SLURRY PUMPING

INTRODUCTION

The science , and art, of slurry pumping system design is a very broad and complex subject. Slurry can be comprised of a wide range of particle sizes, particle Specific Gravity and an infinite variety of particle shapes. The distribution of particle size about a median size affects the solids make up. The solids can be mixed with liquids of various viscosity which can range in temperature, may have entrained gases or impurities, may vary in pH and many other factors which all contribute to the way a slurry will perform. These parameters combine to determine the Rheology of the slurry. The subject of slurry rheology is quite complex, but may be roughly divided into two classifications. Slurries may be classed as “homogeneous” or “heterogeneous”. Without getting too involved in fluid mechanics, a homogeneous slurry is one which does not tend to separate immediately when it becomes still. On the other hand, a heterogeneous slurry is one which will tend to separate immediately when flow movement is halted. Calculations involving the homogeneous slurries are quite complex and rely heavily on careful testing of the particular slurry to establish it’s rheology. These slurries are mostly those with high pulp densities (say > 50% by weight) and with a high proportion of very fine particles (“fine“ being less than 50 microns).

Fortunately, in most mineral processing plants, the common situation is not so complex. The usual slurry pumping duty is one where the slurry to be pumped is classified as heterogeneous. Also, the pipeline length is relatively short, the static lift is usually not great and the pump is “force fed” out of a sump with the slurry level above pump centre line. The pumping liquid is invariably water at near to ambient temperature. The pump usually delivers to either a cyclone or to some vessel open to atmosphere.
This situation lends itself to the application of some “short cuts” and “rules of thumb”, which in the strictest sense reduce the accuracy of the result, but in practice result in reasonable , if conservative outcomes.

The method of pump system calculation and pump selection presented here is useful to check existing or new applications. A pump selected using this method will work. For most plant applications, a little over conservatism is not a problem, and is often a blessing at a later date when some “tweaking” of a plant circuit is required. However, the reader is cautioned that a more rigorous study should be made by an experienced Engineer for duties which are outside the limits of this method.

The method closely follows the familiar procedure developed and published by Warman International Limited, which has been found to be very reliable, for most general plant applications. However, several “shortcuts” have been introduced to simplify the process, at the cost of constraining the application. A summary of the limitations of this method appears below.

Some of the factors required in the worked example can be read off from charts and tables which have been published by various authors. The method used here tries to utilize mathematical formulae where possible, to enable the reader to write their own computer program for the calculations.

SUMMARY OF LIMITS OF THIS METHOD

- Duty requires a single stage centrifugal pump only
- Distance to be pumped is short (< 200 m.)
- Slurry is simple (< 50% pulp density and particle size d50 is > 50 microns
- Particle sizing is not closely graded, and contains some fines.
- Height to elevate slurry is within normal plant limits, say 20 m. maximum.
- Pump is fed positively from a hopper with slurry free surface above pump inlet level
- Transport medium is water between 0 and 60 degrees C.

NOMENCLATURE USED

Cv	Concentration of solids in the slurry mixture, by volume	%
Cw	Concentration of solids in the slurry mixture, by weight	%
D	Inside diameter of pipe	m.
d50	Screen size which would pass 50% of the particles, by weight	microns
ER	Efficiency Ratio	
f	Darcy friction factor	Dimensionless
FL	Durand Facto for limiting settling velocity	Dimensionless
g	Gravity constant	$9.8m/^2$
H	Total head (sum of calculated head losses)	m of slurry
Hf	Head loss due to friction	m of slurry
Hs	Static head	m of slurry
Hequip	Head loss due to equipment in the line	m of slurry
Hw	Total Head converted to water	m of water
HR	Head Ratio	
k	Pipe internal surface roughnes	m.
L	Pipe Length	m.
Leq.	Equivalent length of pipe accounting for fittings loss	m.
M	Mass flow rate of dry solids	t.p.h.
Q	Slurry flow rate	m^3/h
Qw	Volume flow rate of liquid in the slurry (usually water)	m^3/h
Re	Reynolds Number	Dimensionless
S	Specific Gravity of dry solids	
SL	Specifiv Gravity of transporting liquid	
Sm	Specific Gravity of slurry mixture	
V	Velocity of flow in pipe	m/s.
VL	Limiting Settling Velocity	m/s.

