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AIR RELEASE VALVES (ARV) ARE CONVENTIONALLY INSTALLED ON LONG DISTANCE WATER PIPELINES. WHY ARVS ARE NOT REQUIRED ON SLURRY PIPELINES.

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Long distance water pipelines are conventionally installed with air release valves (ARVs) located at high points. In contrast, long distance slurry pipelines do not use ARVs. A literature survey examines various criteria for predicting the critical velocity required to remove air from a downward sloping water pipeline. A force balance model is developed which only applies to very low pipeline slopes but does allow the effect of slurry density and viscosity to be examined. These are found not to explain the differences between water and slurry pipelines as regards ARVs. A method of predicting the velocity required to remove air from a downwards sloping pipeline section of any diameter and slope is recommended. A long-distance slurry pipeline and a recent water pipeline are described and compared with the recommended critical velocity prediction method. The paper urges a rethink on use of ARVs in water pipelines.

KEY WORDS: air release valves, water pipelines

1. INTRODUCTION

Long distance water pipelines are conventionally installed with air release valves (ARVs) located at high points. The ARVs function as a means to release air that may accumulate at the high point. In addition, the pipelines are installed with steady grades to and from each highpoint to ensure all entrapped air readily migrates to the highpoint. With buried pipelines, considerable cost can be incurred in deepening trenches to provide the steady grades thought necessary. The use of ARVs on water pipelines is a long established, but expensive practice which needs to be reviewed.

Long distance slurry pipelines have operated successfully for the past 40 years. The slurry pipelines are buried at a constant depth of about 750 mm below ground level and therefore follow the undulations of the terrain. No special grading of pipeline slopes is employed, other than keeping the slope less than 15% to limit slurry settling problems, and ARVs are not installed. It should also be noted that virtually every mine in the world has a tailings pipeline which invariably does not include ARVs.

2. LITERATURE SURVEY

On upwards slopes, air present in the water is carried with the flow to a high point where it may accumulate and form an air pocket. Fluid forces will drive the air pocket slightly downstream of the high point until the buoyancy force of the air pocket equals the drag forces attempting to drive the air pocket down the slope and a stable air pocket may form, restricting the flow and thereby increasing the overall friction loss in the pipeline.

A very comprehensive 83page literature review has been carried out by Lauchlan et al (2005). They reviewed various criteria to predict when air bubbles/pockets are removed from pipelines. These equations are largely empirical and based on laboratory tests. The major papers identified by the Lauchlan et al (2005) review are discussed below. The papers can be grouped into three categories. The first category involves equations of the general form (1) which give zero critical velocity at zero slope. V_c is the critical velocity, based on the total pipe area, required to remove air from a pipe of down slope θ, D is pipe diameter, and A is a constant differing between investigators.

$$V_c/\sqrt{(g\,D)} = A\sqrt{\sin\theta} \quad (\text{or } A\sqrt{\tan\theta}) \qquad (1)$$

Kalinske and Bliss (1943) conducted tests in pipe diameters 102 mm and 152 mm at various slopes. For downwards slopes greater than approximately 5% (2.9^0) Lauchlan et al (2005) found A = 1.509 (for $\sqrt{\tan\theta}$). Kent (1952) tested pipes of 38 mm and 102 mm at slopes from 15^0 to 75^0 and his results appear to have been the most widely accepted. By equating drag on a pocket to buoyancy Kent gave A = 1.24 (for $\sqrt{\sin\theta}$). Falvey (1980) provided a graph of pipeline slope versus dimensionless flow rate giving critical flow rate for bubbles and for air pockets. His criteria for bubbles fits eqn 1 with A = 1.4 (for $\sqrt{\sin\theta}$). His criteria for pockets cannot be easily similarly recast in equation form but is presented later as a curve in Figure 3.

The second category of criteria involve equations of the form (2) which includes a second constant, B, and which, if extended, do not provide for a zero V_c at zero slope.

$$V_c/\sqrt{(gD)} = A\sqrt{\sin\theta} + B \qquad (2)$$

Mosvell (1976) fitted the data of Kent to eqn 2 with A = 0.50 and B = 0.55 for pipe slopes from 15^0 to 60^0. Wisner et al (1975) plotted all experimental results of Kalinske and Bliss (1943), Kent (1952) and their own data and provided an upper bound to $V_c/\sqrt{(gD)}$ which encompasses all the data, given by eqn 2 with A = 0.25 and B = 0.825.

