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THE EFFECT OF ENTRAINED MICRO-BUBBLES OF AIR ON SLURRY PIPELINE FLOW BEHAVIOUR AND DESIGN

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Froth flotation is a common beneficiation method used in the mining industry. It involves bubbling air through an agitated slurry, to which a flotation agent has been added. The air preferentially attaches to the wanted mineral particles which float to the surface and are removed as a concentrate slurry. Inevitably some of the wanted minerals (with air bubbles) report to the tailings stream. The air can therefore affect both concentrate and tailings slurry pumping behaviour and design. The effect on concentrate pipeline design is investigated in relation to a long distance zinc concentrate pipeline. Air which is present at atmospheric pressure is compressed in the pumps, and at high pressures, all of the air may be fully dissolved in the water. This means that slurry properties under pressure in the pipeline, including rheology, may differ significantly from that measured in the laboratory at atmospheric pressure. The volume flow rate of slurry also reduces as the air is compressed and/or dissolved. These effects complicate slurry behaviour, design, and instrumentation. The effect on tailings pipeline design is illustrated by examining the properties of a range of coal tailings. In the design of a coal tailings pipeline the effect of the air is often modelled as a lower effective solids density.

KEY WORDS: slurry pipeline, froth flotation, coal, micro-bubbles, minerals

1. INTRODUCTION

This paper is concerned with slurry flows which contain micro-bubbles of air which are attached to fine particles in the slurry. Froth flotation is a common beneficiation method used in the mining industry. It involves bubbling air through an agitated ore slurry, to which a flotation agent has been added. The flotation agent causes micro-bubbles of air to attach preferentially to the wanted mineral particles, which float to the surface and are removed as a concentrate slurry. The presence of micro-bubbles of air in a slurry can affect slurry properties and pumping and pipeline flow behaviour. In-plant pumping of the air-rich concentrate slurry often requires special “froth pumps” which are special centrifugal pumps with extra large suction pipe diameters.

If the air-rich concentrate is thickened and filtered for dry product shipping, the air in the concentrate slurry is ultimately not an issue. However if the concentrate slurry is to be transported by slurry pipeline then the air affects slurry pipeline behaviour and design. Air which is present at atmospheric pressure is compressed in the pumps, and at high pressures, all of the air may be fully dissolved in the water. This means that slurry properties under

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pressure in the pipeline, including rheology, may differ significantly from those measured in the laboratory at atmospheric pressure. The volume flow rate of slurry also reduces as the air is compressed and/or dissolved. These effects can complicate slurry behavior, design, and instrumentation.

The coal industry also often uses froth flotation to recover very fine coal, especially coking coal. The flotation product, with air attached to the fine coal particles, is then thickened and added to the "dry" coarse coal product. Since coal is generally transported as a dry product, the air attached to the fine coal particles in the product coal is normally not a problem. However, generally the flotation process does not recover all of the coal, in which case the coal tailings slurry can contain quantities of fine coal particles with micro-bubbles of air attached. In the design of coal tailings pipelines the effect of the air is often modelled as a lower effective solids density.

2. MICRO-BUBBLES OF AIR IN ZINC CONCENTRATE PIPELINE

2.1 THE CENTURY ZINC/LEAD CONCENTRATE PIPELINE

The 304 km Century zinc/lead concentrate pipeline in Queensland, Australia, commenced operation in 1999 and ceased operation in 2015. The project has recently been re-started under different ownership as the New Century project, with the pipeline recommencing operation in 2018. The following refers only to the original Century pipeline design and operation. Descriptions were provided by Hoskins et al (2002), Thomas et al (2002), and Thomas (2012).

The Century zinc concentrate is extremely fine, having $d_{95} = 14$ µm, and $d_{80} = 7.5$ µm, with solids density 4.1 t/m^3. The mineral recovery process involves froth flotation. Because of the extremely fine particle size, the final product concentrate slurry contains significant quantities of air, sometimes up to 24% by volume. This air is generally impossible to remove before entering the pipeline, being described as "tenacious". By measuring the slurry volume and mass in a measuring cylinder, followed by concentration determination by oven drying, and knowing the true solids density, as determined by a gas pycnometer, the percent volume of air can be determined. For pipeline design, rheology tests were conducted on the slurry at various oven-dried concentrations.

