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HIGH CONCENTRATION LAMINAR FLOWS – HISTORICAL DEVELOPMENT AND MAJOR ISSUES

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1. INTRODUCTION

There is increasing interest in pumping tailings at high concentration in laminar flow. The advantages of high concentration disposal include recovery of water directly at the plant plus environmental advantages. However laminar flow pumping involves much higher pressure gradients than normal turbulent flow, partly because of settling issues which are not always clearly understood.

Historically, interest in laminar slurry flow dates back to the mid 1960's, initially in relation to coal transport. The historical development is briefly outlined before considering the major issues involved with high concentration tailings pumping.

2. STATIC STABILITY

Slurries possessing a yield stress are able to prevent certain size particles from settling under static conditions indefinitely. Traynis (1977), Thomas (1977) and Duckworth et al (1983) independently derived the following static stability criterion:

$$\tau_{y,vehicle} = k\, g\, d\, (\rho_{solids} - \rho_{vehicle}) \tag{1}$$

where k is a constant approximately equal to 0.1.

and $\tau_{y,vehicle}$ = yield stress of the vehicle portion of the slurry (Pa)
g = gravitational constant, 9.81 m/s^2
d = particle size (m)
ρ_{solids} = density of solids (kg/m^3)
$\rho_{vehicle}$ = density of vehicle portion of the slurry (kg/m^3)

If the yield stress exceeds that given by Eqn 1 particles will remain suspended indefinitely in a container. But, if the slurry is sheared such as by stirring, it is likely the coarser particles will settle to the bottom of the container. This is the crux of the problem with laminar flow transport in pipelines. Shearing in the pipeline can cause particles to settle.

3. LAMINAR FLOW CROSS COUNTRY PIPELINES - HISTORICAL DEVELOPMENT

3.1 Laminar Flow Transport of Coarse Coal

Researchers Bain and Elliott (1964) at the U.K. Electricity Generating Board, were probably the first to investigate laminar slurry flow on a meaningful scale. They conducted experiments on minus 3 mm (d99=3 mm) coal pumped at high concentration. Elliott and Glidden (1970) report on continued work at the same laboratories in which coals ranging from minus 2 mm to minus 8 mm were pumped in so called "dense phase" laminar flow in pipe loops ranging from 40 mm to 250 mm diameter. The premise of this early work on coal slurries was that the pressure gradient would decrease as the pipe diameter increased as for homogeneous laminar flow, making it very attractive for large diameter pipes.

Traynis (1977) was also investigating high concentration coal pumping in the early 1970's and stated that laminar flow without deposition was possible if the yield stress exceeded the value given by Eqn 1, i.e., he assumed the criteria for static stability was also sufficient to ensure laminar flow in a pipe without deposition. Canadian researchers Charles and Charles (1971) made a similar inference.

At this time general interest in slurry pipelines resulted in the British Hydromechanics Research Association (BHRA) holding the first Hydrotransport conference in 1970. Also the Black Mesa fine coal pipeline began operation in November 1970 and spurred interest in long distance coal pipelines. In the US the interest was mainly in fine coal pipelines and the Slurry Transport Association (STA) was formed and held eleven very well attended conferences between 1976 and 1986.

Meanwhile back to high concentration laminar flows. British researcher Kenchington (1976, 1978) tested sands in clay slurries and considered the pressure gradient in terms of a sliding bed analysis. Based on a sliding bed analysis the pressure gradient would not decrease with pipe diameter but would be relatively independent of pipe diameter. However Kenchington did not conduct tests in a large enough diameter pipe for this effect to become evident.

It was around this time (1978) that Norman Cowper, now Managing Director of Slurry Systems Pty Limited, but at that time working for Williams Brothers in USA, started thinking about coal pipeline transport in the Australian context. He realised that in Australia a coal pipeline needed to be able to transport lump export size coal and instigated testing of lump coal in a fine coal slurry of sufficient yield stress that the lump coal did not settle under static conditions. The concept of pumping such "stabilised" slurries was given the name "Stab-flo". From laminar flow tests in a vertical U tube viscometer his team concluded that the laminar flow pressure gradient would decrease as the pipe size increased, making the technology increasingly attractive in larger pipe sizes (Pertuit et al, 1978). This paper created a huge amount of interest and enthusiasm at the 3rd STA Conference although one questioner (Bill Halvorsen, who had been associated with the coarse coal pipeline at the Loveridge mine) cautioned about the viability of laminar flow because he related experience where such stabilised slurries remained stable in a tank under static conditions but separated out once agitated.

