THE EFFECTS OF SLURRIES ON CENTRIFUGAL PUMP PERFORMANCE

by

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ABSTRACT

For a centrifugal slurry pump to accurately match a pipeline system, it is necessary to know how the presence of solids will affect the pump performance. If accurate corrections are not made, it is likely that the pump and the system will be mismatched, which will accelerate the rate of wear and increase operating and maintenance costs.

When pumps are required to handle slurries, the pump head and efficiency are mainly affected by the solid size, solid concentration and solid density. Settling slurries behave differently from non-settling slurries. Consequently, the head and efficiency reductions and the shape of the performance curves will be quite different. Simple, graphical methods will be presented for predicting how the characteristics of centrifugal slurry pumps, when pumping either settling or non-settling type slurries differ from the clear water performance of the pump in question. The nature of the slurry itself, settling or non-settling, will also be considered.

For slurries with a narrow band distribution of very small particles where the average size is usually less than 100 microns, the slurry will be "non-settling" and will behave as a Newtonian liquid. Consequently, standard viscosity correction procedures can be adopted to predict pump performance, provided the "apparent" or dynamic viscosity of the slurry is known. Based on a number of tests on fine mesh solids, an apparent viscosity-concentration relationship curve is presented, which when used in conjunction with the Hydraulic Institute chart for viscous liquids, will facilitate the plotting of the pump slurry characteristics curves (head, capacity, efficiency and BHP).

Usually slurries with a distribution of larger particles will be "settling" and the particles and the liquid will exhibit their own characteristics. As the liquid passes over the particles, energy will be dissipated due to the liquid "drag" which results in a reduction in pump head and efficiency. The reduction in velocity between the liquid and the particle indicates that the pump performance can be related to the terminal free fall or "settling" velocity of the particles in the liquid.

The particle shape and hindered effects are ignored herein. Nevertheless, a reasonable prediction of head and efficiency reduction ratios are derived for "settling" slurries where water is the conveying medium. These reduction ratios are derived from composite curves based on actual test data reduction and relate the average solids particle size and specific gravity to particle drag and concentration coefficients.

INTRODUCTION

Centrifugal pumps are commonly used in slurry pipeline systems as an economical means of conveying solids over relatively short distances. The characteristic performance curve of a centrifugal pump differs from its clear water performance curve when solids are included and the flow becomes two phase, i.e., the head and efficiency will decrease. The magnitude of the reduction and the shape of the characteristic curve will depend mainly on solids size, volumetric concentration and density.

Due to the complex nature of the problem, only a limited number of studies on pump performance when handling slurries have been conducted. Consequently, there are only a few published methods whereby the head and efficiency reductions can be predicted and none differentiate between Newtonian and non-Newtonian behavior of the mixture.

This treatment expresses the dependence of head and efficiency reduction on solids size, density and concentration. Two specific reduction methods are presented; (a) Viscous correction for slurries classified as "non-settling" (Newtonian), i.e., kaolin, and (b) Drag/concentration correction for "settling" slurries.

Over sixty tests were evaluated which covered a wide range of conditions. A comparison of correction procedures published by Sellgren [1], Burgess and Reizes [2], Vocadlo, et al. [3], McElvain [4], and Cave [5] established that a slightly modified version of the Sellgren equation produced the most accurate results for settling slurries.

The Vocadlo viscosity correction curve for non-settling slurries was adopted but modified to reflect additional data on fine coal and extremely fine grades of kaolin clay.

GENERAL

The effect of included solids on the centrifugal pump performance is a major consideration in the pump selection and slurry system design.

Solids suspended in a liquid cannot absorb, store, or transmit pressure energy, which is a property of liquids; nor

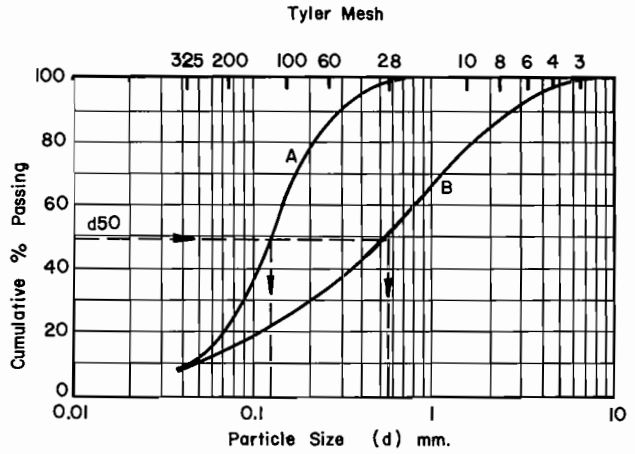

Figure 1. Typical Particle Size Distribution Plots.

can they transmit their kinetic energy to the liquid, since in every case, the liquid moves at a higher velocity.