EXPLANATION OF SOME TERMS

M (Tonnes of Solids to be Pumped): Weight of dry solids to be pumped per hour.
Units are tph (tonnes per hour)

Pulp Density: % of solids in the slurry mixture, by weight. Symbol Cw

Size of Solids: The d50 sizing of the particles to be pumped. Units are in microns
*The span of the particle size range should ideally be determined, to indicate whether the particles are all clustered around a similar size (**closely graded**), or spread across a broad size spectrum (**widely graded**). Generally, closely graded solids sizings will tend to result in a more rapidly settling slurry, while a widely graded slurry will tend to be more slowly settling. This is due to the hindered settling effect of the fines in the grading, which effectively increase the viscosity of the liquid component of the slurry mixture.*
The calculation method used here is not applicable to very closely graded sizing.

Hs (Static Lift) : This is the vertical height through which the slurry is to be raised. For our purposes, it is suitable to take the level difference from the pump to the discharge point.
A rigorous study would require us to specify this as the vertical difference between the free surface of the slurry in the pump sump, and the discharge point. It would then be necessary to calculate the entry losses in the suction piping, and the friction loss from sump outlet to pump mouth. These losses would then be added algebraically to the overall head loss calculation.

For the purpose of this method, and within the limits and assumptions imposed, experience has shown that the average amount of positive suction head, encountered in a typical plant sump, will approximately balance the losses in the suction piping. This allows us to simplify the method by being able to measure the static head (Hs) as the vertical separation from pump to outlet without bothering about the suction side of the pump.
Units are in metres.

Equipment Head: In most plants the most common equipment on the pump line is a cyclone. The process design will dictate the required pressure drop across the device, to achieve it's process duty. This pressure is usually quoted in kPa, and must be converted to metres of slurry head, using the following formula:

$H_{equip}. = kPa / 9.81x\ S_M$ metres

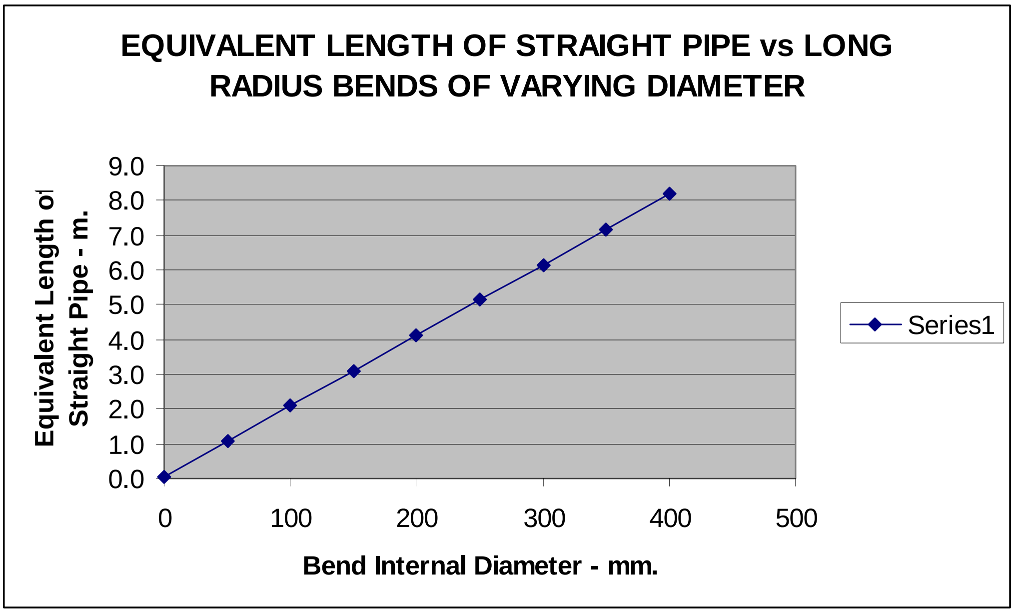
Pipe Material: *The various references list a wide range of materials from which pipe is made. Experience once again shows that in most plants, the slurry is pumped through polyethylene, bare steel pipe or rubber lined steel pipe. This is fortunate, because the parameter in which we are interested is the internal roughness of the surface which contacts the slurry. As it happens, steel and rubber have about the same value, at 0.000045 metres and polyethylene is approximately 0.000015 m.*