In Australia, Thomas (1978) also started investigating laminar flow of sand and coal in clay slurries in pipe diameters up to 105 mm. He found that a considerably higher yield stress was required to prevent deposition under laminar flow than under static conditions. He also argued that, once flow commences, the floc structure is broken and the yield stress, which supports particles under static conditions, is destroyed, and coarse particles settle vertically the same as they would in a viscous Newtonian fluid. (Thomas, 1979b, later confirmed this in settling tests in the gap of a special large bob and cup viscometer). Thomas (1978) concluded that for laminar flow in a pipe to be maintained, the concentration of the slurry must be increased as the pipe size is increased. This is another way of saying that, for a particular slurry, the pressure gradient will not decrease with increase in pipe size in the same way as it does for homogeneous slurries.

Thomas continued his investigations by conducting tests on various size sands in sugar-water solutions with Newtonian viscosities ranging from 5.3 mPas to 270 mPas and on minus 8 mm coal in a clay slurry. The slurries were tested in an extended 105 mm test loop which included a number of clear viewing sections spaced along the pipe length which enabled the slow settling of the coarser particles to be observed as they travelled along the pipe length. (The author is indebted to Neil Mitchell of M.D. Research for suggesting the possibility of slow settling along the pipeline under laminar flow conditions). The results were presented at the 4th STA Conference (Thomas, 1979a).

Thomas (1979a) argued that once all particles have settled the pressure gradient will be given by Wilson's (1974) sliding bed equation, Eqn 2.

$$J = 2\,\mu\,C_b\,g\,(\rho_{solids} - \rho_{vehicle})\,\varphi \qquad (2\ )$$

where: J = pressure gradient (Pa/m)
μ = co-efficient of sliding friction
C_b = maximum packing concentration by volume
φ = geometric function depending on the height of the sliding bed (i.e. the concentration of solids in the bed)

μ is typically assumed 0.4 and C_b 0.6. φ is between 0 and 1 and is approximated by the polynomial approximation given by Eqn 3 in terms of Cv, the percentage in-situ volume concentration of solids travelling in the bed.

$$\varphi = 6.947E\text{-}6\ Cv^3 - 5.672E\text{-}4\ Cv^2 + 2.544E\text{-}2\ Cv + 1.724E\text{-}2 \qquad (3)$$

Around 1979 Professor Alan Duckworth came from the U.K. to Australia and started up a research group at the C.S.I.R.O. in Melbourne to investigate coarse coal pipelining. This group included Lionel Pullum who has had a continuing interest in laminar flows ever since. In 1983 (Duckworth et al, 1983) the group published results of tests of minus 20 mm coal in a fine coal carrier slurry in a 300 m long 150 mm diameter test loop. Based on their pipe loop tests Duckworth et al found that the static stability criteria, Eqn 1 was also sufficient to ensure laminar flow for the slurries studied in the 150 mm pipe.

Further results in 150, 200 and 250 mm diameter CSIRO pipe loops were reported by Lockyer et al (1984). For the minus 16 mm coal mixtures it was found that the pressure gradient was predicted using a Bingham plastic model with the mixture parameters derived from the carrier rheology combined with an increase dependant on the volume concentration of coarse coal. At low carrier concentrations a stationary bed formed and they found that Eqn 1 predicted the demarcation between flow with and without a stationary bed. They concluded that provided the yield stress of the carrier fluid exceeded 3.5 Pa, no stationary bed was formed with minus 16 mm coal of density 1403 kg/m^3.

So by the early 1980's we have Traynis (1977) and Duckworth et al (1983) claiming that the static stability criterion (Eqn 1) also determined whether laminar flow of coal slurries is possible. In contrast, Thomas (1978, 1979a) had found that this stability criterion, whilst applicable to static stability, did not determine whether laminar flow was possible.

There are two probable reasons why Thomas found that settling under laminar flow conditions was much more of an issue than did Duckworth et al. Firstly, Thomas did not confine his investigations to coal but also investigated higher SG materials such as sand and ilmenite (SG 4.7). The higher solids SG means that the sliding bed pressure gradient is much higher than the homogeneous pressure gradient making the differences between the two more evident. Secondly, most of the sands were of narrow size distribution and in all cases the carrier fluid was a very fine particle clay slurry so the size distribution of the combined mixture was "gapped" and not a continuous size distribution. The large gap in the size distribution allowed settling of the coarser particles to be more clearly observed.