The 300 mm nominal ID Century pipeline involves three piston diaphragm pumps in parallel with design pressure 20 MPa and design flow rate 322 m^3/h. The pumps are fed by a centrifugal slurry charge pump. The micro-bubbles of air in the slurry are compressed after passing through the charge pump, and also some air is dissolved in the water thereby reducing the effective volume of air in the slurry. After passing through the piston diaphragm pumps, the air is completely compressed and dissolved in the water phase of the slurry. This means that the slurry volume is reduced and slurry density increased, from what was in the slurry feed tanks. As the slurry proceeds along the pipeline, the pressure decreases and eventually, about 15 km from the terminal, dissolved air starts to come out of solution forming large air bubbles. These large air bubbles can cause issues with the terminal magnetic flow meter reading.

The volume of air after compression can be approximated using Boyle's law where air volume is inversely proportional to pressure at a fixed temperature. The solubility of air in water decreases with increasing temperature and increases with increasing pressure. Based on the main constituents of air, nitrogen and oxygen, the solubility of air in water at 25° C can be approximated as 0.022712×P g/L, with P in atmospheres. Figure 1 illustrates the reduction of free air volume in water as a percentage of total volume against increasing pressure for starting air volumes from 5% to 20%. For a slurry the volume of water would be reduced by the presence of solids, so it would take a somewhat higher pressure to dissolve the air fully in the slurry.

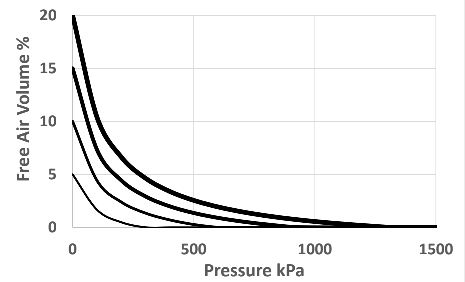

Figure 1. Typical free air volume against gauge pressure

2.2 MICRO-BUBBLES OF AIR AFFECT MEASURED RHEOLOGY

At atmospheric pressure the micro-bubbles of air in the slurry can be expected to increase the slurry viscosity. This was confirmed by the fact that during commissioning of the pipeline, the concentrate slurry contained less than 1% air. Plant throughputs were low allowing more effective feed slurry de-aeration in the feed tanks. In the subsequent years as the plant throughput increased, the air content in the concentrate increased up to a maximum of around 24%. It was found that for the same solids concentration, the slurry viscosity measured at atmospheric pressure approximately doubled as the air content increased over the years from commissioning onwards.

The micro-bubbles of air can be expected to increase the slurry viscosity in a similar manner to spherical particles added to a slurry. In terms of the Bingham plastic model, Thomas (1999) found that coarse particles added to a fine particle Bingham plastic slurry increased both the yield stress and the plastic viscosity in a similar manner. The well-known equation of D.G. Thomas (1965) was found to predict the ratio increase in yield stress and plastic viscosity. In the present context the micro-bubbles of air represent the "coarse" particles. More recently Thomas (2010) proposed the following simpler equation which closely approximates the D.G. Thomas (1965) equation:

$$\text{Ratio increase} = \exp(2.7Vr) \qquad (1)$$

where Vr is volume Ratio of air = Cv/(1-Cv) and Cv is fractional volume concentration of air

For 20% air (Cv=0.20, Vr=0.25) the ratio increase is 1.96 which is consistent with the observed approximate doubling in measured viscosity at atmospheric pressure from commissioning onwards. The fact that all the air in the pressurised Century slurry pipeline is fully dissolved in the water, except in the final 15 km of the pipeline, means that the effective percent air is zero as far as slurry properties within the pipeline are concerned. Hence the slurry viscosity in the pipeline is lower than that measured at atmospheric pressure in the laboratory with micro-bubbles of air present. The higher viscosity measured in the laboratory viscometer needs to be adjusted lower to represent the rheology in the pipeline. Using Equation 1, for a slurry containing 20% air, the yield stress and plastic viscosity for high pressure operation, where air bubbles are fully compressed or absorbed, should be adjusted 1/1.96 = 0.51 times the values measured at atmospheric conditions. i.e. the measured values of yield stress and plastic viscosity need to be almost halved.