The flow of solids through the pump causes additional hydraulic losses (drag) due to the relative motion of coarse particles, which have greater inertia and cannot accelerate as rapidly as the carried liquid. This results in additional friction losses. Large concentrations of small particles create an "apparent" viscous effect.

Published performance curves for centrifugal slurry pumps are always for clear water and when a pump is being selected for a slurry application, it is necessary to derate the performance. If this is not done, the pump may be unable to meet the system requirements, the rate of wear will increase and the motor could overload.

The performance of a pump is mainly affected by the solids concentration, size and density, although other important factors include particle shape, where it is observed that angular particles cause greater losses than rounded particles. A broad size distribution of particles will create a smaller loss effect than a narrow size distribution, since the fine particles in the mixture will tend to reduce separation, resulting in a smaller change in the internal flow characteristics (Figure 1).

If the conveying liquid is water and the average particle size and specific gravity of the dry particles is known, the type of slurry can be categorized (Figure 2). Mostly all mineral and ore processes will be classified as settling.

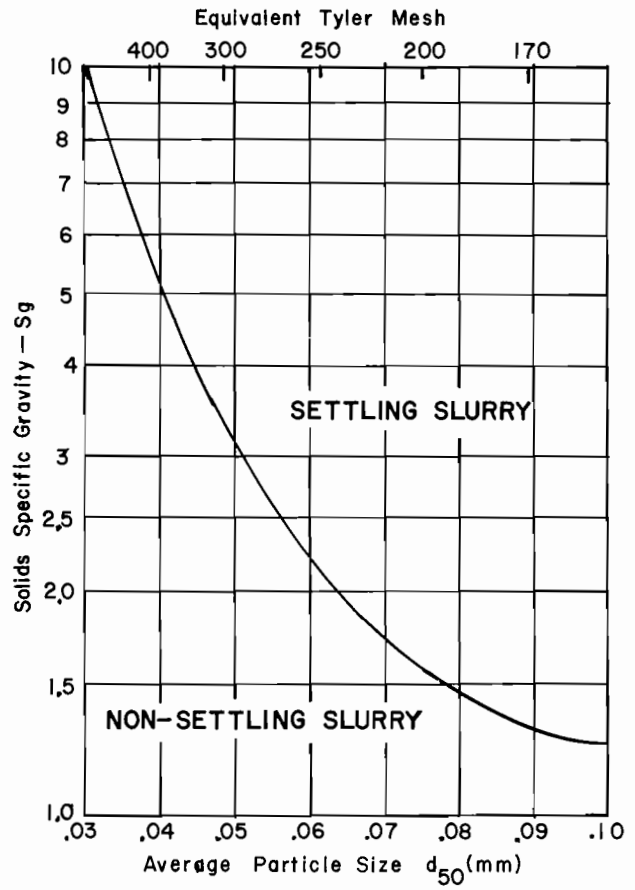

Figure 2. Determining of Slurry Type.

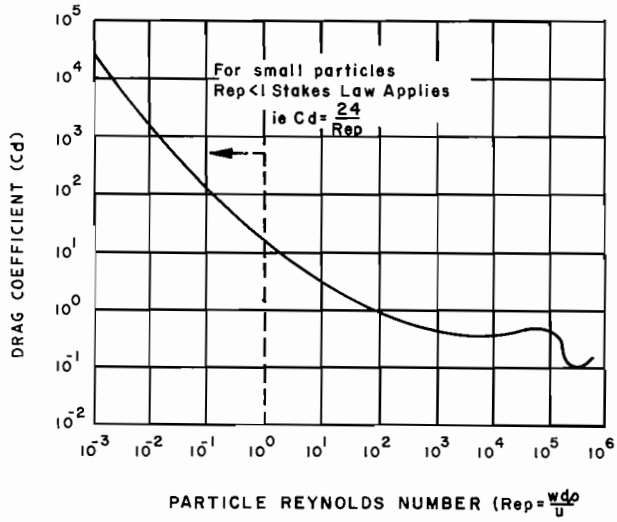

Figure 3. Drag Coefficient Curve for Spherical Particles.