In 1985 the C.S.I.R.O. group constructed a 2 km long, 300 mm diameter prototype facility at a coal mine near Newcastle, Australia. This facility operated for approximately one year. No published papers resulted from this work but it is understood that the test results confirmed that the flow regime was a sliding bed.

Meanwhile in the U.K., in 1984 a joint venture between BP and Bechtel constructed a 300 mm diameter test facility with pipeline lengths up to 7 kms. Some test results were reported in Hydrotransport Conferences 9 and 10. (Brookes and Dodwell, 1984) and (Brookes and Snoek, 1986). A final paper (Brookes and Snoek 1988) concluded that because of the drop in coal prices at that time further testing was unwarranted. They did recommend however that further test work would be required regarding scale up of both pipe diameter and pipeline length suggesting that not all questions had been answered.

Hence by the late 1980's the two large scale laminar flow coarse coal research projects (CSIRO and BP/Bechtel) had both finished with some uncertainty about the viability of the stabilized slurry concept, especially over long distances.

3.2 Laminar Flow Transport of Fine Coal and Other Materials

Attention now shifted from coarse coal laminar flow to laminar flow of fine pulverised fuel (pf) coal slurries, termed "dense coal" or Coal Water Mixture (CWM) slurries, which could be pumped and stored as a fuel and pumped direct into boilers,, e.g. Ferrini et al (1984). There were also a number of other papers on this topic in Hydrotransport 10 (1986) and Hydrotransport 11 (1988).

The most significant of these projects was the 258 km, 500 mm diameter Snamprogetti Belovo-Novosibirsk CWM pipeline in the USSR described by Ercolani, D. (1986). The pipeline began operation in 1989 but encountered continuous problems and was eventually shutdown in 1993. Cowper et al (2010) describe the pipeline and its operational problems. The pipeline operated in laminar flow and even though the coal was minus 0.5 mm, slow settling occurred, resulting in a stationary bed which built up over time. Just before the pipeline was shut down the bed height must have reached about 80% of the pipe diameter because the achievable flow rate had decreased to $1/10^{th}$ of the design flow rate.

The minus 0.5 mm coal was pumped at 60% to 63% concentration under laminar flow conditions. The yield stress of the slurry was 11 Pa to 13 Pa and the effective viscosity between 900 and 1400 mPas. Applying Eqn 1 to this slurry would indicate a yield stress of 0.08 Pa required for static stability. The actual yield stress was 150 times this value and yet deposition still occurred along the pipeline confirming that Eqn 1 is not a sufficient criterion to ensure laminar flow without deposition.

A similar comment as to the unsuitability of Eqn 1 was noted more recently by Aude et al (1996). They discussed the Rugby cement pipeline in the U.K., the Trinidad limestone pipeline and the Belovo-Novosibirsk pipelines, all operating in laminar flow. They noted that whereas for the Rugby pipeline Eqn 1 would give a yield stress of only 0.4 Pa and the actual yield stress of the Rugby pipeline slurry was 2.9 Pa, deposition still occurred under laminar flow. The Trinidad pipeline slurry had a very high yield stress of 50 Pa and yet deposition still occurred over time in the 10 km pipeline and the pipeline has to be pigged every day as the pump pressure slowly increases, even though the particle size is minus 0.3 mm.

3.3 Summary - Cross Country Laminar Flow Pipelines

So by around 1990 it had become fairly clear that laminar flow of slurries was not the holy grail of slurry pipeline transport that had been hoped for in the 1970's and early 1980's. Under laminar flow conditions particles slowly settle in the pipe as flow progresses along the pipeline, eventually forming a stationary bed which results in a steady increase in pressure gradient. With coarse particles, the settling and deposition can occur in very short lengths. Given a long enough pipeline length, deposition even occurs with very fine particles as evident in the Trinidad limestone pipeline and the Belovo-Novosibirsk coal pipeline. Hence pipeline length is an important parameter. The only way deposition is completely prevented is if the pressure gradient is sufficiently high to slide the settled bed along the bottom of the pipe.

4. LAMINAR FLOW TAILINGS PIPELINES – HISTORICAL DEVELOPMENT

4.1 Laminar Flow of Tailings

Tailings have traditionally been transported to the tailings disposal area at low concentration under turbulent flow conditions. The one exception is the extremely high concentration paste backfill pipelines in underground mines, e.g. Verkerk (1984). These represent a special case where the yield stress values are in the hundreds of Pascals and flow is laminar with no possibility of deposition over the relatively short distances involved. The extremely high pressure gradients involved are supplied by the hundreds of metres of vertical head available.