The third catogory of criteria is that of Walski et al (1994) who conducted a model study for a 4.5 km long 500 mm to 920 mm diameter forced sanitary main. They derived the following equation from experiments in a 50 mm diameter pipe. Eqn 3 provides for zero V_c at zero slope but also fits the mid-range data in a similar way as eqn 2.

$$V_c/\sqrt{(gD)} = 1.066\,(\tan\theta)^{0.16} \qquad (3)$$

Little (2002) concluded that there is no well accepted analytical solution for the transport of air pockets or dispersed bubble flow and at present information must be drawn from existing experimental results. He found that published data are not always consistent with each other or with case histories. He recommended the prediction for air pocket movement be based on the work of Kent (1952). The overall conclusion from the comprehensive review by Lauchlan et al (2005) was that “there are no generally accepted formulae for the transport of air bubbles or pockets in pipelines and there is a wide variation between the various prediction equations”.

3. FORCE BALANCE ANALYSIS

A force balance analysis similar to the sliding bed analysis introduced by Wilson (1974) to analyse flows of settling slurries has been applied as illustrated in Figure 1. In the current air pocket analysis, the sliding bed friction of the solid bed is replaced by a resisting buoyancy force.

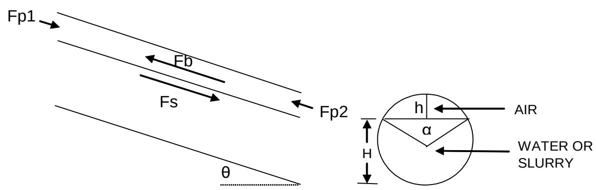

Figure 1 Force balance air pocket in sloping pipe

Consider a pipeline of downwards slope θ with an air pocket of height h occupying a segment at the top of the pipe. A buoyancy force Fb is driving the air pocket up the slope. Fb is given by $g(\rho_f - \rho_a)$ x volume of air x sinθ, where g is the gravitational constant, ρ_f is the density of the fluid (water or slurry) and ρ_a is the density of air. For a unit length, Fb is given by $g(\rho_f - \rho_a)$ x cross sectional area of segment x sinθ. This buoyancy force is resisted by a pressure force at each end of the air pocket and a shear force acting on the lower surface of the air pocket. The shear force between the air pocket and the top of the pipe is ignored and is zero anyway when air pocket is in stationary equilibrium. For an air pocket of unit length, the nett pressure force on each end of the end pocket is given by Fp = Fp1 – Fp2 = J x cross sectional area of segment where J = pressure gradient in Pa/m.

$$J = 2\ f\ \rho_f\ V_w^2\ /\ D_{eq} \qquad (4)$$

where f is the Fanning friction factor, V_w is the velocity of the water in the reduced area below the air pocket, and D_{eq} is the equivalent diameter of the fluid cross section equal to D_{eq} = 4 x cross sectional area / wetted perimeter. The friction factor is calculated using a Blasius type expression due to Knudsen and Katz (1958), [$f = 0.046\ Re^{-0.2}$], with Reynolds number Re based on velocityV_w . The shear force Fs is equal to τ x area of lower surface of air pocket where τ is shear stress at the fluid/air surface approximated by $\tau = D_{eq}J/4 = f\ \rho_f V_w^2/2$. For a unit length of air pocket Fs = τ x chord width. If Fp + Fs exceeds Fb then the air pocket is driven down the slope. The chord width and cross-sectional area of the segment are functions of the angle α. A spreadsheet was developed which calculates chord width, segment area and other variables at one-degree intervals of the angle α, and determines the driving force Fp+Fs and the buoyancy force Fb for the specified flow rate, pipe diameter, pipeline slope, fluid density, and fluid viscosity. For any input flow rate (and hence superficial velocity V) the critical velocity for any value of H/D when Fp+Fs-Fb=0 is determined by inspection of the spreadsheet columns. The effects of pipeline slope, pipe diameter, slurry density and slurry density can be combined using a non-dimensional generalised velocity, V_g given by:

$$V_g = V / \sqrt{[g\ D\ Re^{0.2} \sin(\theta)]} \qquad (5)$$

Figure 2 shows H/D versus V_g for a range of predictions for the force balance model spreadsheet for varying pipe diameters, pipe slopes, slurry density and slurry viscosity. The various predictions fall on the one curve. Figure 2 can therefore be used to predict the variation of H/D with velocity for any combination of variables. Of particular interest is the maximum critical velocity given by V_g = 1.717.

