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CENTRIFUGAL PUMP PERFORMANCE DERATINGS FOR A BROADLY GRADED (4-COMPONENT) SLURRY

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A 4-component model for settling slurry pipeline friction loss has been previously described by Wilson and Sellgren. The goal of the present work is to adapt the concepts of this model to the calculation of centrifugal slurry pump performance deratings (i.e. pump solids effect). Tests were carried out using four different graded silica and crushed granite products representing the four model components. These were then combined and tested in permutations from the individual components to the complete mixture at various concentrations. Closed-loop run times were limited to minimize solids degradation. Primary experiments were carried out using a GIW 8x10 LSA-32 pump and selected corresponding experiments were repeated using a smaller GIW 3x4 LCC-12 pump. In all, 40 tests were performed with particle sizes ranging from minus 40 μm to 12.5 mm, d_{50} particle sizes from minus 40 μm to 7.5 mm, and delivered solids concentrations from 4% to 38% by volume. Particle size distributions varied from very narrow to very broad, with d_{85}/d_{50} ratios ranging from 1.3 to 30. A new 4-component model for the pump Head Reduction Factor (solids effect on head) is proposed and compared with the existing mono-sized model described in the Centrifugal Slurry Pump Standard ANSI/HI 12.1-12.6-2016.

KEY WORDS: Pump Solids Effect, Head Reduction Factor, 4-Component Model

1. INTRODUCTION

A 4-component model for settling slurry pipeline friction loss has been described by Wilson and Sellgren, with the most recent formulation based on a comprehensive series of loop tests carried out in the GIW Hydraulic Lab by Visintainer et al. (2017). Pump performance was also measured during this test program and a new 4-component model for slurry pump solids effect is now proposed for comparison against this data set.

In using the 4-component pipeline model, particles in the slurry are partitioned by size into four volume fractions or “components” according to four established settling slurry flow models. In transferring this to a pump solids effect model, similar categories of particle size are used, as described below:

- The “Carrier Fluid” fraction, X_f includes all particles < 40 μm. These solids are assumed to “combine” with the liquid, altering its density and dynamic viscosity.
- The “Pseudo-homogeneous” fraction, X_p includes all particles >40 μm, up to a limit of $0.2\nu_r$ (mm), where ν_r is the relative kinematic viscosity of the carrier fluid to that of water at 20°C.
- The “Heterogeneous” fraction, X_h includes all particles larger than the upper limit of X_p and smaller than the lower limit of X_s.
- The “Stratified” Fraction, X_s includes all particles larger than 0.015 times the pump discharge diameter.

2. THE 4-COMPONENT PUMP SOLIDS EFFECT MODEL

As a baseline for comparison, the mono-sized pump solids effect model as described by Sellgren et. al. (2017) and incorporated into the Hydraulic Institute Standard for Centrifugal Slurry Pumps (ANSI/HI 12.1-12.6-2016) is used:

$$r_h = S_1(1.11/D_2)^{0.9} \cdot (d_{50})^{S2} \cdot [(S_S-1)/1.65]^{0.65} \cdot (C_V/0.15) \cdot (1-X)^2 \qquad 1$$

where:

r_h = Head Reduction Factor (this is fractional, i.e. 0.01 = 1% derate)

S_1 = $[4.04 + (6.5 - 4.04) \cdot (D_2\text{-}0.41)/(0.89\text{-}0.41)] / 100$ for 0.41 m < D_2 < 0.89 m

= 4.04 minimum for D_2 < 0.41m ; 6.5 maximum for D_2 > 0.89m

S_2 = $0.4d_{50}^{-0.25}$

D_2 = Pump impeller outer diameter (m)

d_{50} = 50% weight passing solids diameter (mm) based on screen sieving.

S_S = Solids specific gravity

C_V = Volumetric concentration of solids

X = Fraction of solids smaller than 0.075 mm.