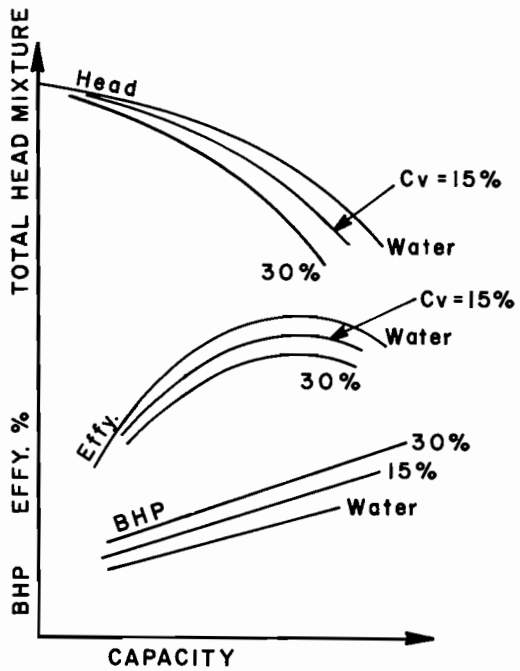

Figure 4. Typical Performance Characteristic Non-Settling Slurries.

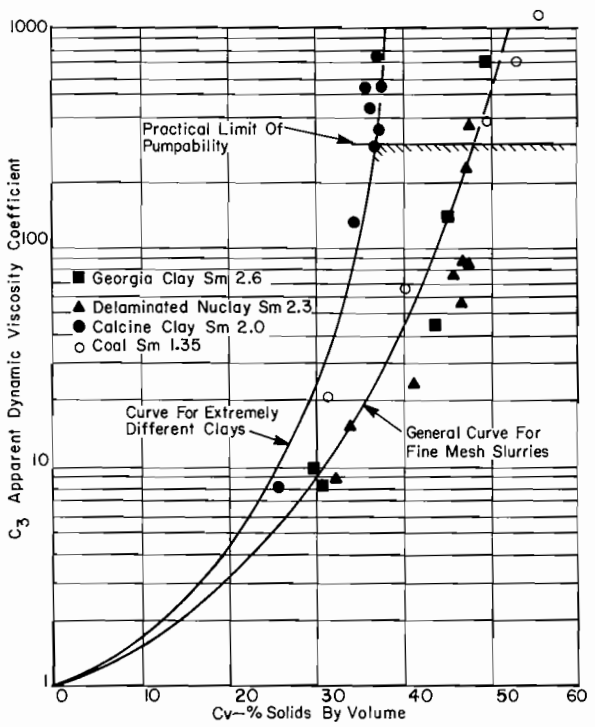

Figure 5. Non-Settling Slurries Viscosity Effect Correction.

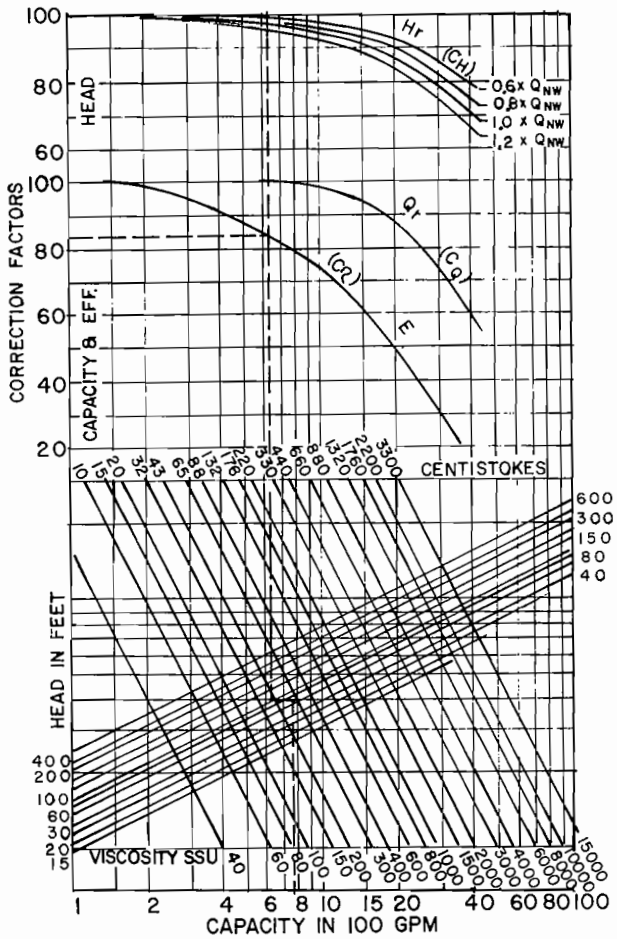

Figure 6. Performance Correction Chart for Viscous Liquids.

