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Application of pipe flow lubrication for reactor feeds

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Abstract

Drag reduction technology (DRT) is a useful technique to increase the solids concentration of feed into reaction vessels, such as autoclaves. The concept is to apply a lubricating film between the pipe ID and the highly concentrated slurry, which reduces wall friction, and thereby pump load. Whilst wall film lubrication is not a new concept, the application for feed into a reactor vessel is novel and CSIRO now have two client sites successfully applying this technique.

The DRT design requires uniform flow of the lubricating fluid to give the best friction reduction performance, and resistance to blockage. The internal design of the DRT is optimised by computational fluid dynamics modelling to give the most uniform flow possible, as well as reasonably large internal passages to prevent blockage. The DRT is tested in the laboratory to ensure that the uniform flow requirements are met and that the pressure loss of the lubricant flow matches the calculations and simulation data.

Assessment is also made as to the best location to fit the DRT on a pipe system to give the maximum drag reduction benefit. Slurry rheology and operating conditions are then used to determine the optimum operating regime in which drag reduction is useful by defining the boundary between laminar and turbulent flow for the slurry in question.

Site trials have shown that benefits from the use of pipe flow lubrication include significant water savings, extension of pump operating envelopes, and increased solids loading into reaction vessels, all of which leads to improved utilisation of capital-intensive vessels such as high-pressure acid leach autoclaves.

Keywords: *pipe flow, friction reduction, reactor feeds*

1 Introduction

Slurry pipe flows within mineral processing plants are required to be reliable as they transfer the processing materials between unit operations such as thickeners and leaching vessels. They can be subject to issues such as scale and erosion, which lead to downtime and associated costs. Increasing the solids concentration of processing slurries is desirable in many instances as that can lead to improved efficiency and/or productivity of operation of high capital cost equipment such as high-pressure acid leach (HPAL) autoclaves. An example relating to mixing intensification is discussed in Wu et al. (2011).

However intensive the mixing or leaching system may be, it is of no use unless the appropriate slurry can be prepared and transported effectively. A possible scenario to increase productivity for an operating plant is for the desired solids concentrations in reacting vessels to be increased, but the upgrading of the slurry feed systems may not be feasible or too costly. For example, if the slurry concentration was to be raised from say 35 to 40% w/w, a significant slurry rheology increase is possible which could exceed the capability of the existing feed or transfer pumps. The expense of completely replacing the pump system may be prohibitive, with new pumps and possibly power distribution systems required. Dilution of the slurry feed may be necessary but is not a desirable option due to the reduction in solids concentration and consequent undesired water entering the reaction vessels.

A suitable alternative to installing a new pump system is to reduce the pumping load by reducing the pipe friction. This can be done be increasing the pipe diameter (assuming that the slurry is homogenous) or by lubricating the pipe wall with a small amount of fluid (usually water). This principle has been previously discussed in the literature. Joseph et al. (1999) discusses the case of bitumen froth where a lubricating layer self-forms as water is liberated from the froth in high shear regions, such a near a pipe wall. The lubricating layer can also form in concrete as described by Secrieru et al. (2017) and lubricating systems for concrete pumping exist.

This paper discusses the option of reducing pipe friction using the wall lubrication method for in-plant pipe systems feeding reaction vessels. Whilst the concept is not new, the application and the details of the implementation are novel, with two industrial sites now applying it as part of their normal operations. The discussion includes details of developing a uniform lubricating film in a compact device which can be readily incorporated into a pipe system. Details are also given of the modelling and testing carried out to prove the satisfactory operation of the device together with site experience.

2 Design of lubricating device

The basic concept of the device is to distribute the lubrication around the pipe wall as evenly as possible and to achieve this objective, a significant pressure drop between the lubricant feed and the device outlet is required. An early version of the concept as developed at CSIRO was to use a porous medium such as sintered metal. Sintered metal could be obtained in the form of tubes which could be supplied with lubricant leading to a homogenous distribution of the lubricant on the pipe wall. Laboratory tests of this concept were successful in terms of the quality of the lubricating film and the performance in terms of the pipe friction reduction but had a stringent quality requirement on the cleanliness of the lubricant, otherwise the sintered metal would block in an unacceptably short time of operation. However, the concept could still be applicable in, for example, fine chemical processing.

The final design concept used was concentric grooves in the internal passages of the device as shown in Figure 1. These could be sized to provide sufficient pressure drop between the inlet and outlet to obtain a satisfactory uniformity of outlet flow yet allowing the internal passages to be large enough to tolerate impurities in the lubricant.