The situation with above ground tailings disposal began to change in 1978 when Eli Robinsky presented a seminal paper (Robinsky, 1978) describing thickened discharge of tailings. The thickened discharge method involves thickening the tailings sufficiently so that when discharged at the disposal area only limited size segregation takes place and the deposit forms a slope of typically up to 5% which has inherent strength thereby negating the requirement for a large containment dam. As the concentration of the tailings increases the term “high density” tailings is used. At still higher concentrations the tailings are referred to as “paste”. However the tailings still have to be transported by pipeline to the disposal area. For deposits of low slopes the tailings may be pipelined in turbulent flow, but at higher slopes pipeline transport will involve laminar flow and so the question of settling under laminar flow arises.

A considerable number of papers have been presented over about the last 15 years describing the economic and environmental advantages of high density tailings disposal, mostly at the fifteen Paste Conferences which have been held since 1998. However there have been few papers which have considered the possibility of settling during laminar flow pipelining of the tailings to the disposal area. Cooke (2002) noted that particles as fine as 100 microns will still settle under laminar flow. He summarised previous work and concluded that a pressure gradient of 1 kPa/m to 2 kPa/m is required to ensure that a settled bed is transported.

Pullum (2004) described work on a two-layer laminar flow model whilst Pullum et al (2006) described results of laminar flow experiments in sloping pipes. Pullum (2007) provided data for minus 3 mm, minus 2 mm and minus 200 micron slurries, all of which settled within 100 to 200 pipe diameters. Pullum et al (2010) concluded that settling is greater than expected and for slurries where the yield stress is only slightly greater than given by Eqn 1, total flow stratification occurs almost immediately once the slurry enters the pipeline.

Paterson (2011) reviewed the work to date and concluded that for successful laminar flow operation a minimum pressure gradient is required, presumably 1 kPa/m to 2 kPa/m as noted by Cooke (2002). The most recent work concerned with laminar flow settling was by Chacon and Barrera (2012) who conducted tests in a 42 m long 160 mm ID horizontal pipe section. Continuous recirculation of iron tailings (yield stress 107 Pa, plastic viscosity 75.4 mPas, d_{50} =38 microns - suggesting d_{99} around 350 microns), resulted in a sudden increase in pressure gradient after 90 minutes recirculation equivalent to about 13 kms pumping distance.

4.2. Summary – Laminar Flow of Tailings

It is now accepted that settling of particles will occur during laminar flow of tailings. Once all particles have settled, a pressure gradient in the range 1 kPa/m to 2 kPa/m is required to maintain flow. The only researchers which appear to have experimentally investigated the length effect appear to be Thomas (1979), Pullum and co-workers between 2004 and the present, and Chacon and Barrera (2012). The work of Pullum and co-workers is the most rigorous but at this point in time there is still no method of predicting the pipeline length required for settling to occur for a wide size distribution tailings slurry. Hence it is very difficult to design a laminar flow pipeline other than to use the approach outlined by Paterson (2011) where either the slurry concentration is selected to give a pressure gradient above about 1 kPa/m to 2 kPa/m or, if the pressure gradient is less, provision is allowed for regular flushing with water. As noted in Section 4, what is required is data from operating pipelines to “calibrate” settling length prediction equations. Given more confidence in the settling length prediction, pipelines could be designed which, although the pressure gradient might be less than the 1 kPa/m to 2 kPa/m sliding bed criteria, the required turbulent flushing sequence could be specified at the design stage.

It is important to realise that even if laminar flow operation is viable, the pressure gradient will almost always be higher than turbulent flow operation. There is almost never justification for high concentration laminar flow purely from a pipeline economics viewpoint. There has to be another reason for wanting laminar flow, which for tailings is of course slope disposal with its associated benefits.

5. CONCLUSIONS

Interest in laminar pipe flow began in the mid 1960’s in relation to transport of coal. However by the mid 1980’s it was generally accepted that the only way laminar flow without deposition could be achieved was if the solids concentration was increased sufficiently to achieve pressure gradients comparable with sliding bed flow, which for typical tailings means pressure gradients in the the range 1 kPa/m to 2 kPa/m.

For lower concentrations and pressure gradients, laminar flow may be possible provided regular flushing occurs. Designing for this mode of laminar flow operation requires the ability to predict settling lengths but at this stage there is no method available to confidently predict settling lengths. What is required is operating data from existing laminar flow pipelines such as red mud pipelines to refine predictions.

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