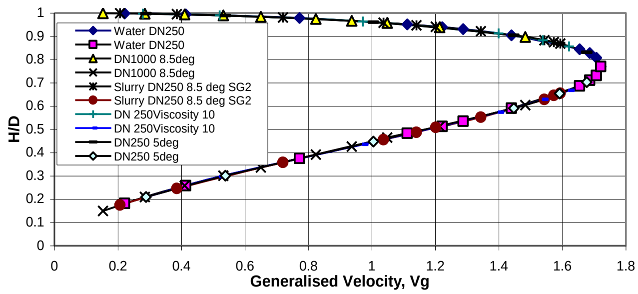

Figure 2 Force Balance Analysis H/D versus Generalised Velocity

According to Figure 2 a pocket of air occupying the top 1% of the diameter of the pipe (H/D = 0.99) requires V_g = 0.5 to drive the air pocket down the slope. If the pocket of air occupies the top 10% of the pipe diameter (H/D = 0.90) V_g = 1.45 is required. Now consider a large pocket of air occupying 80% of the pipe diameter (H/D = 0.20). V_g required to remove this large air pocket is only 0.25 because the actual velocity in the greatly restricted area below the air pocket is much higher. Reductions in $V_c/\sqrt{(g\ D)}$ of similar order for large air pockets are evident in the data of Wisner et al (1975). As the air pocket size reduces, the critical velocity moves up the lower portion of the curve until the maximum critical V_g = 1.717 is reached. This applies to an air pocket occupying the top 23% of the pipe diameter (H/D = 0.77) which is predicted to be the most stable and difficult size air pocket to remove. Interestingly the photos of experiments by Wisner et al (1975) indicate the most stable size occurs for H/D similar to the predicted 0.77.

The analysis predicts only a small effect of slurry density, as evident by the power 0.1 in the Reynolds number term. A typical doubling of the density from that of water only results in a 7% change in the critical velocity. A typical 10 times increase in slurry viscosity above water has a greater effect reducing critical velocities by about 25% according to eqn 5 although the later recommended eqn 7 shows less influence.

4. COMBINING LITERATURE DATA AND FORCE BALANCE

The maximum generalised critical velocity, V_g, from Figure 2 is 1.717 so from eqn 5 the maximum value of V_c is:

$$V_c /\sqrt{(g D)} = 1.717 \, Re^{0.1} \sqrt{\sin(\theta)} \qquad (6)$$

The Reynolds number for water pipelines is likely to range from a minimum (for a laboratory test loop) of around 2.5×10^4 (25 mm diameter pipe, velocity 1 m/s) to a maximum around 1.5×10^6 (1000 mm diameter pipe, velocity 1.5 m/s). The value of 1.717 $Re^{0.1}$ in eqn 6 will therefore range from approximately 4.7 to 7.1. The Reynolds number for a typical slurry pipeline will be around 1.35×10^5 (300 mm diameter, velocity 1.8 m/s, density 2000 kg/m^3, viscosity 8 mPas) giving a mid-range value of 1.717 $Re^{0.1}$ = 5.6.

Figure 3 presents literature predictions using equations 1 to 3 as $V_c/\sqrt{(gD)}$ versus $\sqrt{\sin\theta}$ together with the curve for air pockets taken from the graph presented by Falvey (1980). The predictions of the current force balance analysis for the expected maximum and minimum Reynolds numbers are also shown and provide for the intuitively correct zero $V_c/\sqrt{(gD)}$ at $\sqrt{\sin\theta} = 0$ but with far too high predictions for $\sqrt{\sin\theta}$ greater than 0.1. The force balance analysis is based on removal of an air pocket and does not consider removal of air by generation of air bubbles at the rear of the air pocket and entrainment. However, the force balance model would seem to confirm the basic $V_c/\sqrt{(gD)}$ versus $\sqrt{\sin\theta}$ relationship adopted by most of the literature investigators and also suggests a means of incorporating the effect of Reynolds number.

