Friction reduction in pipe flow of coarse slurry by fines addition – experimental study

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Abstract. Very coarse basalt-water slurry forming fully stratified flow with a sliding bed and producing considerable friction loss was tested in a laboratory pipe. A considerably finer fraction of sand was added in steps to gradually increase the concentration of this fraction in the flowing slurry. The frictional pressure drop was measured together with the slurry discharge and slurry density. Furthermore, solid particles and their motion were observed at the bottom of the pipe. This observation indicated that finer particles in basalt-based bimodal slurry flows positioned themselves below the coarse particles at the pipe wall. The experimental results show that a quite small amount of fines is sufficient to produce a considerable friction reduction in settling slurry flow. Furthermore, the results indicate that there is a certain optimum quantity of fines at which the maximum reduction is reached and further addition of the fines does not bring any further improvement.

1 Introduction

In industrial practice of pipeline slurry transport, it is a well-established experience that broad grading of transported solids has a benign effect on the overall energy loss if settling slurry is transported. Settling slurries are mixtures of carrying liquid (typically water) and solid particles, which tend to settle quickly to the bottom of a pipe if flow is reduced or stopped [1]. Although the benign effect has been confirmed by experiments [2-8], it has not been until recently that sufficiently detailed information was available about conditions and mechanisms associated with the effect. Also, information was insufficient to quantify the effect at specific transport conditions.

Recently, a series of experimental campaigns was carried out in two major slurry-transport laboratories: one in Grovetown, GA, USA [9-11], and the other in Prague, Czech Republic [12-13]. Results of measured friction losses in pipe flows of bimodal- and broad-graded settling slurries composed of water and various fractions of sand and rock revealed that a presence of fine-to-medium- or medium sand significantly reduced friction produced by coarser fractions in slurry flow [14]. It was shown that the friction reduction is associated with a flow stratification and thus with an existence of a sliding bed composed of coarse particles in combination with an existence of a thin layer of finer particles that develops below the coarse sliding bed [12-13]. The thin layer effectively separates the sliding bed from the pipe wall and reduces mechanical friction between particles of the sliding bed and the wall.

The observations have raised two questions. First, how much fine material is required to constitute the separation layer and to make the reduction mechanism effective? Second, how much fine material is required to reach the maximum reduction? This paper reports on results of an experimental study carried out in a laboratory slurry-pipe loop to find answers to the two raised questions.

2 Experiment

The laboratory experiment was carried out in a slurry-pipe loop of the Institute of Hydrodynamics in Prague in 2022. The loop, its equipment and measuring techniques used for slurry flow tests are described in detail in [12]. Therefore, a short summary only is given below.

2.1 Set-up and instrumentation

A pipe of the loop has a nominal internal diameter of 100 mm and contains pressure-drop measuring sections in horizontal and vertical parts of the loop. A measuring equipment of importance for the reported experiment includes a magnetic flowmeter for measuring the mean velocity of slurry \( V_m \), and differential pressure transducers (DPT) sensing manometric pressure differences over the measuring sections. A horizontal pipeline includes a transparent section which enables to observe flow stratification and formation of deposit in the pipe at low velocities of settling slurry flow.

2.2 Tested solids

Stones of rounded basalt were used as a coarse fraction for tested slurries (code BA0816 in Table 1, where \( d_{50} \) is the median particle size and \( d_{85} \) is the particle size at 85

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per cent on a particle size distribution curve of a solids fraction). The BA0816-fraction was narrowly graded and particles were rounded because they had been used previously for other slurry-pipe tests. Three considerably finer fractions of sand (STJ25, SP3031, SP0612) were used as additives to form various bimodal slurries (Table 1).

### Table 1. Properties of tested solids fractions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Fraction code</th>
<th>(d_{50}) [mm]</th>
<th>(d_{85}) [mm]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>basalt</td>
<td>BA0816</td>
<td>12.0</td>
<td>14.8</td>
<td>2860</td>
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<tr>
<td>sand</td>
<td>SP0612</td>
<td>0.87</td>
<td>1.20</td>
<td>2620</td>
</tr>
<tr>
<td>sand</td>
<td>SP3031</td>
<td>0.55</td>
<td>0.78</td>
<td>2600</td>
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<td>sand</td>
<td>STJ25</td>
<td>0.22</td>
<td>0.35</td>
<td>2630</td>
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2.3 Test runs

The main goal of the experiment was to find out how much fine additive is required to produce significant friction reduction in coarse slurry flow and to find out whether there is a certain optimum quantity of additive to reach the maximum reduction. To reach the goal, the experimental procedure was set so that a constant mass of the coarse fraction was introduced to the loop and measured and then a given mass of a finer fraction was added and measured before another mass was added and so on up to the maximum mass (Table 2). The fixed mass of the coarse basalt was 325 kg for each of the test runs. The added masses of the finer sands (either STJ25 or SP3031) were 25, 50, 100, and 160 kg respectively. The coarsest sand (SP0612) was added at one mass only and it was 100 kg.