Pipe Equivalent Length: This is the actual length of pipe installed plus an extra length added for each fitting in the line. There are published tables giving the length of straight pipe having the equivalent resistance to flow as the fitting. This method simplifies the calculations.

Again, experience has shown that most slurry pipelines in plants will consist only of straight lengths of pipe and long radius bends. Figure 1.0 below relates only to the commonly used long radius bend, (those with a radius of approximately 3 times the nominal diameter of pipe)

The full table of fittings is found in most texts on slurry pumping, if required.

FIGURE 1.0



DATA REQUIRED

In most average plant situations, the Process design will require that a specific tonnage rate of solids be transported from a hopper, to a point at a level and distance away from the pump site. The transport medium is water at near ambient temperature. The process will most probably dictate that the slurry must be pumped at a certain pulp density. Thus, the required input data is:

TPH of dry solids to be pumped	M	tph
Pulp Density of slurry (% solids by weight)	Cw	%
S.G. Solids	S	Tonnes per m^3
S.G. Liquid	SL	Tonnes per m^3
Liquid Viscosity	Cp	Centipoise (1 for water)
Solids size	d50	microns
Vertical height separation from pump to discharge point	Hs	metres
Head loss through equipment eg. Cyclone	Hequip	kPa
Pipe Material internal roughness	k	metres
Pipe diameter	D	metres

FORMULAE REQUIRED

Mass flow rate of Water

$$Q_W = \left(\frac{M \times 100}{C_W}\right) - M \qquad \text{m}^3/\text{h}$$

Volume Flow Rate of Slurry

$$Q = \frac{M}{S} + M\left(\frac{100 - C_W}{C_W \times S_L}\right) \qquad \text{m}^3/\text{h}$$

Slurry SG

$$S_M = \frac{S \times S_L}{S - \left(C_W \times \frac{S}{100}\right) + \left(C_W \times \frac{S_L}{100}\right)} \qquad \text{t/m}^3$$

% Solids by Volume

$$C_V = 100 \times \frac{(S_M - S_L)}{(S - S_L)} \qquad \%$$

Durand Factor

$$F_L = 0.4794 + 0.5429\left(\frac{C_V\,\%}{100}\right)^{0.1058}\log d_{50} - 1$$

The Durand factor is an empirically derived factor based on tests on sands of various particle sizes to enable the limiting settling velocity of flow in a pipe to be determined. The factor is used in the next equation.

Limiting Settling Velocity

$$V_L = F_L\sqrt{2gD\frac{(S - S_L)}{S_L}}$$

m/s

This is the theoretical minimum velocity at which the slurry must be pumped to prevent any settlement in the pipeline. (Note that g is the acceleration due to gravity and is 9.8 m/sec^2 , which is acceptable for this calculation.

Reynolds Number

$$R_e = \frac{D \times V \times S_M \times 10^6}{C_P}$$

Dimensionless

Reynolds number is a dimensionless parameter which relates fluid viscosity, flow velocity, solids mass and pipe dimension. For most slurry work, the Reynolds number will be quite high. It is used in the next formula to calculate the friction factor, which is then used to calculate the head loss due to friction between the slurry and the pipe wall.

Swamee Jain Friction Factor

$$f = \frac{0.25}{\left[\log\left(\frac{k}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$$

Dimensionless

The Swamee Jain formula approximates the Colebrook White formula but is mathematically simpler.