The prediction methods of Mosvell (1976) and Wisner et al (1975) extend towards a non-zero value for $V_c /\sqrt{(gD)}$ at zero slope to accommodate experimental data down to $\sqrt{\sin\theta}$ = 0.1 that clearly did not follow the predictions of Kent (1952) and others at these low pipe slopes. The present force balance analysis perhaps explains these differences by providing for the steep increase from the origin up to $\sqrt{\sin\theta} = 0.1$. For pipe slopes above this, other physical mechanisms such as generation of air bubbles and entrainment apparently predominate leading to the reduced rate of increase as predicted by Mosvell and Wisner et al. Figure 3 shows that the prediction method of Walski et al (eqn 3) provides for a similar steep increase from the origin with subsequent flattening above $\sqrt{\sin\theta} = 0.1$. In the absence of further analysis or experimental results the authors recommend the method of Walski et al. The Walski et al prediction is below the method of Wisner et al (1975) for low values of $\sqrt{\sin(\theta)}$ but the examination of the Wisner et al paper suggests that the higher values for Wisner et al in this region appear to be unduly influenced by just two experimental points at $\sqrt{\sin\theta} = 0.25$.

In the force balance model, the effect of Reynolds number is incorporated in eqn 6. It is postulated that the influence of Reynolds number could be similarly incorporated into the Walski et al prediction method resulting in the following equation:

$$V_c/\sqrt{(gD)} = 0.75\ (Re^{0.2}\ \tan\theta)^{0.16} = 0.75\ Re^{0.032}\ (\tan\theta)^{0.16} \qquad (7)$$

Walski et al's experiments were in a 50 mm pipe so typical Reynolds numbers would be around 5E4. Using this value for Re eqn 3 results in the 0.75 constant in eqn 7. The upper grey line in Figure 3 is from eqn 7 for Re = 1.5E6 which would apply in large diameter pipes.

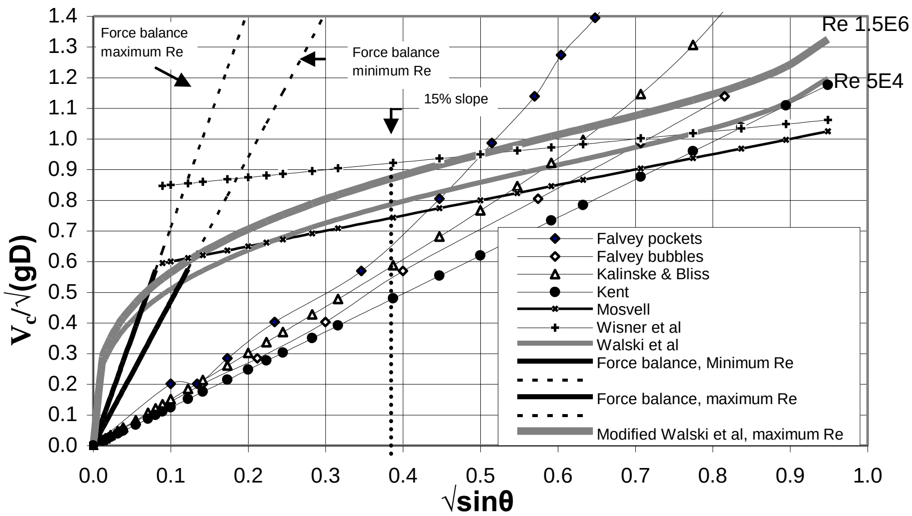

Figure 3 Comparison literature review and force balance analysis

5. AUTHOR'S PIPELINE EXPERIENCE

Long distance slurry pipelines have operated successfully for the last 40 years without ARVs and without special grading of pipeline slope. Pipe diameters range from 100 mm to 500 mm, slurry SG from about 1.3 to 2.2, and Bingham plastic viscosities from about 5 mPas to 15 mPas. Operating velocities range from 1.2 m/s to 1.8 m/s with the higher velocities generally in the larger pipes. The extremes of Reynolds number are therefore from about 1×10^4 to about 4×10^5. The maximum pipeline slopes are limited to 15% from slurry settling considerations. At 15% slope $\sqrt{\sin\theta} = 0.385$ as indicated in Figure 3. Eqn 7 therefore gives $V_c/\sqrt{(gD)} = 0.74$ to 0.84 and V_c ranging from 0.75 m/s in 100 mm pipe to 1.85 m/s in a 500 mm pipe. The predicted V_c are therefore approximately within the normal operating velocity range, confirming the operating experience that air is not a problem in slurry pipelines.