### Table 2. Test runs and used fractions.

<table>
<thead>
<tr>
<th>Test run No.</th>
<th>BA0816</th>
<th>STJ25</th>
<th>SP3031</th>
<th>SP0612</th>
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<tr>
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<td>325</td>
<td>160</td>
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<td></td>
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<tr>
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<td>325</td>
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<td></td>
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<tr>
<td>11</td>
<td>325</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>325</td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

3 Results

For each test run, experimental results for quantities of interest were collected in a range of flow velocities from the maximum 2.5 m/s down to the deposition limit velocity (the flow velocity at which first particles stop moving and start to develop a stationary deposit at the bottom of the pipe) and below. The experimental results included the pressure drop in a horizontal pipe section and the delivered concentration obtained from a pressure drop measurement in a vertical section of the loop. At selected velocities, the motion of particles was filmed at the bottom of the transparent pipe section. In the same section, the deposition limit velocity was observed and evaluated for each test run.

### 3.1 Visual observations

The visual observations were instrumental in an evaluation of the degree of flow stratification if only the coarse fraction was transported in the loop. They confirmed that the basalt-slurry flow was fully stratified in the entire range of installed velocities. If the fines were added then the carrying liquid was no longer clear enough to do visual observations inside the flow except for the very bottom of the pipe. The pipe-bottom observations (and collected videos) revealed that if added to the loop then sand particles of any of the added fraction positioned themselves at the bottom of the pipe below the coarse particles and reduced the contact of the basalt particles with the pipe wall. This was the case for each concentration of a sand fraction, including the lowest concentration associated with the added mass of 25 kg (Figure 1). As discussed below, this behaviour is a key for an explanation of modifications in the frictional pressure gradient caused by sand addition to coarse basalt slurry.

![Fig. 1. Camera images of flow at the bottom of a horizontal pipe at flow velocity 2.5 m/s. Upper image: basalt BA0816 slurry (Test No. 6), lower image: bimodal slurry with added 25 kg of sand SP3031 (Test No. 7).](image-url)
3.2 Frictional pressure gradient

3.2.1 Bimodal slurry tests with STJ25

![Fig. 2. Measured dimensionless frictional pressure gradient for basalt slurry and bimodal slurry with STJ25 additive.](image)

Legend: x = water, + = Test No. 1, blue square = Test No. 2, magenta diamond = Test No. 3, red circle = Test No. 4, green triangle = Test No. 5.

Figure 2 compares dimensionless frictional pressure gradients ($i_m$ for slurry, $i_f$ for water) for various masses of the fine to medium sand (STJ25) added to the very coarse BA0816 slurry (Tests Nos. 1-5). It is apparent that already an addition of a small quantity (25 kg, Test No. 2) of the sand causes a very significant reduction of the frictional pressure gradient at the flow velocities above the deposition limit, which is near 1 m/s. Furthermore, it appears that the reduction in the frictional pressure gradient increases with the added mass up to the mass at which the maximum reduction is achieved, which is 100 kg (Test No. 4) for $V_m < 2$ m/s and 50 kg (Test No. 3) for $V_m > 2.0$ m/s. Test No. 5 with the total added mass of 160 kg of STJ25-sand produces slightly higher overall friction loss than tests Nos. 3-4.

3.2.2 Bimodal slurry tests with SP3031

The results of tests Nos. 6-10 are plotted in Figure 3. The friction behaviour of flow of bimodal slurry in which medium sand (SP3031) is used as an additive, instead of the finer STJ25 used previously, is very similar to the behaviour of the previous bimodal slurry. A small amount of the medium sand (25 kg) causes a very significant reduction of the friction loss at velocities above the deposition limit. Compared to the previous bimodal slurry, values of the frictional pressure gradient are higher, demonstrating that the medium sand is less effective in the friction loss reduction than the fine-to-medium sand. Furthermore, the friction losses for different added masses differ less in the entire range of flow velocities above the deposition limit than it was the case with the previous bimodal slurry.

3.2.3 Bimodal slurry test with SP0612

![Fig. 4. Measured dimensionless frictional pressure gradient for basalt slurry and bimodal slurry with SP0612 additive.](image)

Legend: x = water, + = Test No. 11, red circle = Test No. 12.