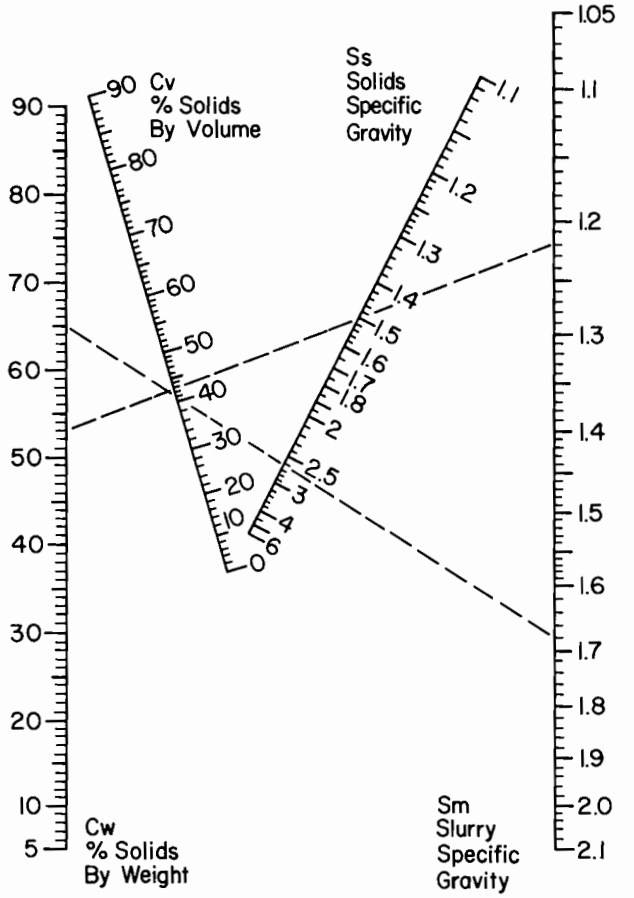

Figure 7. Nomograph of the Relationship of Concentration to Specific Gravity in Aqueous Slurries.

Typical examples of non-settling slurries may be kaolin, silt,and water/coal fuels.

NON-SETTLING SLURRIES

Stokes Law will apply to slurries with a narrow band distribution of very small particles in water (d50 < 100 microns) where the particle Reynolds number will be <1 (Figure 3). The slurry will be non-settling and will behave as a Newtonian liquid (shear stress α shear rate).

A typical centrifugal pump performance characteristic on a non-settling slurry is shown on Figure 4.

Curves for viscosities of concentrated suspensions (Figure 5) are derived from actual pump tests. Caution should be exerted in predicting viscosities of concentrated suspensions with very fine particulate less than two microns, i.e., kaolin clay. The particle shape will create high viscous affects. If an actual pump test precedent has not been established, a pilot trial test at the pump manufacturer's premises or at site should be considered.

Once the slurry viscosity has been determined, the Hydraulic Institute Standard 14th Edition viscosity correction chart can be used to predict the pump performance (Figure 6). For convenience, a nomograph relationship of concentration to specific gravity in aqueous slurries is presented in Figure 7.

Slurries containing very fine particles retain liquid-like characteristics at volumetric concentrations very close to the limiting voidage. Limits, therefore, are related to the effects of high viscosity. A worked example is presented in *Appendix A*.

SETTLING SLURRIES

Where there exists a density difference between the conveying liquid and the solid particles, the particles will tend to settle. Usually slurries with a distribution of larger particles will be "settling," and the particles and the liquid will exhibit their own characteristics. As the liquid passes over the particles, energy will be dissipated due to the liquid "drag" which results in a reduction in pump head and efficiency. The difference in velocity between the liquid and the particle indicate that pump performance can be related to the terminal free fall (or "settling") velocity of the particles in a liquid [6].

Naturally, the shape of the particle will have an influence on the magnitude of the terminal settling velocity. Non-spherical particles typically will settle at a velocity 10 percent to 20 percent lower than spherical particles of the same volume. Particles which are hindered from settling by the presence of other particles in the liquid obviously have lower settling velocities.

The settling velocity is normally determined by an iterative process from the Drag Coefficient-Particle Reynolds number relationship, but it is more convenient to ignore the shape and hindered effects, and treat the particle as a simple sphere of average particle size (d50). The average of effective particle size d_{50} (meaning 50 percent by weight, is smaller than the average particle size), is chosen to compensate for effects of size distribution.

Sellgren [1] suggested that, within limits, Equation 1 would be valid for head and efficiency correction within an error band of ±15 percent.

$$H_r = 0.32 \times C_w^{0.7} \times (S_s - 1)^{0.7} \times \bar{C}_d^{-0.25} \quad (1)$$

where

$\bar{C}_d$ is the weighted drag coefficient.