Friction Head Loss

$$H_f = f \times \frac{L \times V^2}{D \times 2g}$$

metres

The above formula is the well known Darcy Weisbach formula for pipe friction, in metres of head lost.

$$HR = 1 - 0.000385(SG - 1)\left(1 + \frac{4}{SG}\right)C_W \times l_n\left(\frac{d_{50}}{22.7}\right)$$

Dimensionless

The above formula calculates a number called the Head Ratio. The HR is a factor which allows for the reduction of pump performance due to the difference in rheology of the slurry as compared with water. Pump performance curves are produced from tests on water, so it is necessary to correct for the effect of slurry. This same parameter is also called the Efficiency Ratio, ER.

$$kW = \frac{Q \times H_W \times S_M}{Efficiency\%_{WATER} \times 3.67}$$

Calculates the power required at the pump shaft

CALCULATION PROCEDURE

1) Calculate the water required to add to the solids to achieve the required solids concentration by weight
2) Calculate the volume flow rate of the slurry
3) Calculate the slurry SG (or pulp density)
4) Calculate the Volume % solids
5) Calculate the Limiting Settling Velocity, using the Durand factor and the Durand formula
6) Choose a trial pipe internal diameter.
7) Calculate the actual velocity in the trial pipe, and compare to the Limiting Settling Velocity. Adjust pipe diameter until LSV is less than or equal to the actual velocity.
8) Calculate Reynolds number
9) Calculate the Friction factor
10) Calculate the equivalent length of the pipeline to allow for the fittings
11) Calculate the friction head loss
12) Add Friction head, Static head and Equipment head to obtain Total head (metres of slurry)
13) Calculate the Head / Efficiency Correction Factor
14) Divide slurry head by the correction factor to obtain the Equivalent Water head.
15) Using the Volume flow rate of slurry, and the Equivalent Water head, select a suitable pump from the performance curves. Refer to the paragraph on pump selection.
16) Mark the duty point on the pump curve and read off the pump efficiency at that point.
17) Calculate the required power
18) Factor up and select the next highest kilowatt motor frame size.
19) From the pump curve, read off the required pump speed.
20) Select the appropriate motor speed. This is usually the four pole speed (1440 to 1480 rpm).
21) Select a belt drive suitable for the speed and power.

WORKED EXAMPLE

A pump is required to deliver 110 tonnes per hour of 2.7 SG solids as a slurry of 35% pulp density by weight, to a cyclone. Pressure drop across the cyclone is 90 kPa, and the vertical lift from the pump to the cyclone is 15 metres. The line length is 43 metres, and there are 3 sweep bends in the line. The solids sizing is d50 of 75 microns, and d80 is 200 microns. It is proposed to use Medium Density Polyethylene pipe. The pump sump is fed and controlled to operate with a slurry level of 1 to 3 metres positive head over the pump suction.

Input data is:

M = 110 tph. Dry solids
SG solids = 2.7
Cw = 35% wt/wt
Static Head Hs = 15 m.
Equipment Head Hequ.= 90 kPa.
Line length = 40 m. with 3 bends
Transport Medium is water so viscosity is 1 Centipoise
Pipe is MDPE, so roughness factor k = 0.000015 m.

Water required $Q_W = \left(\frac{M \times 100}{C_W}\right) - M \quad = \left(\frac{110 \times 100}{35}\right) - 110$ = 204 m^3/h

Slurry volume $Q = \frac{M}{S} + M\left(\frac{100 - C_W}{C_W \times S_L}\right) \quad = \frac{110}{2.7} + 110\left(\frac{100 - 35}{35 \times 1}\right)$ = 245 m^3/h

Slurry SG

$$S_M = \frac{S \times S_L}{S - \left(C_W \times \frac{S}{100}\right) + \left(C_W \times \frac{S_L}{100}\right)}$$

$$S_M = \frac{2.7 \times 1}{2.7 - \left(35 \times \frac{2.7}{100}\right) + \left(35 \times \frac{1}{100}\right)}$$