Test No. 12 was carried out to find out whether a relatively coarse sand, which itself tends to develop a coarse sliding bed at flow velocities not too far above the deposition limit is capable to reduce friction in flow of slurry containing much coarser particles like the basalt particles. The test result is quite interesting. It turns out that the medium-to-coarse sand (SP0612) contributes weakly to friction loss reduction at velocities above the deposition limit (Figure 4) but this threshold velocity is considerably higher than in slurry flow of basalt without the added SP0612-sand. In the bimodal flow, the SP0612 particles stop sliding over the bottom of a pipe at the flow velocity of about 1.55 m/s, i.e., the velocity at which the basalt particles still move.

3.3 Deposition limit velocity

Incipient deposition (the moment at which first particles stop sliding at the bottom of a pipe) was observed visually in the transparent section of a horizontal pipe in each test run. It did not vary significantly for different
test runs and typically it was detected at flow velocities slightly above 1 m/s. One-species basalt slurry exhibited the deposition-limit velocity $V_d$ of about 1.1 m/s based on the visual observation. It can be seen in Figures 2-3, that this velocity corresponds with the velocity at which the reduction starts to be felt in bimodal flows, because the measured relations between the dimensionless pressure gradient $i_m$ and flow velocity $V_m$ for bimodal slurries start to deviate from those for the one-species coarse basalt slurry. If the plots are zoomed in this range of velocities (Figures 5-6), it appears that there is a weak sensitivity of $V_d$ to the composition of the bimodal flow, at least for the STJ25-containing bimodal slurry flow. In Figure 5, $V_d$ values estimated from the friction curves vary from the maximum value of about 1.1 m/s (Test No. 2) to the minimum value of approximately 0.9 m/s (Test No. 4).

![Fig. 5. Measured dimensionless frictional pressure gradient for basalt slurry and bimodal slurry with STJ25 additive. Legend: black = Test No. 1, blue = Test No. 2, magenta = Test No. 3, red = Test No. 4, green = Test No. 5.](image)

The bimodal slurries containing SP3031 (Test Nos. 7-10) exhibit less variation in the $V_d$ values estimated from the shapes of the friction curves (Figure 6). This is consistent with the very weak variation in the friction loss over the entire range of flow velocities for these slurries, as shown in Figure 3. Based on the shapes of the friction curves (i.e., on the deviation of the bimodal-slurry curves from the basalt-slurry curve), $V_d = 1.0$ m/s (see Figure 6).

4 Discussion and comparison with model predictions

4.1 Reduction of friction loss

4.1.1 Friction reduction mechanism

In [12-13], it is described how the fine-to-medium sand STJ25 reduces the friction loss if it is added to slurry flows of very coarse sand (particles of about 2 mm). It has been shown that the prevailing mechanism responsible for the friction loss reduction is associated with the reduction of mechanical friction between the sliding bed, composed of the coarse particles, and the pipe wall. The friction reduction is caused by a reduction of contacts of the sliding coarse particles with the wall which is a result of the development of a thin layer of STJ25-sand particles at the pipe wall.

The new tests with considerably coarser sliding particles (BA0816) and three sand fractions (STJ25 and two coarser sand fractions) show that a loss reducing fraction can be coarser than fine to medium sand provided that a particle size of the coarse fraction is sufficiently bigger than the particle size of the finer fraction. However, it seems that sand particles coarser than say 1 mm may not produce friction reduction, at least in a 100-mm pipe. Note that a development of a layer of added sand below a sliding bed of BA0816 has been observed for all three sand fractions used in the new tests. Therefore, the same mechanism as in the previous tests is considered to be a prevailing mechanism responsible for the loss reduction in the current tests.

4.1.2 Comparison with friction loss model for broadly graded settling slurry

Sliding friction is a major contributor to the frictional pressure gradient in the discussed basalt-based slurry flows. Furthermore, the reduction of sliding friction is a major cause of the observed friction loss reduction in the bimodal flows. Therefore, if the friction loss is to be predicted in such flows, then a suitable predictive model must take the sliding-friction mechanism explicitly into account. An example of such a model is the Vsm-model for fully stratified flow of narrowly graded settling slurry [1], or the 4-component model for flow of broadly graded settling slurry (4CM) [1]. According to the 4CM methodology, if the solids is narrowly graded and sufficiently coarse, then the 4CM reduces to the Vsm-model.

In the models mentioned above, the sliding friction contribution to the total friction loss is related to the submerged weight of the sliding bed and the coefficient of sliding friction, $\mu_s$, between particles of the bed and a pipe wall. This coefficient depends on a shape of a solid
particle and naturally it must be affected also by a presence of the fine layer, which is detected in the observed bimodal flows. Therefore, a simple and physically sound modification of sliding friction in the friction-loss models is a variation of a value of the coefficient $\mu_s$ according to conditions at the pipe wall. An analysis of this approach revealed that the approach is more successful if applied to 4CM than to the Vsm-model.