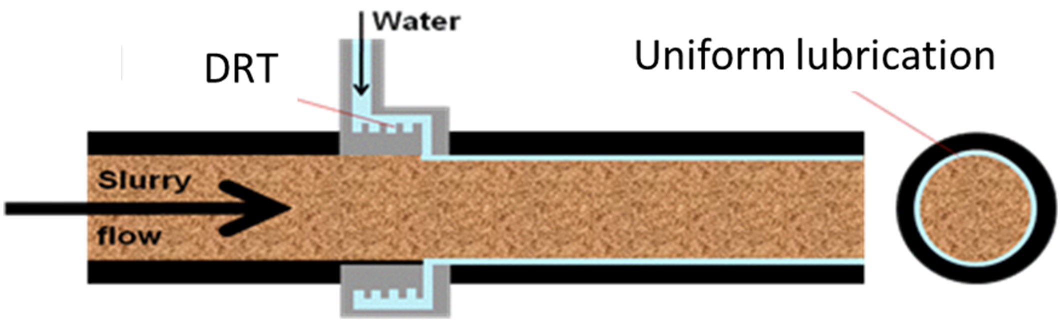

Figure 1 Concept of CSIRO drag reduction technology (DRT)

The size and number of the grooves is influenced by the nominal pipe size of the DRT device as well as the required lubricating flow rate range. Initial sizing and determining the number of grooves was estimated by using a simple analytical procedure.

More detailed modelling was carried out using computational fluid dynamics (CFD) to confirm the design of the internal passages of the DRT for a particular application.

The DRT wetted geometry was obtained from a CAD model and imported into mesh generation software to prepare for CFD modelling in OpenFOAM. The CFD modelling used a standard k-ε model together with wall functions to account for wall effects. The inlet flow rate was specified to be typical of expected full-scale lubricant flow rates for the pipe size in question, the present example being for a 250 mm NB pipe.

The resulting overall flow throughout a typical DRT unit is shown in Figure 2. A vector plot of the flow in the region of the grooves and inlet is shown in Figure 3, clearly showing recirculation within the grooves. The outlet flow distribution is given in Figure 4 where the uniformity is seen to be satisfactory, although it is interesting to note the slight decrease in the outlet flow velocity in the vicinity of the flow inlet. In practice, this flow distribution was satisfactory and compared well with physical tests

A further decrease in the internal passage size which would improve the uniformity was rejected as increasing the risk of blockage of the internal passages.

