IRR CONFERENCE

INNOVATIONS – IMPROVING THE EFFICIENCY OF SLURRY TRANSPORT

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1. INTRODUCTION

From a pumping viewpoint the optimum slurry is one where the particle size is fine enough such that the slurry flows homogeneously but not so fine that high rheology limits the maximum concentration. A lot depends on the exact slurry properties but as an indication the optimum slurry has a mean particle size in the range 50 to 100 microns as indicated in Figure 1. As the particle size becomes finer than 50 microns the rheology starts increasing and the flow becomes laminar unless the concentration is decreased. If the concentration remains constant then the pressure gradient increases as indicated in Figure 1. Under laminar flow conditions settling issues become important and the pressure gradient will be in the range 1000 kPa/km to 2000 kPa/km, or else the pipe will block. Laminar flow settling is discussed in a separate paper at this conference. As the mean particle size increases above 100 microns the pressure gradient rapidly increases. The deposit velocity in a 300 mm pipe also rapidly exceeds 2 m/s and in fact the velocity will need to be increased.

Figure 1

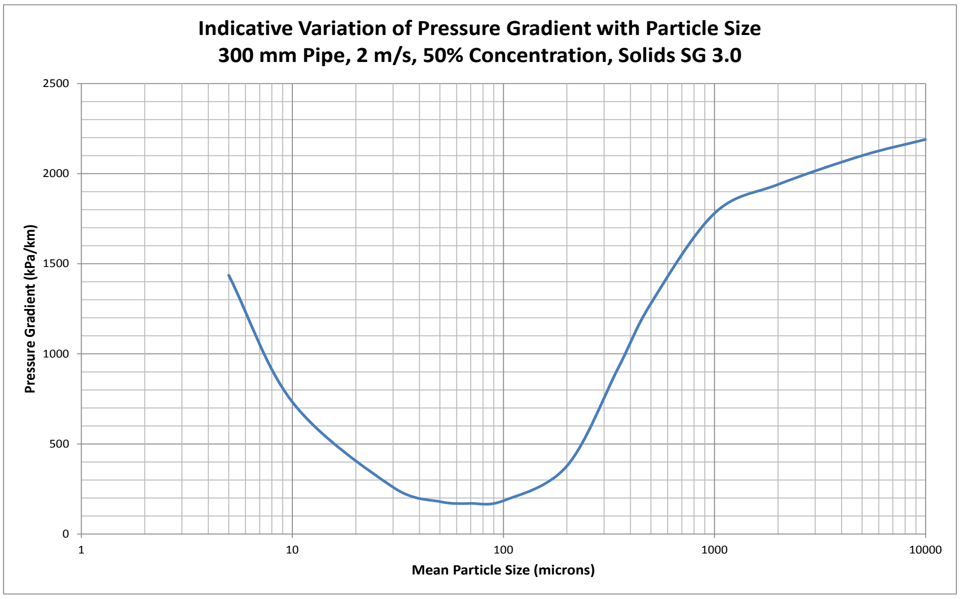


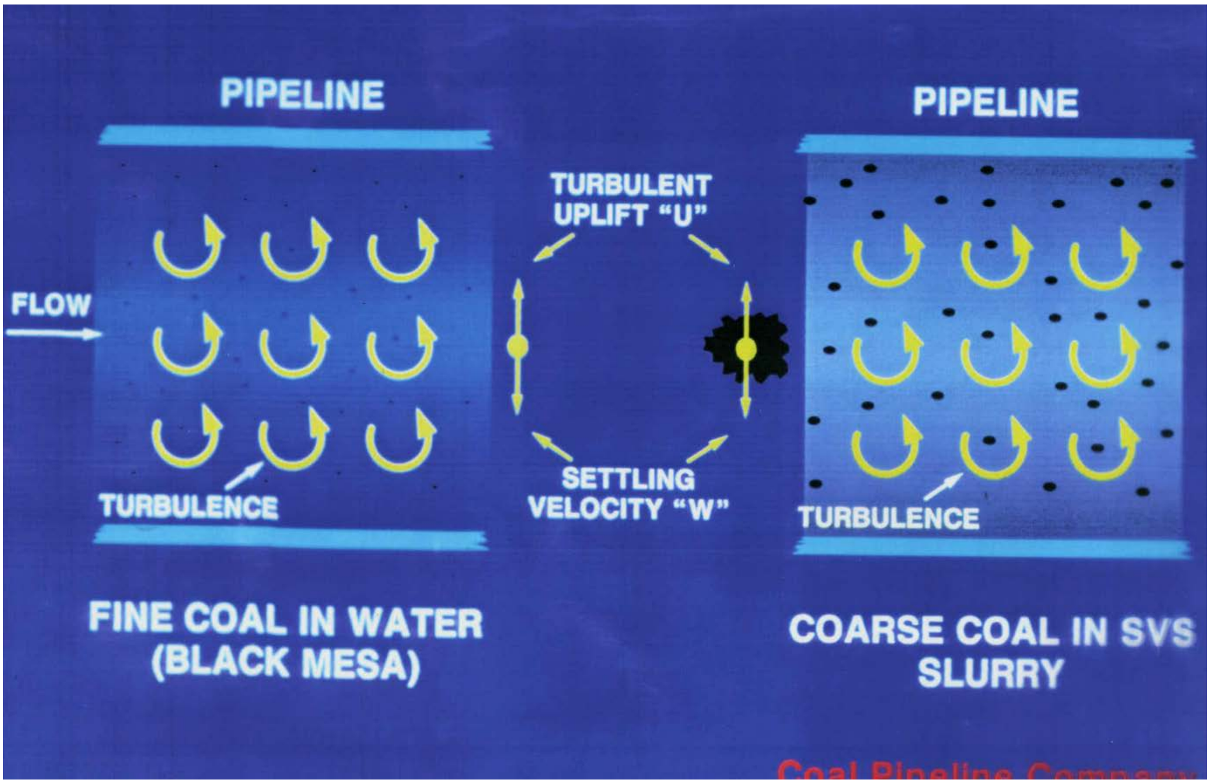
Figure 1 shows that there is a relatively narrow range of particle size which is optimum. Unfortunately we generally don't get to choose what type of slurry we want to pump. If the particle size is coarse it is generally not economic to crush or grind finer just because that would then be easier to pump. However there are sometimes other ways to improve the pumpability. Some innovative methods which have been developed over the years to transport different materials by slurry pipeline are now discussed. In relation to Figure 1, many of these methods effectively extend the optimum low pressure gradient region to the right in the case of coarse particle slurries and to the left in the case of fine particle slurries.