The Drag Coefficient for a falling sphere in still water can be expressed as follows:

$$Cd = \frac{4}{3} \times \frac{g\,d\,(Ss - 1)}{V_t^2} \quad (2)$$

or

$$V_t = \frac{4}{3} \times \frac{g\,d\,(Ss - 1)^{0.5}}{Cd} \quad (3)$$

For a settling slurry where water is the conveying medium a good estimate of the Head Correction factor (H_r) can be derived by substituting the expression for C_d into Equation (1).

$$H_r = 1 - 0.075 \times C_w^{0.7} \times (S_s - 1)^{0.45} \times V_t^{0.5} \times d_{50}^{-0.25} \quad (4)$$

or

$$H_r = 1 - 0.075 \times C_1 \times C_2 \quad (5)$$

where

$$C_1 = C_w^{0.7} \times (S_s - 1)^{0.45} \quad (6)$$

$$C_2 = V_t^{0.5} \times d_{50}^{-0.25} \quad (7)$$

For ease of application curves of the particle "concentration" and "drag effects" are presented on Figure 8 and Figure 9, respectively. These curves are valid for water in the temperature range of 0° to 100°C, since the change in dynamic viscosity and Reynolds Numbers will have a negligible effect.

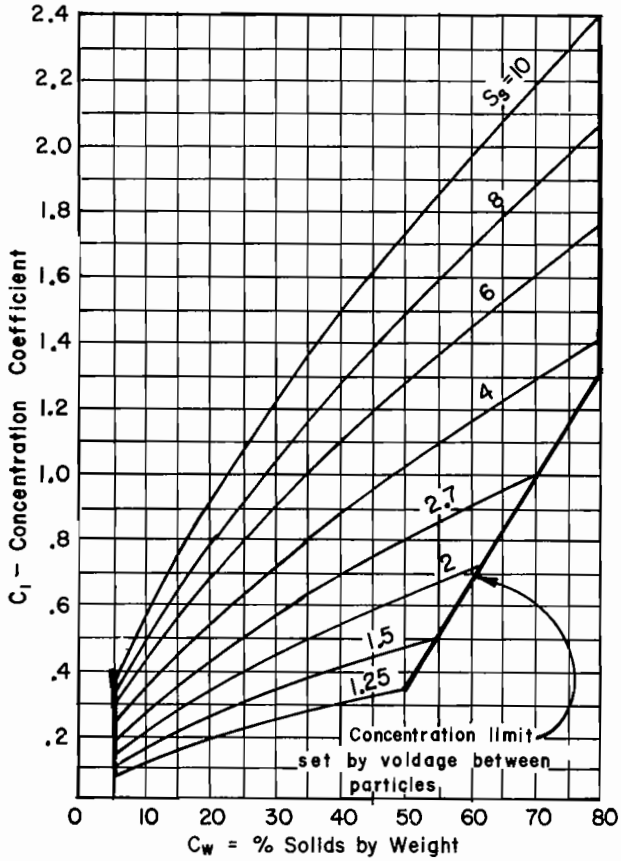

Figure 8. Settling Slurries—Head and Efficiency Correction. Concentration effect.

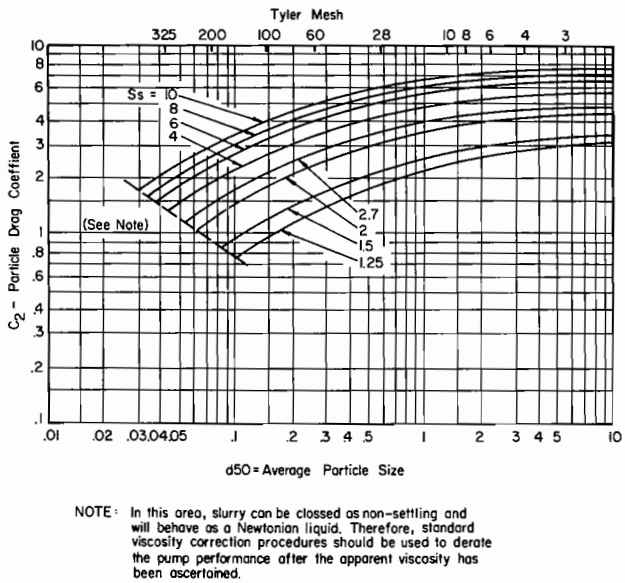

Figure 9. Settling Slurries-Head and Efficiency Correction Particle Drag Effect.

Overall, the particle size remains the most important parameter in settling slurry pump performance correction.

Actual pump performance tests on slurry would indicate that for practical purposes, the amount of head correction would be the same as the efficiency correction, i.e.:

$$H_r = E_r = \frac{Hm}{Hw} = \frac{Em}{Ew} \tag{8}$$

A typical centrifugal pump performance characteristic on a settling slurry is shown on Figure 10.