An important factor which does not seem to have been addressed in relation to water pipelines is the reduction in volume of an air pocket under pressure and the dissolving of air into the water. These effects are very significant, even at the relatively low pressures involved in water pipelines. For example, the most stable air pocket (H/D = 0.77 in Figure 2) represents about 17% free air volume at atmospheric pressure. With the combined effects of air compression and dissolving of air into the water, at 500 kPa pressure this 17% volume of free air will be reduced to about 1.2%, equivalent to H/D = 0.96, reducing the critical velocity to about 0.6 of the maximum critical velocity with 17% free air according to the force balance analysis. Since all the laboratory data are obtained at atmospheric pressure this suggests the critical velocities obtained could be reduced by up to half at a pipeline pressure of 500 kPa. This means that an air pocket which may not be able to be removed at atmospheric pressure may be able to be removed in the higher-pressure regions of a pipeline. This also means that the fact that ARVs may release air from a pipeline when the pipeline is shutdown does not necessarily mean that this air would not be capable of removal from those high points when the pipeline is under pressure. It can be noted that water containing up to 9% free air at atmospheric pressure will contain no free air at 500 kPa pipeline pressure.

Dissolving of air is very evident in the 300 km, DN300 Century zinc and lead concentrate slurry pipeline in Queensland, Australia (Thomas et al, 2002). The zinc concentrate is produced by a froth flotation process and at 54% solids concentration typically contains about 15% free air. After dilution to 37% solids concentration and a pressure increase to 420 kPa in the centrifugal charge pump the volume of compressed free air is reduced to 1.9%. With further increase in pressure in the mainline piston pumps all the air is dissolved. The air only starts coming out of solution over the last 15 kms of the pipeline. The pipeline route profile is very flat but does include a number of submerged river crossings with 15% slopes including two in the last 15 kms. The velocity is 1.2 m/s giving $V/\sqrt{(gD)} = 0.7$, just under the Walski et al prediction in Figure 3.

The authors were recently involved in the design of a 62 km return water pipeline associated with the Whyalla OneSteel magnetite pipeline described elsewhere at this conference (Cowper et al, 2008). The general overall pipeline slopes are only around 2% but over a short distance there is a maximum slope of 15% and a number of short lengths around 10% slope. The 394 mm ID pipeline operates at a velocity of 1.28 m/s giving $V/\sqrt{(gD)} = 0.65$ which is below the critical value required by the Walski et al prediction in Figure 3. Two centrifugal pumps in series are used with discharge pressure 3500 kPa. No ARVs are installed and air was initially removed by pigging the pipeline.

6. CONCLUSIONS

Following a review of the literature on air in water pipelines combined with a force balance analysis the authors recommend a modified Walski et al (1994) prediction method (eqn 7) which incorporates Reynolds number. Eqn 7 indicates that the critical velocity for slurries compared with water is little affected by the higher slurry density but the higher viscosity does reduce V_c by about 10%. This, combined with the 15% (8.5^0) slope limit and the generally smaller pipe size, means that air is less of a problem in slurry pipelines. The significant reduction of free air volume under pressure due to air dissolving into the water and compression does not seem to have been considered in regard to water pipelines. There would seem to be a case to reconsider the use of ARVs in water pipelines, especially the smaller diameter pipelines of moderate slope, and taking into account the effect of pipeline pressure on free air volumes. One important aspect is the initial filling of a pipeline. With slurry pipelines a foam pig is used to ensure all air is removed. Pigs are generally not used in water pipelines and the ARVs are used to release the air during commissioning. There may be case for pigging water pipelines and reducing or eliminating the ARVs.

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