2. SPECIAL VEHICLE SLURRY (SVS)

Pipeline transport of lump coal by pumping in water involves very high velocities with resulting high pressure gradients and high pipe wear and is only economic over short distances. We will be discussing later in this conference the concept of pumping coarse coal as a stabilised slurry under laminar flow conditions and show how laminar flow operation proved unviable.

To enable lump coal to be pumped over long distances Slurry Systems developed the Special Vehicle Slurry (SVS), (Cowper et al, 2010). The SVS concept is illustrated in Figure 2.

Figure 2



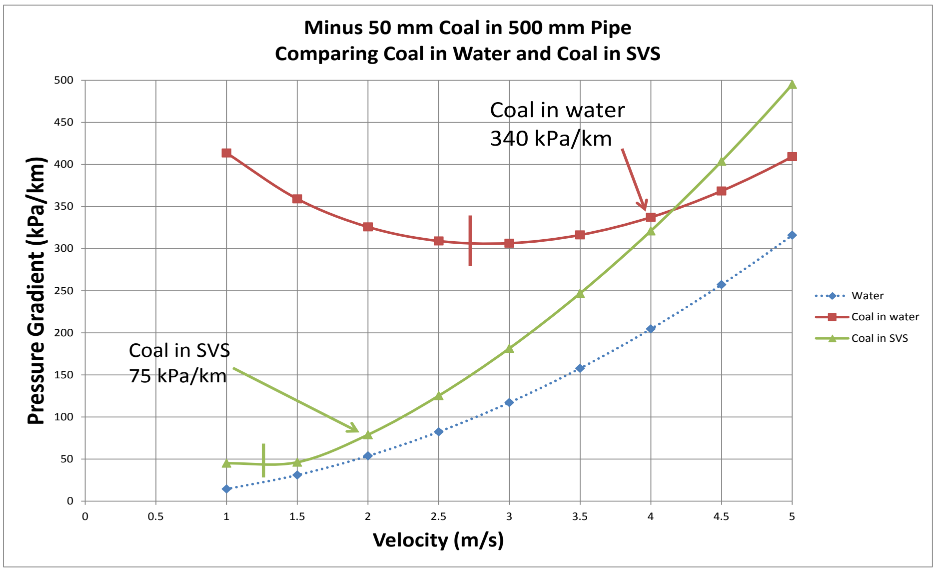
The basic principle is to create a slurry to transport conventional product coal that simulates the successful fine coal slurry hydraulics proven in the Black Mesa slurry pipeline.

SVS involves transporting the coarse coal in turbulent flow in a special vehicle slurry comprising a mixture of fine magnetite and fine coal. The ratio of magnetite to fine coal and the total solids concentration are selected to give a vehicle slurry SG the same SG as the coarse coal, typically in the range 1.35 to 1.40.

Figure 3 compares the pressure gradient for minus 50 mm washed coal (SG 1.35) in water with the same coal in SVS in a 500 mm diameter pipe. For the coarse coal in water, deposition occurs at 2.7 m/s and the operating velocity is 4 m/s with a pressure gradient of 340 kPa/km. At 4 m/s pipe wear rate is very high and special wear resistant pipe is required and the pipe needs to be rotated regularly to prolong pipe life. Restart after a shutdown can be difficult with the possibility of pipe blockage.

For the coarse coal in SVS, deposition coincides with laminar-turbulent transition at 1.25 m/s and the operating velocity is 2 m/s with the pressure gradient 75 kPa/km. Pipe wear is minimal and ordinary steel pipe is sufficient. On shutdown the coarse coal remains suspended in the vehicle slurry and remains fluid and can easily be restarted.

Figure 3



SVS hydraulics have been proven by SSE in tests on a minus 20 mm coal conducted in a 105 mm test loop at M.D. Research in Sydney. SVS was also tested separately by Rio Tinto in a 250 mm diameter test loop at a NSW colliery in the 1990's. It was incorporated in the circuit of a dense media washery and both the predicted low pressure gradient and low pipe wear were confirmed. SSE has also conducted numerous Wheelstand tests on SVS slurries which have confirmed the low pipe wear rates. Although SSE has conducted a number of feasibility studies, no system has yet been built.

The use of magnetite in the vehicle slurry enables the coal to be made neutrally buoyant. Another major advantage of using magnetite is that it can be separated from the fine coal portion of the vehicle slurry using magnetic separators as commonly used in coal washeries. A magnetite carrier vehicle could be used to transport materials heavier than coal and, although neutral buoyancy would not be achieved, it would still result in reduced pressure gradients and may offer economic advantages. These would need to be assessed on a case by case basis.