Figure 2 shows typical zinc concentrate rheology test data at Cw=37.5% with 20% air by volume (at atmospheric pressure). The fitted straight line gives a measured Bingham yield stress 4.8 Pa and plastic viscosity 7.3 mPas. In the pressurised pipeline there is zero free air because the air has been compressed and dissolved in the water phase of the slurry. Hence the yield stress and plastic viscosity are reduced by the 1/1.96 factor to give yield stress 2.45 Pa and plastic viscosity 3.72 mPas. The lower line shows the predicted rheogram. If the slurry was tested at the high pressure existing in the pipeline, the resulting rheogram would be similar to the predicted line in Figure 2.

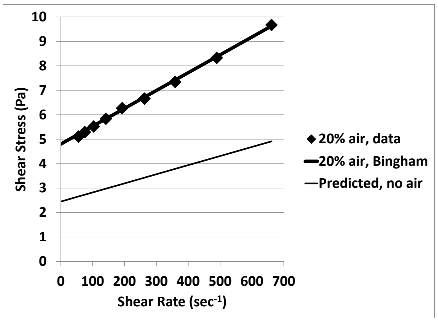

Figure 2. Measured zinc concentrate rheogram with 20% air, and predicted with zero air

The reduced yield stress and plastic viscosity result in a predicted lower pressure gradient closer to the actual pressure gradient in the pipeline and a lower laminar-turbulent transition velocity (Vt). Wilson and Thomas (2006) derived the following equation for the transition velocity of a Bingham plastic slurry. Vt in m/s, yield stress in Pa, and slurry density in kg/m^3.

$$Vt = 25\ (\text{yield stress} / \text{slurry density})^{0.5} \qquad (2)$$

Using the yield stress measured at atmospheric pressure with 20% air present (4.8 Pa) Equation 2 gives Vt = 1.46 m/s which exceeds the maximum 1.27 m/s design velocity in the largest internal diameter section of the pipeline. But at the predicted lower yield stress in the pressurised pipeline (2.45 Pa), Equation 2 gives Vt = 1.04 m/s, meaning that turbulent flow exists at the typical 1.2 m/s operating velocity as is required.

3. THE EFFECT OF AIR IN COAL TAILINGS

The previous section described the effect of micro-bubbles adhered to flotation concentrate mineral particles on concentrate transport pipeline system design. This section will describe the effect of adhered micro-bubbles on tailings/reject materials rejected from flotation processes. While concentrates by nature have tightly controlled material properties, very often of a single mineral species, tailings are the opposite in that they can contain: -

- A wide range of minerals, rock and clay types whose concentrations vary with time, dependent on mining section and feed blend.
- Potentially, a wider range of particle size distributions, often with discontinuities because the product/concentrate has been removed from the mixture.
- Some product/concentrate content, depending on the separation process efficiency, and the response of the particular feed and the reagent dose used. This means that the concentration of solid particles with adhered microbubbles will be lower when compared to product/concentrate streams.

An additional complication for tailings streams containing coal particles is that some coals contain micro fissures that are most often filled with water. This reduces the apparent solids density of the particle. Once the coal particle has been oven dried in a laboratory, thus removing some or all of the moisture in the fissures, measurements via gas pycnometry reveal a higher, true solids density (often called the skeletal density).

The potentially wide-ranging properties, that can vary with time, in the short and long term, very often complicate the process parameters for pumping tailings. Against this, it is likely that tailings will need to be transported only a short distance relative to the case for the zinc concentrate described previously. As such, the effect of wide and varying parameters upon the design of the tailings pumping system is less critical to system performance, capital and operating costs.

Unlike mineral beneficiation processes, raw coal is typically crushed to pass between sieve sizes 150 mm and 50 mm and then separated into three size fractions, each fraction beneficiated in a separate process, each generating a separate rejects stream, each handled separately, or in various combinations. The reject reporting to the tailings system may be the combined fine (1.00 mm by 0.25 mm) and ultrafine (0.25 by 0 mm) fractions, or the ultrafine fraction only. If a froth flotation process is used, it is generally only applied to the ultrafine fraction.