= 1.28 t/m^3

% Solids by Volume $C_V = 100 \times \frac{(S_M - S_L)}{(S - S_L)} \quad = 100 \times \frac{(1.28 - 1)}{(2.7 - 1)}$ = 16.47 %

Durand Factor $F_L = 0.4794 + 0.5429\left(\frac{C_V\,\%}{100}\right)^{0.1058} \log d_{50} - 1$

$$F_L = 0.4794 + 0.5429\left(\frac{16.47}{100}\right)^{0.1058} \log 75 - 1 \qquad = 0.87$$

Choose a pipe diameter. A good starting point is to calculate a diameter to give a velocity of approximately 3 m/second. Transposing the formula, Q = V x A, to A = Q/V, a diameter can be selected.
(Note that Q must be converted to m³/second by dividing by 3600)

$$A = \frac{Q}{V} \qquad A = \frac{245}{3 \times 3600} \quad = \quad 0.0227 \text{ m}^2$$

and diameter $D = \sqrt{\frac{4 \times A}{\pi}}$ $\qquad D = \sqrt{\frac{4 \times 0.0227}{\pi}}$ $\quad = \quad 0.17$ m.

Therefore, select 200 PN8 MDPE poly pipe. (*The internal diameter is 0.176 m. and PN8 has a pressure rating of 8 bar, or approx. 80 m. Since most single stage, centrifugal slurry pumps do not exceed a discharge pressure of 80 m., PN8 usually is adequate.)*

D = 0.176 m.

Limiting Settling Velocity $\quad V_L = F_L \sqrt{2gD \frac{(S - S_L)}{S_L}}$

$$= 0.87\sqrt{2 \times 9.81 \times 0.176 \frac{(2.7 - 1)}{1}} \qquad = 2.11 \text{ m/s}$$

Calculate the actual velocity in the selected pipe, and compare with V_L (Actual velocity must be > V_L)

$$V = \frac{Q}{A} \qquad V = \frac{245 \times 4}{3600 \times \pi \times 0.176^2} \qquad = 2.8 \text{ m/s OK, is} > 2.11$$

In some cases it may be necessary to try some alternate pipe diameters to arrive at the most cost efficient pipe size which satisfies the design requirement.

Calculate the head loss due to friction.

Reynolds Number $\quad R_e = \frac{D \times V \times S_M \times 10^6}{C_P} \quad = \frac{0.176 \times 2.8 \times 1.28 \times 10^6}{1}$ $\quad = 630784$

Swamee Jain Friction Factor $\quad f = \frac{0.25}{\left[\log\left(\frac{k}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$

$$f = \frac{0.25}{\left(\log\left(\frac{0.000015}{3.7\times 0.176}+\frac{5.74}{630784^{0.9}}\right)\right)^{2}}$$ = 0.0139

This step requires the pipe equivalent length $L_{eq.}$ This is computed by adding the actual length of pipe to the total equivalent length of any fittings. From the graph in Figure 1.0, a 200 NB pipe bend is equivalent to about 4 metres of pipe. Therefore three bends require the addition of approximately 12 m.
Thus $L_{eq.}$ = 43 + 12 = 55 m.

Friction Head Loss $$H_f = f\times\frac{L_{eq}\times V^2}{D\times 2g} = 0.0139\times\frac{55\times 2.8^2}{0.0176\times 2\times 9.81}$$ = 1.74 m.

Equipment loss is quoted as 90 kPa. This must be converted to head of slurry.

$$H_{equip} = \frac{kPa}{g\times S_M} = \frac{90}{9.81\times 1.28}$$ =7.15 m. slurry

The total head loss H, often referred to as total dynamic head, can now be evaluated.