3. TRANPORT OF HEAVY MINERAL SANDS IN SLIMES

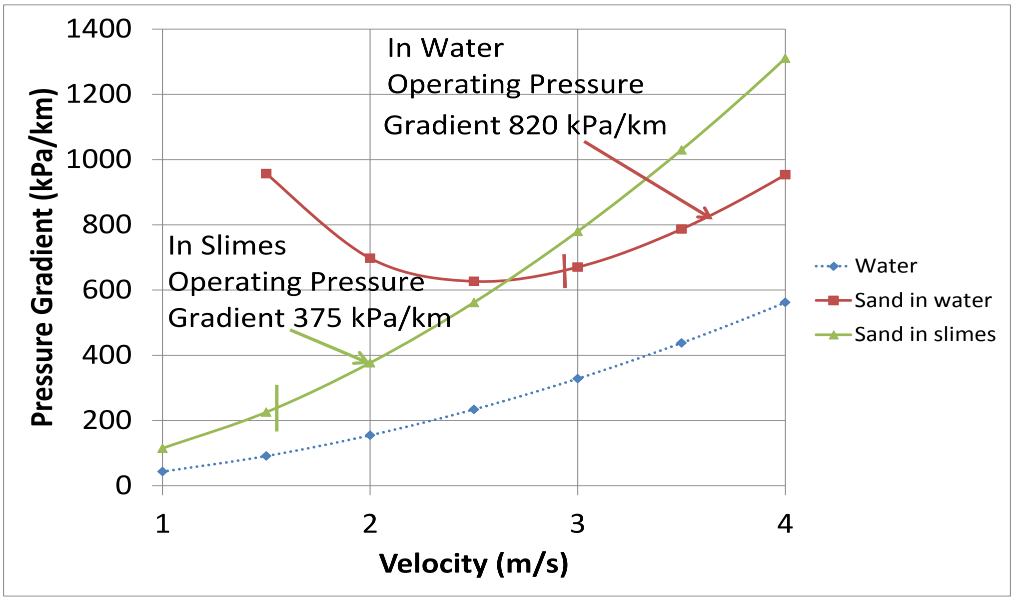
Mineral sands often occur in clay bands and the heavy mineral sand is separated from the slimes by washing before the sands are transported. Once washed, the mineral sands require high velocities and pressure gradients to pump, as for example occur in the New Zealand iron sand pipeline (Venton and Cowper, 1986).

An adaptation of the SVS concept to mineral sands involves pumping the sand in the slimes, separating the slimes at the pipeline terminal using conventional cyclones, then returning the slimes via a separate pipeline. Many slurry pipeline projects now require a water return pipeline so pumping the sand in the slimes achieves the same water recycling but with the added advantage that the slimes reduces the pressure gradient in the mineral sands pipeline.

Figure 4 compares predicted pressure gradients for the N.Z. iron sand in water and in a 20% concentration slimes vehicle slurry in the 187 ID pipe. The deposit velocity in water is 2.85 m/s but this reduces to 1.6 m/s in slimes. The pressure gradient reduces by more than half. However to get the same solids throughput in the slimes the pipe size is increased to DN250 (ID 242 mm). The operating velocity is 2.15 m/s and the pressure gradient reduces to 320 kPa/km. Importantly the wear rate is much lower and depending on the corrosivity of the slurry, unlined steel pipe may be viable, or at least a much cheaper polyethylene liner may be used rather than polyurethane.

Whereas the previously discussed SVS system relied on magnetic separators to separate the recyclable magnetite from the fine coal portion of the carrier, separation of the mineral sands from the slimes carrier relies on the fact that the mineral sands have a narrow size distribution with particle sizes which do not extend down to the slimes range. The pressure gradient could be further reduced by use of a viscosity modifier to allow higher slimes concentration. Viscosity modifiers are discussed next.