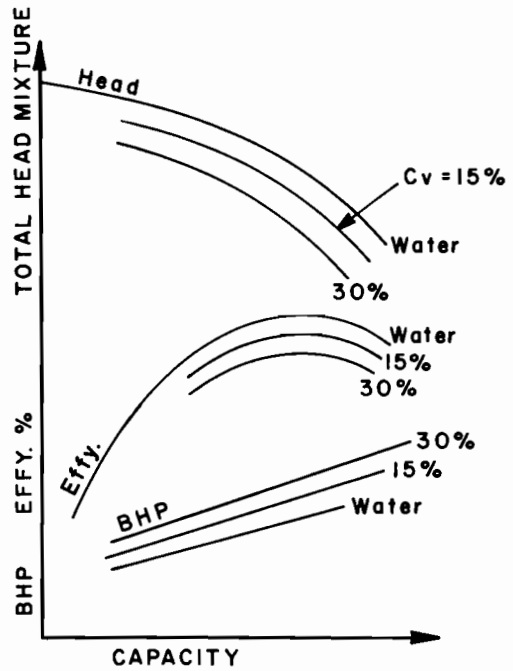

Figure 10. Typical Performance Characteristic Settling Slurries.

Arising from an analysis of the test results, the following observations can be made:

- When pumping settling slurries, the head and efficiency are reduced by the same ratio below that obtained on water. *Note*: It was observed that the efficiency drops at a greater rate than the head when the volumetric concentration is very large. The correction formula has been adjusted to allow for this.
- When pumping settling slurries the "best efficiency point" does not change.
- When pumping settling slurries, the head and efficiency ratios were found to be independent of flowrate.
- When pumping settling slurries, it was observed that the head and efficiency reduction ratios were virtually independent of pump size and specific speed.
- When pumping settling slurries, the head and efficiency reduction ratios remained the same regardless of rotational speed of the pump.
- For a settling slurry, the BHP of the pump will be directly proportional to the mixture specific gravity.

It is important to appreciate that there is a maximum concentration for a given slurry beyond which the pump may not "deliver," if only for the reason that it is approaching the limit set by the "voidage" between the particles. The greatest concentration is obtained when the voids among the larger particles are partially filled with smaller particles. The maximum concentration of randomly packed particles which a pump can handle is on the order of 50 percent by volume (Cv).

To illustrate this, a centrifugal slurry pump can easily handle a magnitite/water slurry of Cw = 60 percent and Ss = 5.2, since by calculation, this would give a Cv = 22.4 percent.

The same pump, however, would have difficulties in handling a bituminous coal/water slurry of the same Cw = 60 percent, but having a much lower Ss = 1.3 since by calculation, this would give a Cv = 54 percent.

For heterogenous slurries, the power will be directly proportional to the specific gravity of the mixture and can be determined from the equation:

$$BHP_m = \frac{Qm \times Hm \times Sm}{3960 \times Em} \tag{9}$$

The slurry flow requirements can be determined from the expression:

$$Q_m = \frac{4 \times \text{Dry Solids (tons/hr.)}}{Cw \times Sm} \tag{10}$$

where

$$1 \text{ Ton} = 2000 \text{ lb}$$

A worked example is given in *Appendix B*.

DISCUSSION

Over sixty sets of slurry pump performance data were analyzed which covered a wide range of conditions.

Average particle size	0.01 to 4 mm
Particle distribution band	Varied from narrow to broad
Particle specific gravities	1.35 to 4.7
Concentration	Cw 12 to 65%; Cv 4 to 47%
Solids handled	Sand, illmenite, iron ore, phosphate, Kaolin, silt, magnetite, gravel
Capacities	50 to 16,000 gpm
Pump sizes	3 to 20 in

Tests were conducted in-house. Details of the test facility are shown in Figure 11.

An error analysis for head and efficiency reductions for settling slurries was conducted, (Figures 12 and 13 respec-

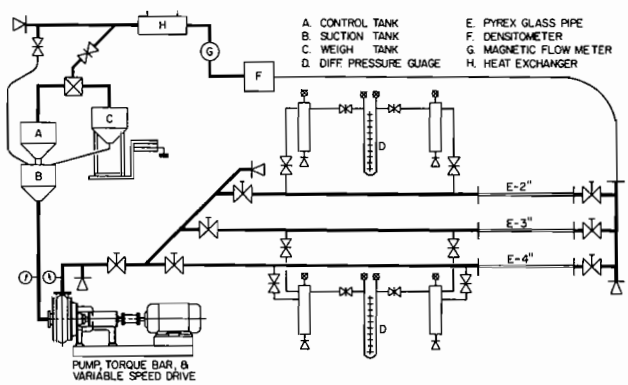

Figure 11. Outline of Slurry Test Facility.