In this formulation, the five terms for r_h represent:

1. An empirical correlation for the effect of pump size relative to a baseline impeller diameter of 1.11 m.
2. The effect of particle size. (Note that the empirical correlation $(d_{50})^{S2}$ is proportional to the inverse root of the drag coefficient, $C_d^{-0.5}$, for a d_{50} sized particle in water.)
3. The effect of solids specific gravity relative to that of water at 20°C.
4. The effect of volumetric solids concentration relative to a baseline of 15%.
5. The effect of fine particles, defined as those with diameter < 0.075 mm.

The proposed 4-component model for pump solids effect follows the same strategy as the 4-component pipeline friction model, dividing the slurry solids into four volume fractions X_f , X_p , X_h and X_s as described above. This 4-component formulation should allow for more accurate modeling of unusually broad, narrow or even bi-modal particle size distributions by accounting for the individual contributions of each particle size fraction, rather than assuming a global effect based on the overall d_{50}.

Note that the fractions are defined relative to the total volume of particles, so that:

$$X_f + X_p + X_h + X_s = 1 \qquad 2$$

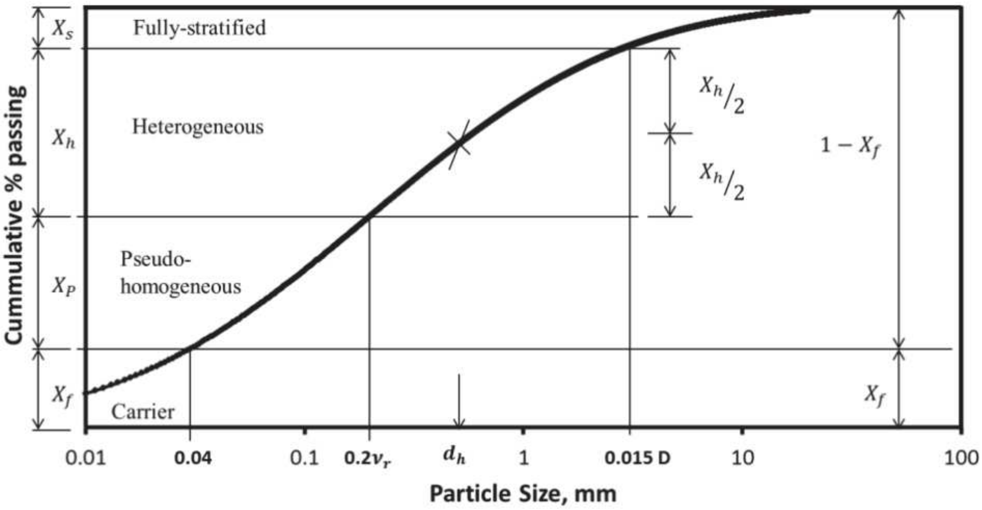

Fig. 1. Representation of the four component fractions and their particle sizes.

The proposed 4-component solids effect model is described as follows:

$$r_h = r_{h,p} + r_{h,h} + r_{h,s} \qquad 3$$

where:

$$r_{h,p} = S_l(1.11/D_2)^{0.9} \cdot C_{d,p}^{-0.5} \cdot (S_S\text{-}S_f)/1.65 \cdot (X_p \cdot C_V/0.15)$$
$$r_{h,h} = S_l(1.11/D_2)^{0.9} \cdot C_{d,h}^{-0.5} \cdot (S_S\text{-}S_{fp})/1.65 \cdot (X_h \cdot C_V/0.15)$$
$$r_{h,s} = S_l(1.11/D_2)^{0.9} \cdot C_{d,s}^{-0.5} \cdot (S_S\text{-}S_{fph})/1.65 \cdot (X_s \cdot C_V/0.15)$$

The individual r_h terms represent the contributions of the X_p, X_h and X_s fraction solids. Within these, the form of the pump size term remains the same.