The proportions of total solids in the fine and ultra-fine fractions will vary, though it is common that they will be roughly equal, which has been assumed in this paper. The misplaced coal content in each of these fractions will also vary, between say 15% and 50%. Therefore, as a proportion of the total solids, coal particles with adhering micro-bubbles in the tailings stream will: -

- Not exist where froth flotation has not been applied,
- Vary from say 8% to 25% where froth flotation has been applied and the tailings stream contains 1.00 mm by 0 mm solids, (i.e. -1 mm solids).
- Vary from 15% to 50% where froth flotation has been applied and the tailings stream contains only 0.25 mm by 0 mm solids.

These smaller proportions of solids with adhering micro-bubbles will have a proportionally smaller effect on pumping parameters when compared to the case for a flotation concentrate/product described in Section 2.

The examples of tailings slurries described in the following arise from two different coal beneficiation processes, one that utilises flotation to recover the ultra-fine coal fraction (normally only coking coal), and one that does not. In each case the coal seams are hosted by shale, mudstone and clay formations and contain relatively low concentrations of rock and quartz, all of which report to the tailings stream.

In-house data for a number of samples of coal tailings and a product coal, are shown below in Table 1. The nature and source of the samples are as follows: -

- Samples 1 to 3 are tailings samples containing combined fine and ultrafine reject streams where froth flotation has been applied to the ultrafine fraction. Sample 4 is a flotation product/concentrate sample which is included for reference. Samples 5 and 6 are tailings samples containing combined fine and ultrafine reject streams where froth flotation has not been applied.
- Samples 1 to 4 are from an operation in Central Queensland Australia. Samples 5 and 6 are from an operation in Central New South Wales Australia.
- Samples 1 to 4 were from a tailings filtration test programme, 5 and 6 from a tailings pumping investigation.
- Site measured solids particle densities were derived from thickener underflow samples via back calculation from the mass and solids concentration of a known volume of sample.
- Lab measured solids particle densities were determined via gas pycnometry, samples 1 to 4 using helium, samples 5 and 6 using nitrogen.
- Mineral properties were measured via XRD for samples 1 to 3, carbon content was not, however, it has been assumed that the Amorphous (non-crystalline) content represents carbon. For samples 5 and 6, XRD analysis was not carried out, but ash (mineral) content was determined. This allowed an estimate of the coal content of each sample to be made except for sample 4 where neither XRD nor ash content was determined.
- An estimate of the volume of adhering air in the form of microbubbles was derived from the difference between slurry densities for the average site-measured and lab measured particle densities.

Inspection of Table 1 shows the following: -

- Site measured apparent particle densities are less than the “true” solid densities as derived by gas pycnometry. The difference between these values is not predictable.
- The variation between the apparent particle and “true” solid density between samples is quite large and does not correlate with coal content.
- The calculated slurry air volume is generally small when compared to the zinc concentrate described in Section 2.

Table 1

Properties of Tailings Solids for Fine & Ultrafine Coal Tailings

Sample No.		1	2	3	4	5	6
Material		Coal Tailings	Coal Tailings	Coal Tailings	Coal Product	Coal Tailings	Coal Tailings
Source		Spirals & flot tails Th U/F	Spirals & flot tails Th U/F	Spirals & flot tails Th U/F	Flot product Th U/F	Spirals tails Th U/F	Spirals tails Th U/F
Soilds Particle Density	ρs						
- Site Measured (Average)	t/m^3	1.91	1.88	1.66	1.24	1.75	2.19
- Lab Measured (Pycnometer)	t/m^3	2.19	1.91	1.79	1.35	1.85	2.34
- Difference from Average (Lab - Site Average)	t/m^3	0.28	0.03	0.13	0.11	0.10	0.15
- Difference ÷ Site Average	%	14.7%	1.4%	8.0%	8.6%	5.7%	6.8%
- Lab Measured ÷ Site Average	%	114.7%	101.4%	108.0%	108.6%	105.7%	106.8%
Total Clay Content	%	51.0%	37.0%	33.0%			
Amorphous (Coal)	%	31.0%	47.0%	56.0%			
Total Mineral Content	%	69.0%	53.0%	44.0%		47.0%	65.0%
Total Coal Content	%	31.0%	47.0%	56.0%		53.0%	35.0%
Air Content (Vol)	%	2.6%	1.1%	1.9%	2.5%	1.9%	1.8%