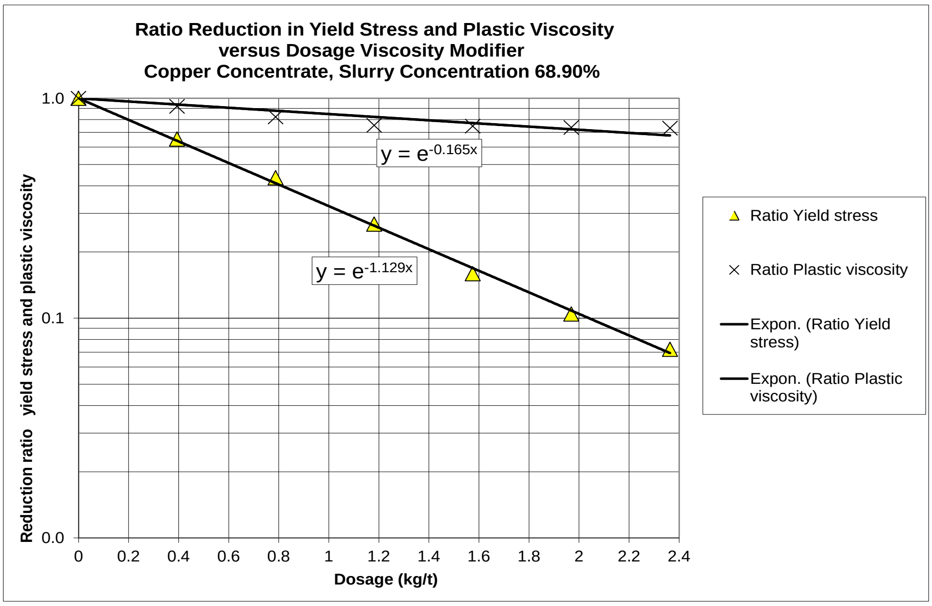
Figure 4



4. VISCOSITY MODIFIERS

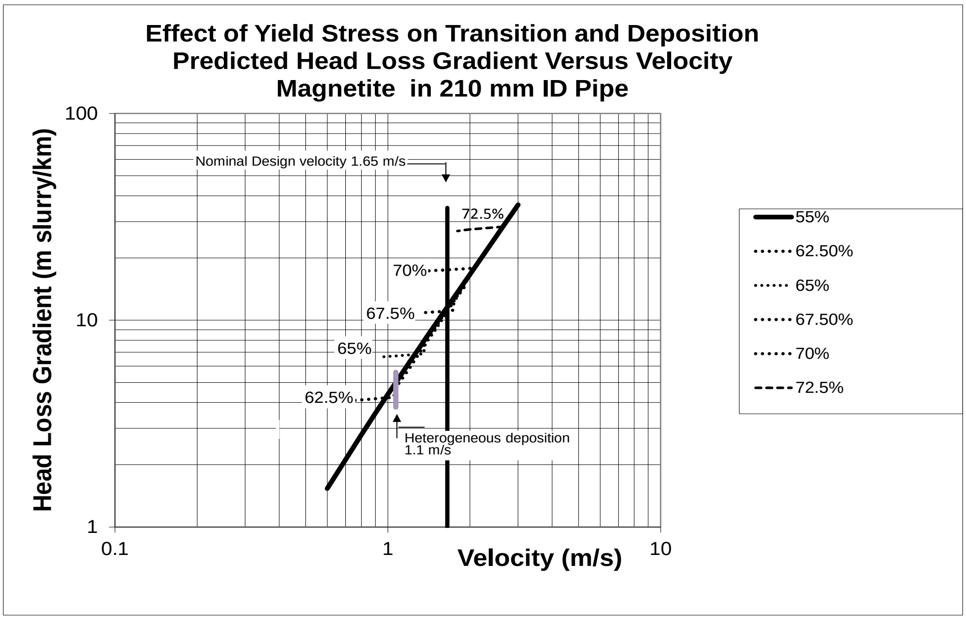
Viscosity modifiers are chemical additives which reduce the yield stress of a slurry, but generally have little influence on the plastic viscosity. This is illustrated in Figure 5 which compares the ratio reduction in yield stress and plastic viscosity for a particular viscosity modifier on a copper concentrate slurry.

Figure 5



The transition velocity between laminar and turbulent flow is largely determined by the yield stress so addition of a viscosity modifier allows higher concentrations to be pumped whilst still maintaining turbulent flow. The situation is illustrated by Figure 6 which is a plot of head loss gradient (metres of slurry per km) versus velocity for a minus 100 micron magnetite slurry in a 210 mm ID pipe.

Figure 6



The steep angled bold line represents the turbulent flow head loss gradient and is practically the same for all concentrations when expressed in terms of head loss gradient rather than pressure gradient. The flatter dashed curves on the left represent laminar flow predictions assuming homogeneous flow. These are largely dependant on the yield stress. The intersection of the turbulent and laminar flow curves represents the transition velocity. For any particular concentration, as the velocity is decreased the head loss gradient will follow the turbulent flow line down until the transition velocity after which the head loss gradient will follow the laminar flow curve shown but only assuming homogeneous flow, which in fact will not be the case for the concentrations shown in Figure 6. Deposition will actually occur as soon as the velocity falls below the transition velocity.

Operating velocities in the range 1.5 to 2 m/s generally provide the most economic balance between pumping costs and pipeline costs. For this particular slurry and pipe size the selected operating velocity is 1.65 m/s as indicated by the vertical dashed line. For concentrations below 62.5% the predicted heterogeneous deposit velocity is around 1.1 m/s as indicated by the barred vertical line. For these concentrations deposition occurs under turbulent flow conditions although for 62.5% concentration the deposit velocity also coincides with the transition velocity.

The highest feasible concentration in Figure 6 is 65% for which deposition will occur at the 1.35 m/s transition velocity, 0.3 m/s below the operating velocity. It would not be desireable to operate at 67.5% concentration because transition coincides with the operating velocity, meaning that a stationary/sliding bed would be present with the potential to cause unstable operation and increasing bottom pipe wear.

Now suppose a viscosity modifier is added which reduces the yield stress by a factor of 4. The 72.5% laminar flow dashed curve would reduce by a factor of 4 to approximately coincide with the 65% laminar flow curve in Figure 6. The transition velocity would reduce from 2.65 m/s to 1.35 m/s and turbulent flow would be present at the operating velocity of 1.65 m/s.

At 72.5% concentration the solids throughput is 356 tph compared with 279 tph at 65% concentration, an increase of 28%. The pressure gradient would increase by about 12% but pump pressure could increase by much less if there is significant static head advantage, due to the higher slurry density. In relation to Figure 1 viscosity modifiers are effectively extending the optimum low pressure gradient region further to the left.