The specific gravity terms are modified to use fractional reference values representing the density of the carrier fluid + all preceding smaller size fractions. These fractional terms are calculated in the same way as with the 4-component pipeline friction model:

$$S_f = S_l + \frac{X_f \cdot C_v \cdot (S_s - S_l)}{1 - C_v \cdot (1 - X_f)} \qquad 4$$

$$S_{fp} = S_l + \frac{(X_f + X_p) \cdot C_v \cdot (S_s - S_l)}{1 - C_v \cdot (1 - X_f - X_p)} \qquad 5$$

$$S_{fph} = S_l + \frac{(X_f + X_p + X_h) \cdot C_v \cdot (S_s - S_l)}{1 - C_v \cdot (1 - X_f - X_p - X_h)} \qquad 6$$

The exponent dependence for the specific gravity terms has been reduced to one, as this provides a better fit to the available data and simplifies the relationship.

The particle size terms are based directly on the drag coefficient (C_d) and are calculated according to the average particle size for each fraction. Wilson et al.(2006) describes a method of calculating the terminal settling velocity, v_t ,of a spherical particle in a Newtonian fluid without iterations. Leading parameters are the particle settling shear velocity, $V^*=((\varrho_s-\varrho_f)gd/6\varrho_f)^{0.5}$ and the shear Reynolds number, $Re^*=\varrho_f V^* d/\mu_f$, where d is the particle size. The C_d coefficient is related to v_t/V^* through the following relationships:

$$C_d = 8 / (v_t/V^*)^2 \qquad 7$$

where:

v_t = particle terminal settling velocity

V^* = particle settling shear velocity

$v_t/V^* = Re^* / [3(1 + 0.08\, Re^{*1.2})) + 2.8/(1 + 3 \cdot 10^4\, Re^{*-3.2}]$, for $Re^*<10$

$= 10E[0.2069 + 0.5\log(Re^*/10) - 0.158 \log(Re^*/10)^{1.72}]$, for $10< Re^*<Re^*_{max}$

$= 10E[0.2069 + 0.5\log(Re^*_{max}/10) - 0.158 \log(Re^*_{max}/10)^{1.72}]$, for $Re^*> Re^*_{max}$

Note the Re^*_{max} value used above is normally set = 260, in order to provide a minimum C_d value of 0.45 over a large span preceding the point of starting boundary layer separation. The degree of turbulence within a centrifugal pump together with particle surface roughness may promote an earlier transition to turbulent boundary layer where C_d is 0.1-0.2. Analysis of the measured pump performance data shows that a C_d of 0.34 is here empirically more appropriate for coarse particles with larger Reynolds numbers. Therefore, in the present analysis, an Re^*_{max} value of 2000 is used, which allows the C_d value to descend to a minimum of 0.34.

The C_d value for each fraction is calculated using a particle shear Reynolds number (Re^*) based on the average particle size of that fraction ($d_{50,p}$, $d_{50,h}$ and $d_{50,s}$) and a mixture density which includes the previous, smaller particle fractions:

$$\begin{aligned} Re^*_p &= 1000S_f \cdot [\, (S_s/S_f - 1) \cdot 9.81\, d_{50,p}/6\,]^{0.5} \cdot d_{50,p}/\mu_f \\ Re^*_h &= 1000S_{fp} \cdot [\, (S_s/S_{fp} - 1) \cdot 9.81\, d_{50,h}/6\,]^{0.5} \cdot d_{50,h}/\mu_f \qquad 8 \\ Re^*_s &= 1000S_{fph} \cdot [\, (S_s/S_{fph} - 1) \cdot 9.81\, d_{50,s}/6\,]^{0.5} \cdot d_{50,s}/\mu_f \end{aligned}$$

The effect of fine solids on the dynamic viscosity of the carrier fluid (liquid plus X_f fraction) is determined by applying Gillies' correction (Gillies et al. 1999), which was chosen because it gave good agreement for the pipeline modelling of these same slurries:

$$\frac{\mu_f}{\mu_l} = 1 + 2.5 \cdot X_f \cdot C_v + 10 \cdot (X_f \cdot C_v)^2 + 0.0019 \cdot e^{20 \cdot X_f \cdot C_v} \qquad 9$$

The concentration terms use the volumetric concentration of each individual fraction and the "fines" term from the mono-sized model is removed, since the 4-component formulation automatically accounts for the effect of the fine particle fraction.