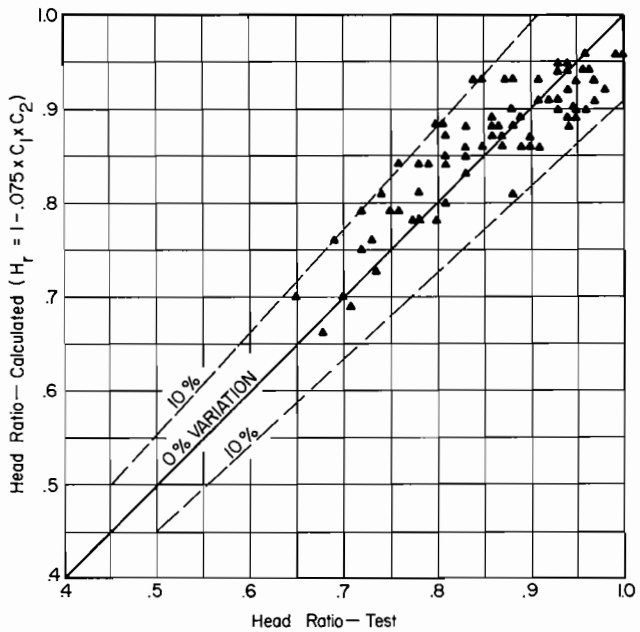

Figure 12. Performance Reduction Error Analysis—Head.

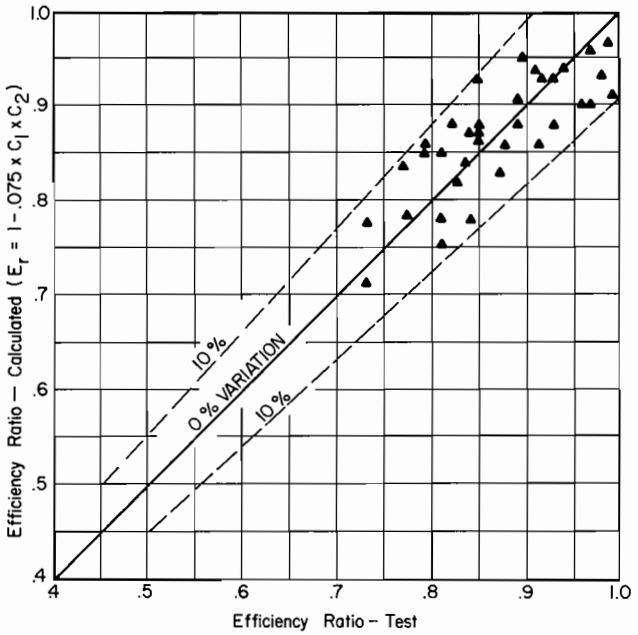

Figure 13. Performance Reductin Error Analysis—Efficiency.

tively), which shows maximum deviations of ±10 percent. This compares favorably with correction methods presented by earlier investigators, particularly where high concentrations of higher density solids are considered.

The concentration viscosity relationship curves for non-settling slurries were derived from actual pump tests where the Hydraulic Institute correction chart was used to estimate the apparent viscosity. A correlation with Brookfield viscometer tests on samples was unsuccessful, since the shear rate within the pump changed as the mixture passed through the impeller. The viscosity coefficient derived from Figure 5 is therefore an average.

CONCLUSION

Practical methods for predicting the performance of centrifugal slurry pumps for extremely fine and coarse particles are given in terms of relationships between particle size, density and concentration. It is evident that the particle shape and roughness has an impact on the pump performance and accounts for most of the deviation. While this has not been quantified, the correction curves have been conservatively drawn to allow for this.

When correcting for high concentrations of non-settling slurries with extremely fine particulate such as kaolin clay, caution should be exerted, since the particle shape will have significant effects on performance. Pilot tests at the pump manufacturer's works should be considered if a precedent has not already been established.