5. TURBULENT DRAG REDUCTION USING DRAG REDUCING ADDITIVES

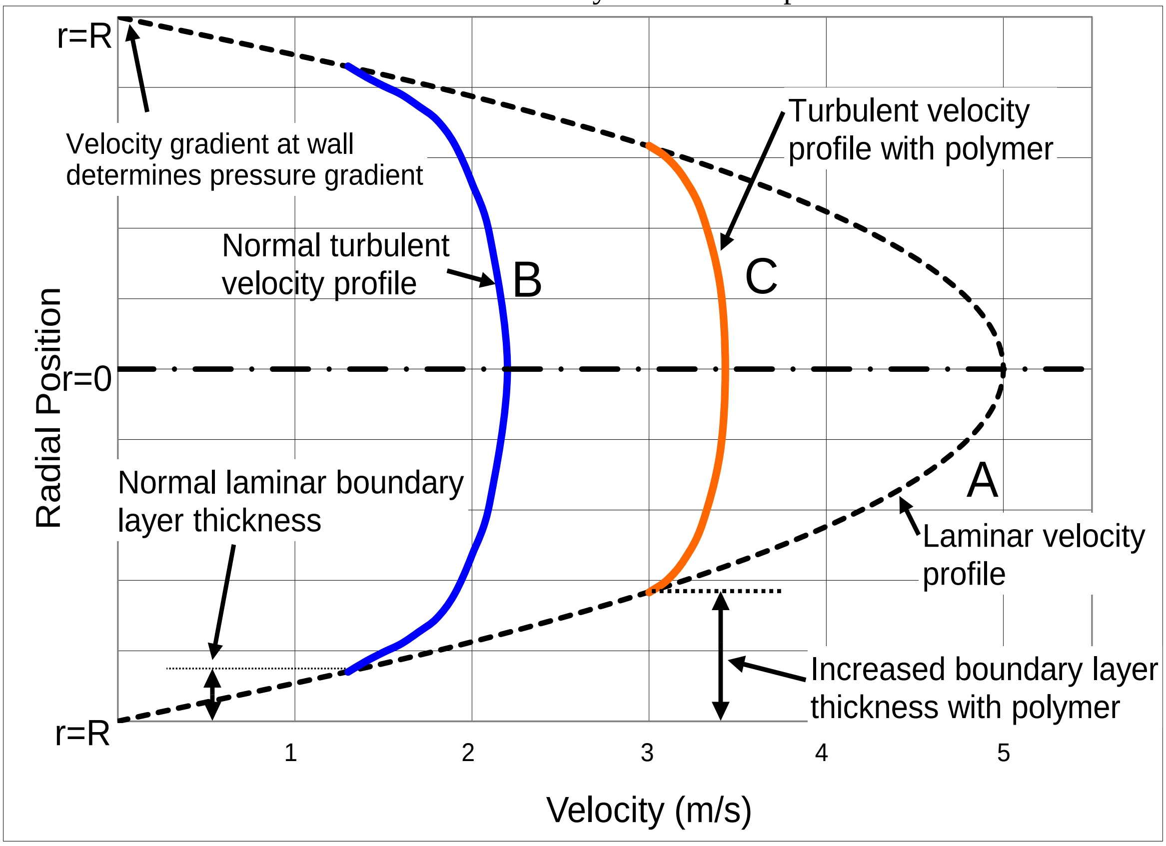
5.1 Introduction

The addition of certain long chain polymers to water has been known for many years to increase the flow rate by up to 80% with no change in the pressure gradient. The dosage rate required is very small, typically around 30 ppm. The polymers act by suppressing turbulence in the wall region thereby effectively increasing the thickness of the boundary layer. Such polymers are routinely used in oil pipelines such as the Trans Alaska pipeline. In PNG the Kutubu pipeline flow rate increased from 120,000 bbl/d to 200,000 bbl/d with drag reducer. However these oil pipeline enhancers are not miscible in water and therefore probably not suitable for water based slurries.

5.2 Drag Reduction due to Thickened Boundary Layer

Laminar and turbulent velocity profiles in pipe flow are illustrated schematically in Figure 7.

Figure 7
Schematic of Velocity Profiles in Pipe Flow



The dashed curve A represents the parabolic laminar flow velocity profile. The laminar flow pressure gradient, $\Delta P/L$, is determined by the velocity gradient, (dV/dr) at the wall as per Eqn 1.

$$\Delta P/L = (4\ \mu\ /D)\ \ (dV/dr)_{r\ =\ R} \qquad (1)$$

where μ is the viscosity
D is the pipe diameter
V is the velocity at a particular radius, r, in the pipe
R is the radius at the wall = D/2

Equation 1 applies to laminar flow. Flow of water, except in extremely small pipes, is turbulent. Curve B in Figure 7 is a schematic of the normal turbulent velocity profile. In the laminar boundary layer region adjacent to the wall the flow is laminar and the profile initially follows the same profile as the laminar flow profile. But once the velocity in the boundary layer reaches a certain value, inertial effects cause turbulent eddies to develop and the profile B deviates away from the laminar profile and becomes blunter as indicated. Now, even though the pressure gradient, as determined by the velocity gradient at the wall, remains the same as per Eqn 1, the average velocity and hence flow rate is less than if laminar flow had persisted. In Figure 7 the average velocity for turbulent profile B can be visualised as being significantly less than the average velocity for the laminar flow curve, A.

Comparisons between Curves A and B illustrates how, for the same pressure gradient, the flow rate with turbulent flow is less than if laminar flow occurred throughout the pipe. Conversely, for the same flow rate, the pressure gradient for turbulent flow is greater than for laminar flow.

It must be emphasised that Figure 7 is purely schematic. In actual fact the boundary layer thickness is very small, just a few mm in a 200 mm pipe. Hence the turbulent flow profile will break away from the laminar flow profile much sooner than indicated in Figure 7 and will be much blunter than shown. Therefore the difference between the average velocity of the turbulent flow profile and the laminar flow profile will be much greater. Also, there is a buffer layer between the laminar boundary layer and the turbulent core region which is not shown in Figure 7.

5.3 Effect of Polymer Addition on Velocity Profile

Velocity profile C schematically illustrates the effect of addition of polymer. The long chain polymer suppresses turbulent eddies in the buffer layer thereby effectively increasing the thickness of the buffer layer although in Figure 7 this effect is indicated as an increase in the thickness of the laminar boundary layer.

Figure 7 shows how increasing the thickness of the boundary layer causes the turbulent velocity profile to move from Curve B to Curve C. The effect is to increase the average velocity, and hence flow rate, with no change in the pressure gradient which is still determined by the velocity gradient immediately adjacent to the wall.