3. DESCRIPTION OF THE EXPERIMENTS

In order to provide a comprehensive data set for validation and calibration of the model, a series of full sized pipe loop experiments were carried out over a range of particle size distributions, concentrations and pipeline diameters. In all, 28 individual tests were run in a 203 mm pipe loop using a GIW 8x10 LSA-32 pump with 254 mm suction, 203 mm discharge and 806.5 mm impeller. Twelve of these tests were repeated in a 103 mm pipe loop using a GIW 3x4 LCC-12 pump with 100 mm suction, 75 mm discharge and 310 mm impeller to provide additional size-scaling data.

Slurries were "constructed" by combining four individually sourced silica and granite based products, each with a particle size distribution falling substantially within one of the four component particle size limits. During testing, these fractions were combined in various "blends", from the narrowly graded individual products through various combinations of two or three or all four together. The test matrix of actual measured concentrations and particle fraction contents is shown in Table 1.

Table 1.

Test matrix showing actual measured fraction content and volumetric concentration from the 8x10 LSA-32 tests.

Test	1	2	3	4a	4b	5a	5b	6a	6b	7a	7b	7c	7d	8a	8b	8c	8d	8e	9a	9b	10a	10b	11a	11b	12	13	14	15
Xf	.05	.02	.03	.01	.03	.03	.04	.01	.03	.82	.33	.12	.15	.82	.48	.34	.22	.24	.01	.06	.02	.03	.01	.07	.02	.07	.04	.06
Xp	.03	.01	.02	.05	.08	.66	.35	.17	.19	.15	.51	.23	.20	.17	.10	.05	.06	.15	.06	.07	.77	.38	.17	.16	.05	.33	.02	.01
Xh	.04	.02	.03	.86	.50	.31	.15	.76	.45	.03	.15	.61	.45	.01	.01	.02	.35	.30	.85	.49	.20	.09	.74	.45	.86	.10	.06	.09
Xs	.89	.96	.92	.08	.40	.00	.46	.06	.32	.00	.00	.04	.21	.00	.41	.59	.36	.31	.08	.39	.01	.50	.07	.32	.07	.50	.89	.84
Cv	5%	11%	15%	12%	16%	5%	10%	16%	21%	4%	8%	20%	24%	8%	14%	18%	34%	38%	22%	29%	10%	21%	31%	35%	25%	30%	20%	30%

To limit particle degradation, solids were loaded into the pipeline at velocities near or below the limit of stationary deposition so that they did not recirculate during loading, but deposited in the pipe loop. All solids were substantially angular as received and remained angular or sub-angular throughout testing.

Once loaded, the pipeline velocity was increased to 7 m/s in the 203 mm loop and 5.5 m/s in the 103 mm. These velocities represent the maximum practical velocities obtainable in these experimental setups, and also are, in most cases, equal to or greater than typical operating velocities in industrial slurry systems of these sizes. All tests were run from this maximum velocity downward to deposition, and each test was continued until stationary deposition was observed. The data collected at each velocity included slurry flowrate (by magnetic induction meter), slurry density (by inverted U-loop as described in Wilson (2006)), pump suction, discharge and differential pressure, pump rotational speed and shaft power (by strain gauge torque bar), and slurry temperature.

Slurry samples for measurement of the particle size distribution (PSD) were taken using a device specifically designed for these experiments. During sampling, a pneumatic/mechanical system was used to lift the sump inflow pipe above the water line by about 0.5 m. A trapezoidal slurry sampler was then passed through the flow stream, cutting through the entire cross section of the flow twice, once in each direction. A PSD sample was taken at 5 m/s in the 203 mm loop and 4 m/s in the 103 mm loop during the first data run for each slurry. These velocities are approximately midway between the maximum deposition and pseudo-homogeneous velocities for a 0.015D sized particle in each system.

A number of clear water tests were also performed throughout the test program to determine the baseline performance (head and efficiency) of the pump, against which the solids effect would be calculated. Additional details regarding the system layout and test methodologies may be found in Visintainer et. al. (2017).