NOMENCLATURE

BHP_w Brake Horsepower—Water
BHP_m Brake Horsepower—Slurry
C_w Concentration Solids by Weight
i.e.,—Ratio of weight of dry solids to weight of slurry (%)
C_v Concentration Solids by Volume
i.e.,—Ratio of volume of dry solids to volume of slurry (%)
C_d Particle Drag Coefficient
C_1 Drag Correction Coefficient
C_2 Concentration Correction Coefficient
C_3 Apparent Dynamic Viscosity Coefficient (Non-settling Slurries)
d Particle Size (mm)
d_{50} Average Particle Size of Solids (mm)
i.e.,—50% passing, 50% retained by weight
E_r Efficiency Correction Factor
E_m Efficiency—Slurry
E_w Efficiency—Water
H_r Head Correction Factor
H_m Head—Slurry (Feet)
H_w Head—Water (Feet)
Q_m Pump Delivery—Slurry (GPM)
Q_w Pump Delivery—Water (GPM)
S_ℓ Specific Gravity—Conveying Liquid
S_m Specific Gravity—Slurry
S_s Specific Gravity—Dry Solids
μm Apparent Viscosity Slurry—Absolute or Dynamic (Centipoise)
υm Apparent Viscosity Slurry—Kinematic (Centistokes)
υ_ℓ Apparent Viscosity Liquid—Absolute or Dynamic (Centipoise)
R_e Reynolds Number = $dw\rho/\mu_\ell$ Where W relative velocity between conveying liquid and particle 1 = density
V_t Particle terminal settling velocity which is a function of the Particle Reynolds Number/Drag Coefficient
g Acceleration due to gravity

APPENDICES

Appendix A
Worked Example—Non-Settling Slurry

Given that a 4 in horizontal end suction pump delivers at its best efficiency point 1000 gpm water at 100 ft total head at 68 percent efficiency (BHP = 37.1), what will the equivalent

performance be when handling a fine coal/water slurry with the following characteristics: Ss = 1.5, Cw = 53 percent. Particle size distribution (Tyler) cumulative percent passing = 20 percent (325) 80 percent (200) 100 percent (100)

1. Determine d_{50} from Figure 1.
   From distribution plot d_{50} = 0.058 mm
2. Determine slurry type from Figure 2.
   d_{50} = 0.058, Ss = 1.5; therefore, slurry is non-settling.
3. Determine Sm and Cv from Figure 7.
   Cw = .053, Ss = 1.5; therefore, Cv = 0.43 and Sm = 1.22
4. Determine apparent viscosity from Figure 5.
   Cv = 0.43; therefore, C_3 = 0.85

Kinematic viscosity $\upsilon_m = \frac{C_3 \times \mu_m}{Sm} = \frac{85 \times 1}{1.22} = 69.6$ centistokes

5. Determine performance corrections from Figure 6.
   υ_m = 69.6 centistokes Hw = 100 feet Qw = 780 gpm
   Qr = 1, Hr = 0.96, Er = 0.80
   Qm = 1000 × 1 = 1000 gpm
   Hm = 100 × 0.96 = 96 feet
   Ew = 0.68 × 0.80 = 0.544
6. Determine BHP on slurry (Equation 9)

$$BHP = \frac{1000 \times 96 \times 1.22}{3960 \times 0.544} = 54.36$$

SUMMARY

Pump will diliver 1000 gpm slurry at 96 ft head with bhp of 54.36.

A 75 hp motor rating with a 1.0 service factor would be more than sufficient to cover for system upsets and startup conditions.

Note: The Hydraulic Institute Standards 14th Edition gives detailed worked examples of correcting pump performance to water, if the viscosity effects are known.

Appendix B
Worked Example—Settling Slurry

Given the same situation as before, what will the equivalent performance be when handling a sand/water slurry with the following characteristics:

Ss = 2.7, Cw = 65 percent, d_{50} = 0.1 mm

1. Determine slurry type from Figure 2.
   d_{50} = 0.1, Ss = 2.7; therefore, slurry is settling
2. Determine Sm from Figure 7.
   Cw = 0.7, Ss = 2.7; therefore, Sm = 1.68
3. Determine C_1 from Figure 8.
   Cw = 0.65, Ss = 2.7; therefore, C_1 = 0.95
4. Determine C_{22} for Figure 9.
   d_{50} = 0.1, Ss = 2.7; therefore, C_2 = 1.75
5. Determine head and efficiency corrections.

$$\frac{Hm}{Hw} = \frac{Em}{Ew} = 1 - 0.075 \times C_1 \times C_2$$
$$= 1 - 0.075 \times .95 \times 1.75$$
$$= 0.875$$

Hm = 0.875 × 100 = 87.5 feet
Em = 0.875 × 0.68 = 0.595

6. Determine BHP on slurry (equ. 9)

$$BHP = \frac{1000 \times 87.5 \times 1.68}{3960 \times 0.595} = 62.4$$

SUMMARY

Pump will deliver 1000 gpm slurry at 87.5 feet head with BHP of 62.4. A 75HP motor rating with a 1.0 service factor should be sufficient.

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