5.4 Maximum Possible Drag Reduction

The maximum possible drag reduction occurs when the buffer layer thickness is increased to the extent that it reaches the centre line of the pipe. In Figure 7 the profile would then be the same as the laminar profile but in reality, because Figure 7 ignores the buffer layer, this is not the case.

Virk (1975) studied the maximum possible drag reduction and concluded that the theoretical maximum Drag Reduction Factor is 0.19, the Drag Reduction Factor being defined in Eqn 2.

$$\text{Drag Reduction Factor (DRF)} = [f_{\text{additive}} / f_{\text{no additive}}] \quad \text{(for the same velocity)} \qquad (2)$$

5.5 Application to Slurries

A number of early researchers have investigated drag reduction with slurries in small scale laboratory scale test loops. For example Poreh et al (1970) tested a 0.9 mm sand slurry, volume concentration 20%, in a 20 mm diameter loop. They found that energy savings up to 70% could be achieved by addition of small quantities of a complex soap (cetry trimethyl-ammonium bromide-1-Naphthol). Polymer solutions were not found to be as effective.

Sellin (1989) reviewed a number of earlier papers including the results of Fujimoto and Tagori (1974) who tested Separan AP30 with an iron ore slurry up to 40% by weight concentration in a 25 mm pipe. They found up to 50% drag reduction but the drag reduction reduced as the concentration increased. Sellin also notes Golda (1984) who tested a range of coal slurries in a 40 mm tube and obtained a maximum drag reduction of 40% with Separan AP-45. Limited tests were also conducted in a 254 mm pipe loop.

Sellin (1989) offers the general conclusion “that the longer the pipeline the more likely it is that polymers could be advantageous. It would appear that although most polymers are vulnerable to degradation in centrifugal pumps, the risk of them degrading in long pipe runs due to flow induced wall shear stress is low”

Large scale field trials were conducted by Interthal et al (1983). They tested a sand/water slurry with sand of d_{50} = 0.23 mm at a concentration of 27% by wt in a 3.2 km long, 300 mm pipeline. They obtained what they described as an “astonishing” 44% increase in sand throughput with 40 ppm addition of a high molecular weight polymer drag reducer, due to the increase in flow rate and also because they were able to pump at higher concentrations with additive.

Because the dredge trial involved a centrifugal pump, the reduction in friction loss with additive allowed the system curve to move out on the pump curve resulting in an increase in flow rate which contributed to the increase in solids throughput.

The drag reduction measured by Interthal et al (1983) applies to a sand slurry in water with few fines for which the boundary layer is almost pure water and it is likely that drag reduction is most effective with this type of slurry. Wide size distribution, viscous mineral processing slurries, where the boundary layer will comprise very fine slurry, may be less amenable to significant drag reduction.

6. RECYCLE FINES SYSTEM (RFS)

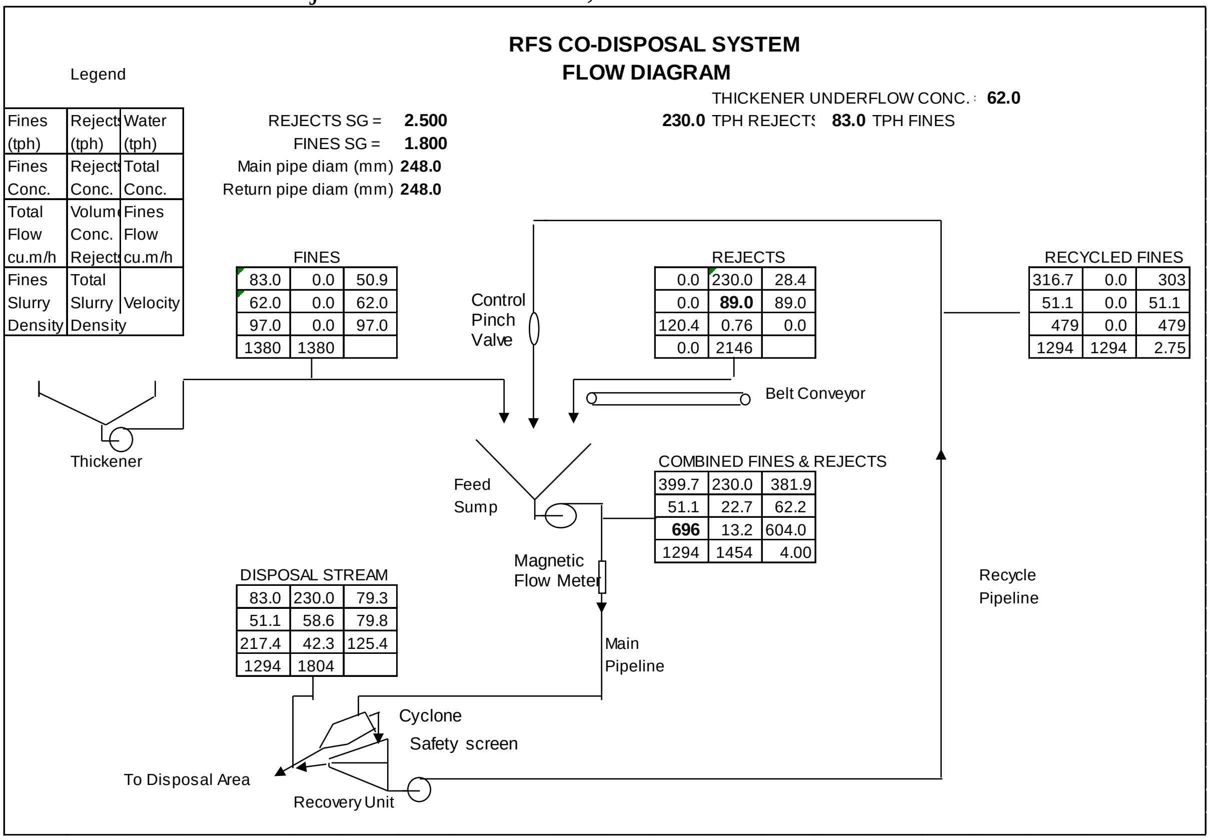
In the coal industry, coarse (minus 50 to 100 mm) rejects are generally trucked to disposal whilst the fine tailings (minus 2 mm) are pumped to tailings dams. However a number of mines in Queensland employ the co-disposal technique whereby the coarse rejects are combined with the tailings and pumped to disposal. The problem is that the relative ratios of coarse rejects to fine tailings means that a considerable amount of water has to be added to reduce the volume concentration of the coarse rejects to a pumpable 20% or less. The result is that instead of the tailings being at a high, thickener underflow, concentration, so much water is added that the tailings concentrations ends up quite dilute. At the pipeline discharge the watery slurry immediately segregates with the coarse rejects dropping out and the fine tailings washing down to the toe of the deposit. Large quantities of water must be managed and returned.