4. ANALYSIS OF THE DATA

Due to the scope of the tests, it is not possible to present all the data within the confines of one paper, nor to examine all of the individual results observed. Presented here is a point by point evaluation of the mono-sized and 4-component pump solids effect models against the full range of collected data for the 8x10 LSA-32 pump. To provide a qualitative feeling for the scope of these data, Figure 2 shows the measured Head Reduction Factors for all 28 tests using the 8x10 LSA-32 pump and Figure 3 the measured PSDs obtained during sampling for these tests.

Flow control during the tests was accomplished by varying both pump speed and system valving. Therefore, data were collected at a range of pump rotational speeds and flowrates. Figure 4 shows pump speed as a function of pipeline velocity and Figure 5 the corresponding %BEPQ flowrates (i.e. percentage of pump flowrate relative to the best efficiency flowrate at each speed). It must be noted that %BEPQ flowrates above 76% were not reached with the 8x10 LSA-32 pump, due to the head demands of the piping system. This is not ideal, since data at 100% BEPQ are of most interest, but, as the following analysis shows, a strong dependence on %BEPQ was not seen. Furthermore, data up to 115%BEPQ were collected for the smaller 3x4 LCC-12 pump with similar results.

In comparing the measured data to the model predictions, data were evaluated point-by-point according to the above described equations, using the measured values for slurry concentration and temperature at each data point. (Due to the nature of closed loop testing, slurry concentration will change slightly with velocity, and slurry temperature will change with time.)

The resulting error between measured and calculated values is expressed as a percentage, but this percentage represents the absolute difference in the Head Reduction Factor, rather than a relative error, as follows:

$$\text{error} = r_{h,\,\text{CALCULATED}} - r_{h,\,\text{MEASURED}} \quad \text{(expressed as \%)} \qquad 10$$

For example, a +1% error indicates a calculated Head Reduction Factor which is one percentage point (i.e. 0.01) greater than the measured value. This provides a better context for the analysis, since the Head Reduction Factor is already expressed as a percentage and the absolute error is a better measure of model success in actual application. Using a ratio error calculation would magnify the perceived error where solids effects are small and skew a proper understanding of the results.

Figure 6 shows the error analysis for all 8x10 LSA-32 tests using the standard ANSI/HI method. There is scatter in the error values, with the greatest deviations seen for tests having a significant X_s component at higher concentrations, or a bi-modal particle size distribution. The errors are largely unaffected by changes in flowrate and fall within a band of 8 Head Reduction % points, with an average value near -4%.

Figure 7 shows the error results for the same data using the proposed 4-component model. A better clustering of results is seen. The errors are again largely unaffected by changes in flowrate or %BEPQ and fall within a band of 4 Head Reduction % points, with an average value near -2%.

