\sqrt{\frac{f}{2}}$ friction velocity, m/s
V	mean velocity, m/s
W_t	terminal settling velocity of solid particle, m/s

Greek Symbols

ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
δ	laminar sublayer thickness, m
ε	pipeline roughness, m

Subscripts

asym	asymmetric
c	critical

l liquid
max maximum
s solid
sl slurry
v volume
w water
wt weight

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