A preferred process would be if the fine tailings could be pumped at thickener underflow concentration so the viscous nature of the fines prevents them separating from the coarse rejects and a homogeneous sloping deposit is achieved.

RFS Codisposal Pty Ltd is the owner of a patented system for co-disposing of coarse rejects and thickener underflow. The system involves pumping the rejects with the fines at the normal thickener underflow concentration. At the disposal area a recovery unit separates the coarse rejects from the fines and some of the fines are returned in a separate recycle pipeline. By this method the discharge stream is at maximum concentration, typically between 50% to 70%, allowing a near homogeneous cone deposit, with minimal water return necessary.

Figure 8 shows the flow diagram at nominal throughputs and concentrations for a particular mine studied. Tails concentration delivered to deposit is 51.1%. Concentration of rejects in the main pipeline is a comfortable 22.7% by weight (13.2% by volume). In Figure 8 the separation at the disposal area is shown using a cyclone but a 2 mm screen is an alternative. The screening does not have to be very efficient since only 79% of the fines are recycled.

Figure 8
Nominal throughput 230 tph Rejects, 83 tph dry tails
Rejects at 11% moisture, tails at 62% concentration



The advantages of the RFS system in the above example are:

- Based on 11% rejects moisture and 62% underflow concentration the tails concentration delivered to deposit is 51.1%.
- Total concentration of solids (tails plus coarse rejects) delivered to the deposit is 79.8%.
- Uses existing centrifugal pumps and pipelines.

- Coarse rejects volume concentration in pipeline is only 13.2% meaning reliable operation with minimum potential for blockage.

In the conventional co-disposal alternative where the tails and rejects are just combined, an additional 243 tph of water must be added to the two streams to keep the volume concentration of rejects below a pumpable 20%. This dilutes the tails concentration to 20% by weight compared with 51% with RFS, and the total delivered concentration is 49% compared with 80% with RFS.

Although there is some reduction in pressure gradient by pumping the coarse rejects in the higher concentration tailings, the main benefit of the RFS system is that it results in a higher concentration, more homogeneous deposit with less water needed to be recycled. The RFS concept offers the potential for applications for tailings disposal in mines other than coal mines.

7. FLOCCULENT ADDITION AT END OF TAILINGS PIPELINE

A new concept has recently been instigated at some Queensland coal mines and some Eastern States mineral sands operations. It may be in use elsewhere as well. High clay content tailings having very high rheology may be able to be thickened to a paste consistency but pumping pressures are then very high and there may be settling problems under laminar flow conditions. The alternative is to pump at lower concentration under turbulent flow but then under normal circumstances the solids may settle extremely slowly in the dam.

This is overcome by adding flocculent at the discharge of the tailings pipeline. Large dose rates are employed, sometimes up to 1 kg/tonne, and the large flocs cause water to separate. This concept is currently used at the Ashton and Bulga coal mines in the Hunter Valley and at Wilkie Creek and New Acland coal mines, and the Stradbroke Island mineral sands operation in Queensland.

8. ON-LINE VISCOMETER (OLV)

Most mineral processing stages, including grinding and pumping, are currently controlled on slurry density whereas in fact it is the slurry rheology, and in particular the yield stress, which really determines the process efficiency. An On-Line Viscometer is a preferred method of control, especially during the initial years of operation when rheology may vary significantly. In later years, experience in blending and processing resulting in more uniform slurry properties may mean that density control is sufficient.

Slurry Systems markets an On-line Viscometer (OLV) based on the tube viscometer principle. The instrument is of rugged design and able to handle particles up to 2 mm in size. A number of instruments have been installed at mines in Australia and Africa. The OLV provides a continuous reading of Bingham yield stress and is ideal for pipeline control where the rheology of the slurry varies. The instrument is illustrated in Figure 9.

Figure 9

9. WHEELSTAND TEST RIG

The Wheelstand was believed first invented by Russian workers in the 1960's. SSE's Wheelstand test rig consists of 200 NB steel pipe bent into a circular shape to form a wheel supported by spokes. The wheel rotates in the vertical plane about a horizontal axis, driven by a variable speed motor. The diameter of the wheel at the pipe centreline is 2.685 m. The pipe ID is 206.3 mm. The rig is shown in Figure 10 in operation at the Maitland, NSW, ALS laboratories. The Wheelstand allows measurement of pipe wear, particle attrition and rheology changes over time. It has the advantage over a test loop in that it does not involve repeated passage through a pump and so is ideal for monitoring attrition and rheology changes. SSE has tested numerous slurries including various coals, both coarse and fine, SVS coal slurries, coal rejects, magnetite, and various tailings. SSE has tested a SVS coal slurry for an equivalent pipeline length of 500 kms. A particularly interesting test was on a nickel ore slurry for a potential 150 km pipeline in which the slurry rheology changed over time.