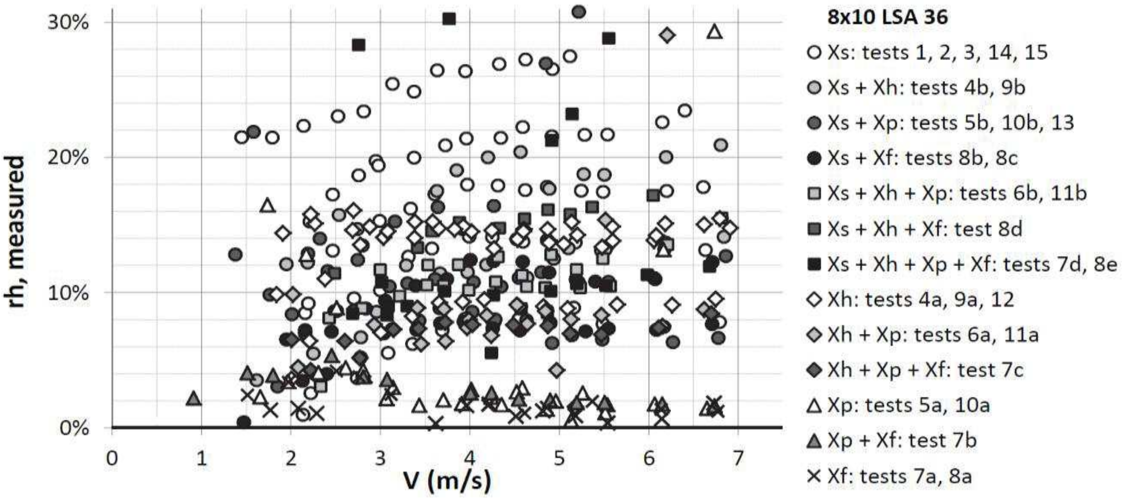

Fig. 2. Head Reduction Factors measured during testing for the 8x10 LSA-32 pump.

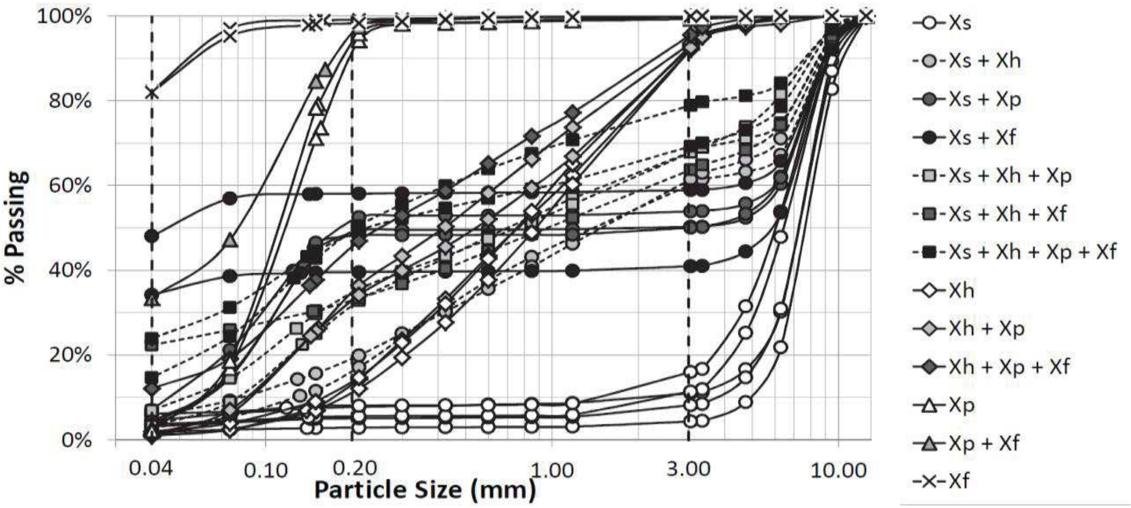

Fig. 3. Particle Size Distributions measured during testing for the 8x10 LSA-32 pump.