Total Head = Hs + Hequip. + Hf = 15 + 7.15 + 1.74 = 23.9 m. slurry

Pump Selection

Pump curves are the result of tests on water, and because the pump efficiency is reduced due to the viscosity effects of the slurry, it is necessary to correct the slurry head back to water so that a point on the curve may be plotted. This is done using the Head Ratio/Efficiency Ratio (HR/ER) factor, an empirically developed formula. Warman and others publish a nomograph to pick this factor, but the following formula allows the figure to be calculated.

$$HR = ER = 1 - 0.000385(S-1)\left(1+\frac{4}{S}\right)\left[C_W\times l_n\left(\frac{d_{50}}{22.7}\right)\right]$$

$$= 1 - 0.000385(2.7-1)\left(1+\frac{4}{2.7}\right)\left[35\times l_n\left(\frac{75}{22.7}\right)\right]$$ = 0.93

Calculate equivalent head on water

$$H_W = \frac{TotalHead}{HR} = \frac{23.9}{0.93}$$ = 25.7 m. water

The pump can now be selected. The attached pump curve for a Warman 6/4 DAH with a 5 vane closed polymer impeller is suitable. There are other suitable selections.

Note that the units of flow on the X axis are litres per second. It is therefore necessary to divide our value of Q m³/h, by 3.6 to convert to l/sec.
Thus, 245 m³/h /3.6 = 68.06 l/s

The values of Hw and Q are used to locate the duty point on the curve. This should be close to the line of maximum efficiency, and ideally always on or to the left of that line. Any point on the line is known as the Best Efficiency Point (BEP) for that particular speed. Attempt to select the pump which best fits these requirements.
With the duty point located, the pump efficiency and the speed can be read off. In this case, the speed is 1120 rpm and the efficiency is 71%.

Power Required

Power can now be calculated. The ER value is applied to the pump efficiency, to correct for viscosity effects.

$$kW = \frac{Q \times H_W \times S_M}{Efficiency\%_{WATER} \times 3.67} \qquad = \frac{245 \times 25.7 \times 1.28}{71 \times 3.67} \qquad = 30.93 \text{ kW}$$

Motor Selection

It is good practice to factor up this calculated value to cover variations or surges in plant throughput, fluctuations in slurry density and as is often the case, the need to be able to squeeze a little more from the circuit. When centrifugal seals are used on the pump, up to 5% extra power is consumed.

A common factor is 20%, but this is really up to the judgement of the designer.

Thus, 30.93 x 1.2 = 37.12 kW.

Use 37 kW motor.
(NOTE: If result had been significantly higher than 37 kW, the next standard motor would be chosen)

The number of poles in the motor governs the motor speed. It is most efficient to select a motor speed which is closest to the required pump speed. This results in a more economical and efficient belt drive. Fortunately in most cases, a four pole motor (1440 rpm) motor will be the best selection.

Drive Selection

The drive can be selected from a manufacturers manual. The ratio is selected to produce the required pump speed, and a series of service and other factors are applied to arrive at the number of belts required to transmit the power. Motor and pump shaft diameters must be considered in the selection of the pulley locking bushes.

It is usually wise to involve the drive supplier in these selections, and they are always very pleased to help.

WEIR SLURRY GROUP

TYPICAL PUMP
PERFORMANCE CURV

WARMAN PUMP

SIZE	FRAME		TYPE
6/4	D	DD	**AH**
	E	EE	
	Q	R	

IMPELLER: E4147

VANES	TYPE	IMPELLER MAT'L	VANE ø	LINER MAT'L
5	Closed	Polymer	365	Metal/Polymer

GLAND SEALED PUMP

WPA
64A03A

ISSUED
MAY 1987

Frame	D	DD	E	EE	Q	R
Rating [kW]	60	110	120	225	150	300

NORMAL MAX. SPEED
1350 r/min

MIN. PASSAGE SIZ
33
mm SPHERE

CURVE SHOWS APPROXIMATE PERFORMANCE FOR CLEAR WATER. (To International Test Standard ISO2548 Class C) : For media other than water, corrections must be made for density, viscosity and/or other effects of solids. WARMAN INTERNATIONAL LTD. reserve the right to change pump performance and/or delete impellers without notice. Frame suitability must be checked for each duty and drive arrangement. Not all frame alternatives are necessarily available from each manufacturing centre.