Figure 10

10. WELDED COUPLING FOR POLYURETHANE LINED STEEL PIPE

Pumping of heavy mineral sands, including iron sands, requires high velocities with consequent high pipe wear rates. Wear resistant lining is required for a long life pipeline. As an example Slurry Systems designed the 18 km New Zealand Steel iron sand pipeline in New Zealand transporting sand of median size 120 microns (Venton and Cowper, 1986). This pipeline operates at 3.6 m/s and requires two positive displacement pump stations supplying a total pressure of 18 MPa. Ordinary steel pipe was not suitable because of the high wear rate and the pipeline is lined with polyurethane. Special welded couplings were developed in conjunction with McConnell Dowell and the pipeline is buried and fully welded. It has operated successfully for 25 years. The coupling enables the polyurethane lined steel pipe to be welded which is more suitable for a long life buried pipeline than flanges. A photo of the coupling is shown in Figure 11.

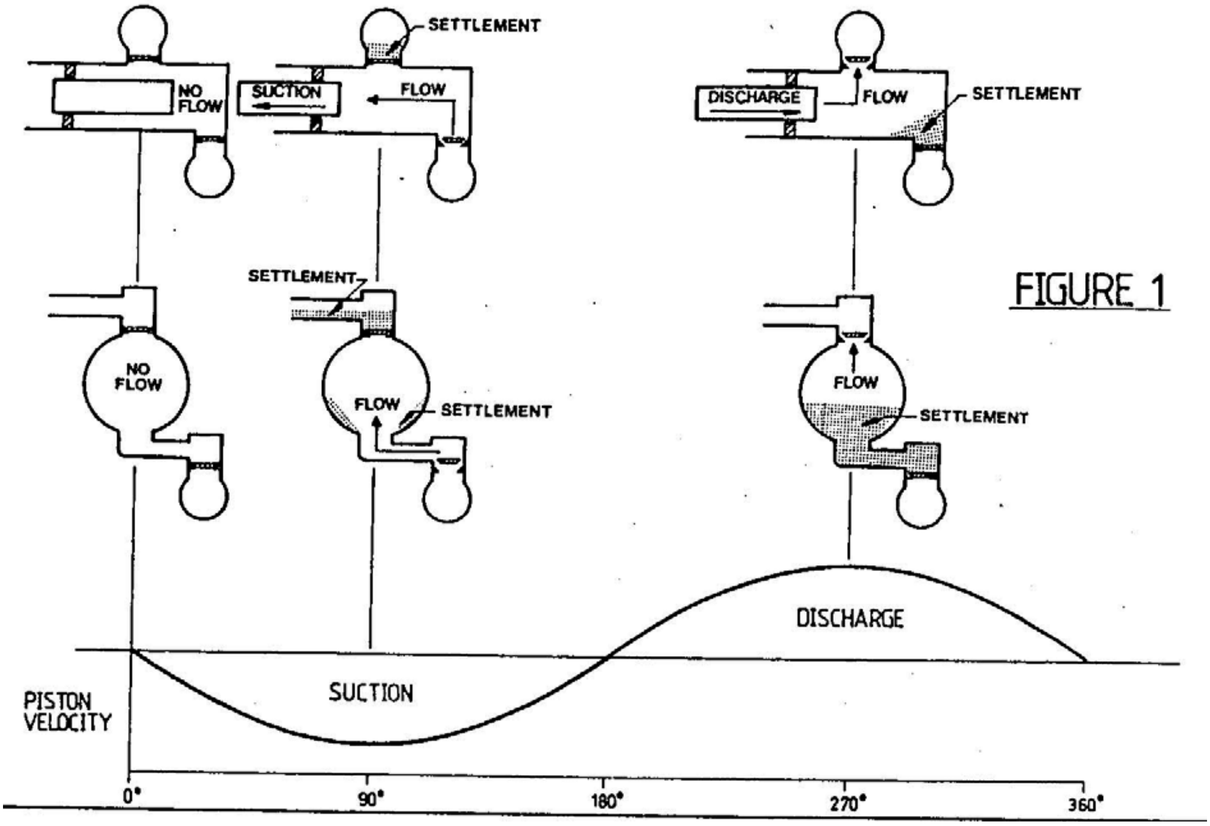
Figure 11
Welded Coupling

11. USE OF POSITIVE DISPLACEMENT PUMPS TO PUMP IRON SAND

Another innovation in the N.Z. Steel pipeline was the use of positive displacement pumps to pump a coarse, rapidly settling iron sand. The perceived technical concerns relating to settling within the pump are illustrated in Figure 12.

Pumping tests were undertaken at Geho’s test facilities in Holland to confirm the concerns were not an issue. A key aspect was that the iron sands readily fluidised.

Figure 12



12. FUTURE DEVELOPMENTS

Slurry Systems is currently developing new control technology to maximise the solids throughput in a slurry pipeline. For typical slurries delivered from a thickener, the deposit velocity in pipeline flow for the concentrations of interest is controlled by the laminar-turbulent transition velocity. This was discussed in relation to a magnetite slurry in Figure 6. It was noted that the maximum pumpable concentration was 65% which provided a 0.3 m/s margin between the operating velocity and the transition velocity. It is desirable to always operate at the maximum concentration consistent with maintaining this 0.3 m/s margin, regardless of any variations in rheology of the slurry.

The new technology will allow the pumps to be controlled at this optimum point, regardless of variations in slurry rheology, thereby maximising solids throughput and minimising power and water usage.

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