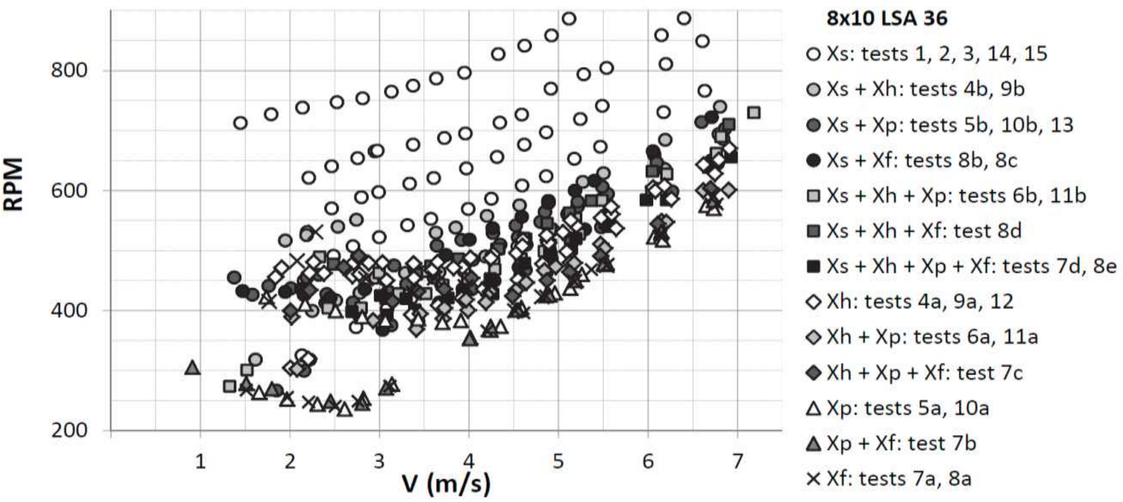

Fig. 4. Pump rotational speeds measured during testing for the 8x10 LSA-32 pump.

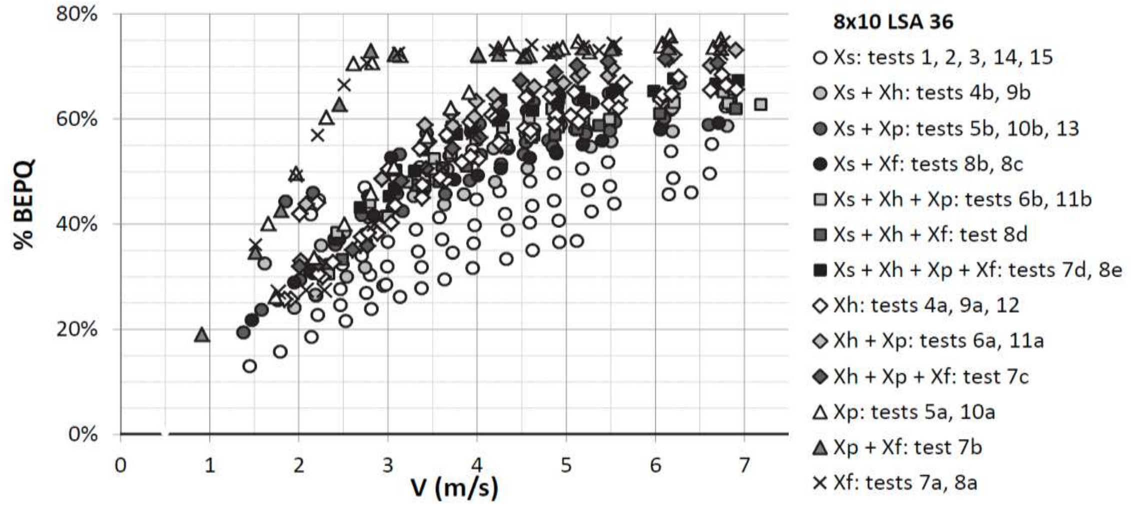

Fig. 5. Pump %BEPQ measured during testing for the 8x10 LSA-32 pump.