In summary, coal tailings are very often a complicated mix of solid species, the composition and size distribution of which can vary significantly over time. If coal is a component of the stream, its apparent particle density is likely to be lower than the “true” solids density for reasons of particle morphology and adhering micro-bubbles in the case where froth flotation is part of the beneficiation process employed. The volume attributed to micro-bubbles adhered to coal particles is small and unlikely to affect slurry viscosity significantly, particularly given that tailings pumping systems generally comprise short pumping distances and relatively low pumping pressures when compared to long distance concentrate transport pipelines.

4. CONCLUSIONS

This paper has considered the effect on pipeline hydraulics of micro-bubbles of air in slurries resulting from the use of froth flotation to recover the wanted minerals. Section 2 considered the Century zinc concentrate pipeline in which slurry air volumes up to 24% can occur. The micro-bubbles of air increase the slurry viscosities measured at atmospheric pressure which, if used directly, would give erroneous predictions for the transition velocity and pressure gradients. Because of the high pressures in the pipeline, the air is compressed and dissolved in the water phase meaning there is zero free air in the pipeline. A method of adjusting the rheology measured at atmospheric pressure to predict the actual rheology in the pressurised pipeline has been presented.

In Section 3, air in coal tailings pipelines is discussed. Test results for a range of coal tailings shows that the air content in coal tailings is typically only a few percent, meaning that the applicable rheology within the pipeline will be little different from that measured, especially because of the lower pressures compared with Century. However the air causes the effective solids density, as measured on-site using a measuring cylinder, to be lower than the true solids density as measured by a gas pycnometer. It is common for coal tailings pipeline design to be based on the site measured solids density, which is an alternate method of allowing for the air content compared to the percent air approach used in the Century zinc concentrate pipeline design discussed in Section 2.

REFERENCES

1. Hoskins, M., Gandhi, R.L., and Weston, M.D., 2002. Experiences with the Century zinc/lead slurry pipeline. Proc. 15th Int. Conf. on Hydrotransport, Banff, Canada, 3-5 June. BHR Group, Cranfield, U.K.
2. Thomas, A.D., 1999. The influence of coarse particles on the rheology of fine particle slurries, Rheology in the Mineral Industry II, United Engineering Foundation Conference, Turtle Bay, Hawaii, March 1999.
3. Thomas, A.D., Gaultier, P. and Hoskins, M., 2002. Two 300 km concentrate pipelines compared. Century zinc/lead concentrate pipeline, Australia and Antamina copper/zinc concentrate pipeline, Peru. Proc. 15th Int. Conf. on Hydrotransport, Banff, Canada, 3-5 June. BHR Group, Cranfield, U.K.
4. Thomas, A.D., 2010. Method of determining the inherent viscosity of a slurry and other rheological trends as illustrated by a data bank of over 200 different slurries. Proc. 18th Int. Conf. on Hydraulic Transport of Solids, Rio de Janeiro, Brazil, 22-24 September, BHR Group, Cranfield, U.K.
5. Thomas, A.D. 2012., The design of the Century zinc-lead concentrate pipeline – the longest single pump station slurry pipeline in the world, IRR 2nd Annual Slurry Pipelines Conference, Fremantle, Western Australia, 20-21 Nov, 2012.
6. Thomas, D.G. 1965. Transport characteristics of suspensions: Part VIII. A note on the viscosity of Newtonian suspensions of uniform spherical particles, J. Colloid Sci., 20, p267
7. Wilson, K.C. and Thomas, A.D., 2006. Analytic model of laminar-turbulent transition for Bingham plastics. Canadian Jnl Chem. Eng., Vol 84, October 2006, 520-526.