Figure 7 compares the measured gradients $i_m$ with the gradients predicted by 4CM for basalt slurry flow and flows of the corresponding bimodals with added SP3031 sand. The model prediction matches the experimental values of $i_m$ of the basalt slurry flow if $\mu_s = 0.41$ (Test No. 6). A successful prediction the corresponding bimodal slurry flows requires a lower value of the coefficient and $\mu_s = 0.32$ provides a good match with the experimental results for $V_m > 1.5$ m/s in all the bimodal test runs (Test Nos. 7-10).

![Fig. 7. Comparison of measured and predicted dimensionless frictional pressure gradients for basalt slurry and bimodal slurry with SP3031 additive.](image)

In Figure 8, a comparison of the measured and predicted gradients $i_m$ for basalt slurry flow and flows of the corresponding bimodals with added STJ25 sand shows very similar trends as discussed above. The only difference is a suitable value of $\mu_s$ for the 4CM predictions. For the basalt slurry flow (Test No. 1), $\mu_s = 0.41$ is used as for the basalt-slurry test (Test No. 4) in Figure 7. A successful prediction of the corresponding bimodal slurry flows requires two different values of the coefficient. For Test Nos. 2 and 4-5, $\mu_s = 0.24$ is suitable, and Test No. 3 requires $\mu_s = 0.21$ to produce a good match of the 4CM predictions with the experimental result for $V_m > 1.5$ m/s.

For Test No. 12 (an addition of medium-to-coarse sand SP0612), a $\mu_s$ value must be reduced by less than 10 per cent to match the experimental gradient with a 4CM prediction.

![Fig. 8. Comparison of measured and predicted dimensionless frictional pressure gradients for basalt slurry and bimodal slurry with STJ25 additive.](image)

**4.2 Effect of fines on deposition limit velocity**

The observation that an addition of fines has a great impact on the friction loss but a considerably less effect on the deposition limit velocity is consistent with previous observations [15].

For a prediction of the effect that an addition of fines has on $V_{dl}$, the same strategy should be successful as used for a prediction of the friction loss, i.e., a modification of the sliding friction coefficient $\mu_s$ in a predictive model for the deposition limit velocity. The VSCALC model [1], which is implemented in the Vsm-model and 4CM, give predictions which exhibit the same trends as the experimental observations.

For slurry flow of basalt only (Test Nos. 1 and 6), the predicted $V_{dl}$ = 1.04 m/s for $\mu_s = 0.41$, i.e., for the $\mu_s$ value found suitable for the friction loss prediction. The predicted value of $V_{dl}$ is less than 10 per cent lower than the observed one. Predictions for the bimodals with SP3031 give $V_{dl}$ values round 0.92 m/s for the Test Nos. 7-10, in which $\mu_s = 0.32$ is used as in the friction loss predictions. The drop in $V_{dl}$ of approximately 0.1 m/s due to the addition of the SP3031 fraction is in an agreement with the experimental observations. For the bimodals with STJ25, $\mu_s$ values are lower (0.21 and 0.24) and so are values of the predicted $V_{dl}$, spanning the range from 0.72 to 0.79 m/s. These values are approximately 15 per cent lower than those obtained from the experiments.

It can be concluded that although the predicted $V_{dl}$ is slightly lower than the experimental one for all tested slurries (except Test No. 12), a qualitative trend in a $V_{dl}$ change due to the finer fraction addition to coarse slurry is captured well by the predictive VSCALC model.

**5 Conclusions**

The laboratory loop tests with the bimodal slurries composed of very coarse basalt (median size of 12 mm) and selected one of the three fractions of sand as an additive revealed that even a quite coarse fraction of
sand (particles of median size of 0.9 mm) is still capable to reduce sliding friction between basalt particles and a pipe wall and so to contribute to a reduction of the total frictional pressure gradient in slurry flow in a pipe. However, the observed reduction is weak for sand particles of this size. The friction loss reduction is most effective if the finest tested sand fraction (median size of 0.2 mm) is added, although the medium sand particles (median size of 0.55 mm) also produce a considerable loss reduction. The maximum friction loss reduction is reached at a certain ratio of the mass of the added sand to the mass of the coarse fraction. In the presented tests, the optimum mass ratio was approximately 1:3.

The observed friction loss reduction can be quantitatively captured by a friction loss model for broadly graded settling slurries (the 4-component model) provided that a modification is included of a value of the coefficient of sliding friction between the coarse basalt particles and a pipe wall.

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References