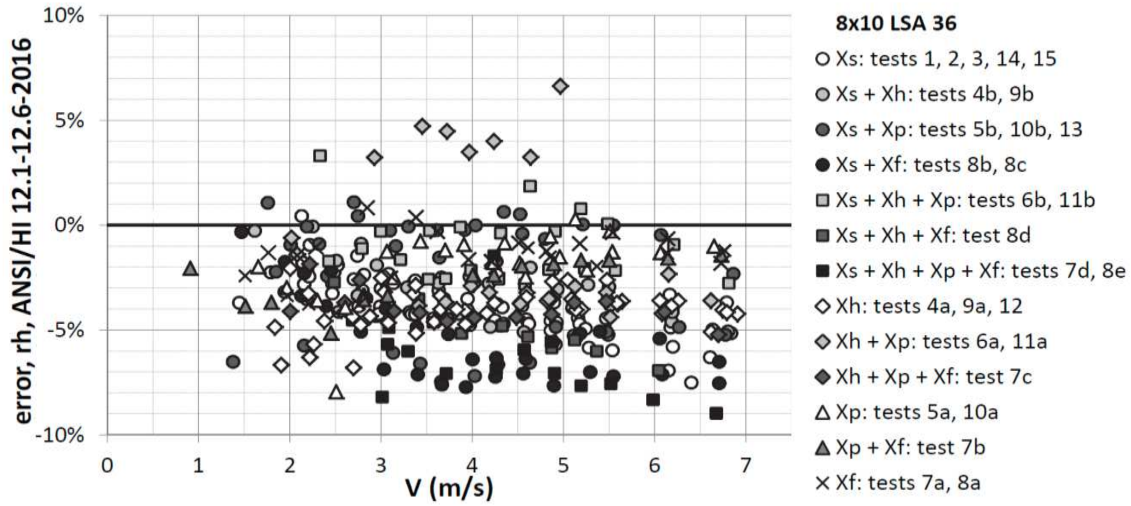

Fig. 6. Solids effect error for the 8x10 LSA-32 pump using the mono-sized ANSI/HI method.

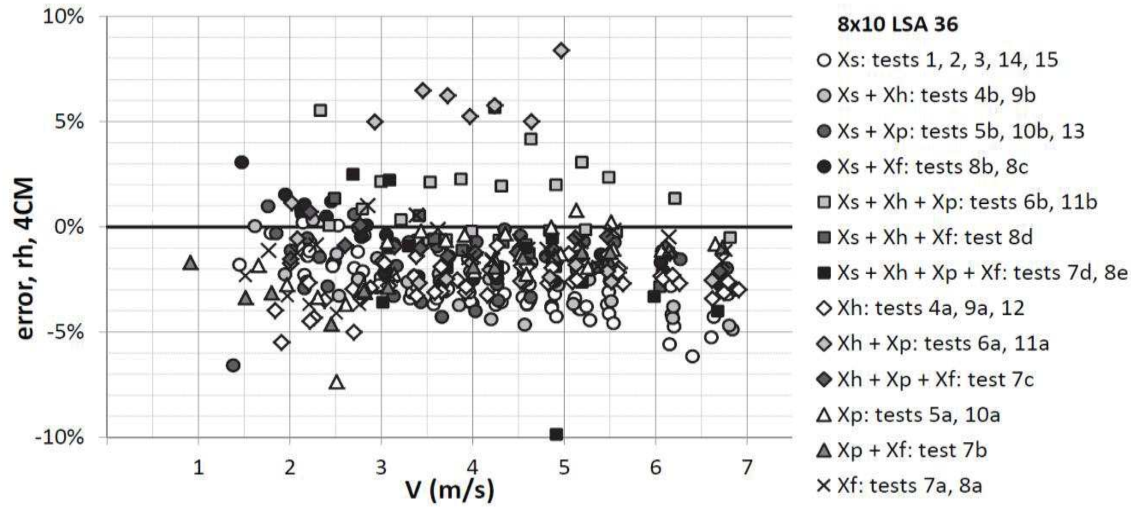

Fig. 7. Solids effect error for the 8x10 LSA-32 pump using the proposed 4-component method.

Although the improvement afforded by the 4-component model is not large, it is significant and demonstrates the viability of the approach. In particular, a better result is obtained for the broadly graded and bi-modal slurries.

Similar results were obtained for the 3x4 LCC-12 pump, although these results indicate that some adjustment of the pump size effect term will be needed for the 4-component model. This will be the focus of a future study, preferably including supporting data from additional pump sizes.

The solids effect on pump efficiency (r_e) was also examined for both pumps in this study. In general, the standard assumption that $r_e = r_h$ provided the best overall fit to the data, but more scatter is seen in the efficiency derates. This topic also warrants further study.

5. CONCLUSIONS

The viability of a 4-component model for centrifugal slurry pump solids effect, similar in concept to the pipeline version of the model, has been demonstrated.

The 4-component solids effect model improved predictions for the Head Reduction Factor of a GIW 8x10 LSA-32 slurry pump when tested on a wide variety of slurry particle size distributions and concentrations, as compared to the mono-sized particle method described in the Centrifugal Slurry Pump Standard ANSI/HI 12.1-12.6-2016.

Further work is needed to refine the pump size effect term of the model and to examine the relationship between the head and efficiency reduction factors.

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