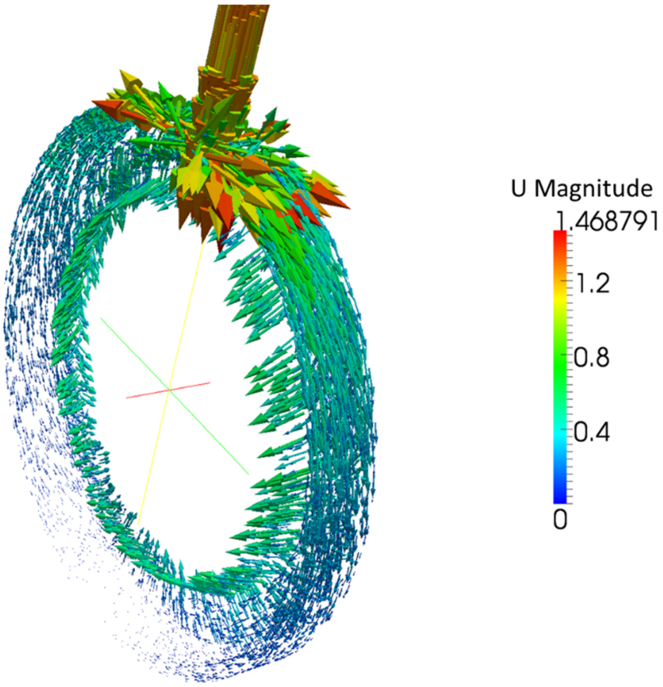

Figure 2 Overall flow vectors throughout drag reduction technology

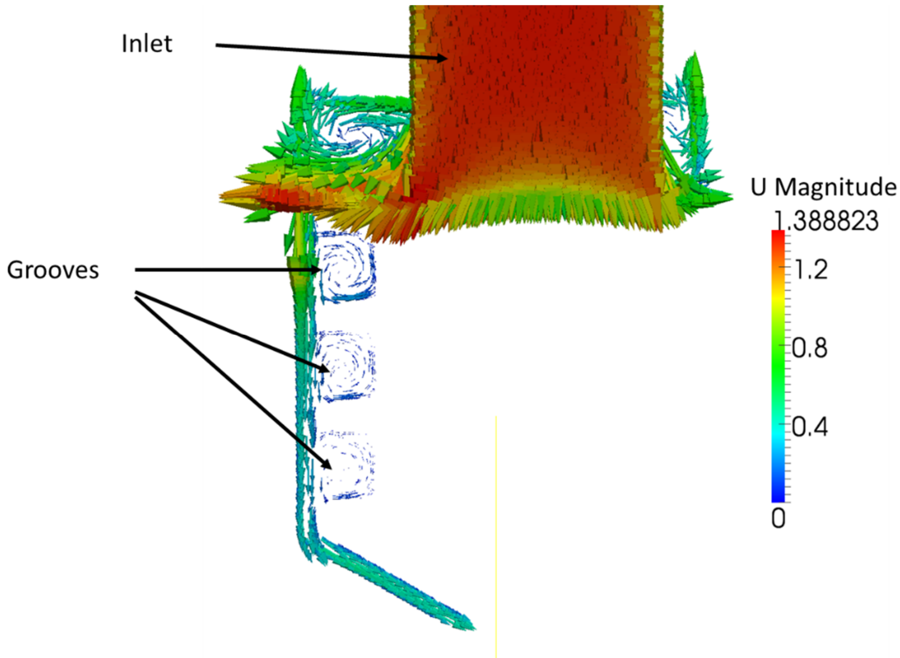

Figure 3 Detail of flow within the grooves of the drag reduction technology

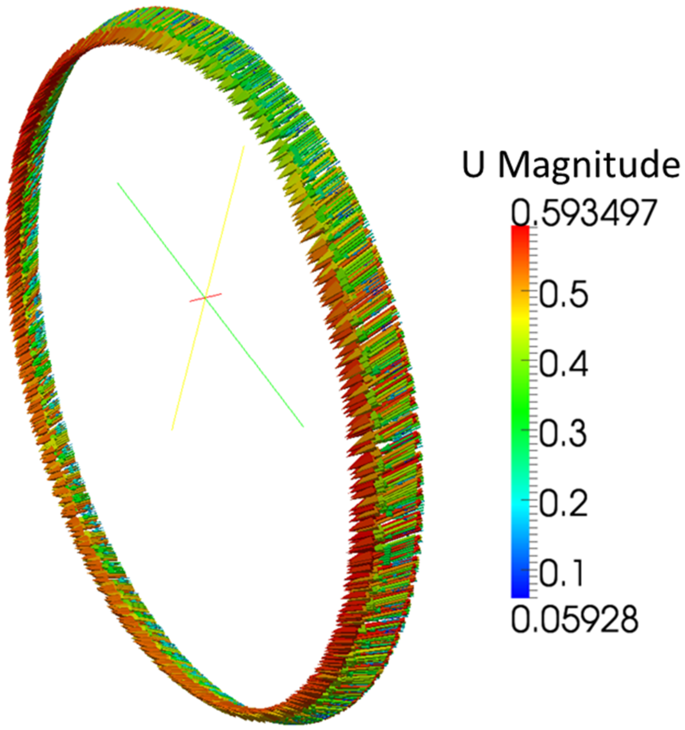

Figure 4 Outlet flow from drag reduction technology

The design of the DRT also requires structural considerations as well as practical implementation requirements. These include:

- The DRT must be sufficiently strong to withstand maximum pressures in the pipe system.
- Compatibility with existing pipework and flanges. It is also important that the internal diameter of the DRT matches that of the connecting pipe work (including any rubber lining etc.) to minimise disruption of the lubricating film.
- Material compatibility with the existing or proposed pipe system in terms of chemical resistance etc.
- Geometric constraints such as other hardware in the vicinity of the DRT location. These constraints impact on the arrangement of the grooves within the device; highly constrained locations may demand a longitudinal arrangement of the grooves. Ideally, the device would fit between standard pipe flanges in use on the target pipe system to ease installation.
- Installation of a suitable lubricant feed system and associated monitoring such as flow rate and pressure of the fluid entering the device.
- The machining of the components requires close tolerances and fine surface finish to ensure even flow distribution through the device.

The location of the DRT within a pipe system is a critical consideration. The ideal location is upstream of a straight pipe section which is the longest available in the system in question. This requirement can be a challenge in existing plants where pipe runs contain fittings, valves, sharp bends etc. which can disrupt the lubrication film. If bends are unavoidable, larger radius (e.g. 5D bends) would be preferable. For the site installations at the time of writing, significant straight pipe lengths were available where the DRT could be effective. Further work would be needed to quantify the effect of lubricating film disruption in particular cases where such impediments to the film were present. Indeed, it may be possible for pipes to be rerouted to include more straight sections if the need of reducing the friction loss were sufficiently compelling to counter the cost. The pipe does not have to be horizontal for effective friction reduction.

3 Experimental tests

The drag reduction system was tested at CSIRO to confirm the modelling results as well as to validate the drag reduction performance.

Figure 5 shows a visualisation of the lubricating film produced from a laboratory model (250 mm NB) DRT which was produced to validate the full-scale design. The water flow rate was 6.8 m^3 h^{-1} and the uniformity of the film is evident and is consistent with the CFD results. At lower flow rates (e.g. 1 m^3 h^{-1}), the pressure drop through the device is too low to provide a uniform lubrication film as shown in Figure 6. Thus, it is important to understand the required operating range of the device such that the device provides a uniform film for the main slurry flows specified. The normal aim for the device is for a uniform lubrication flow up to 1–2% of the main slurry flow. In the case of the 250 mm NB device, the recommended lubricating flow rate ranges from 4 to 15 m^3 h^{-1} to give a satisfactory lubricating film, with the minimum flow rate which gives drag reduction being preferred as that leads to the highest solids concentration and least water consumption. The higher flow rates can be used for flushing out the device if necessary.

Pressure drops though the device obtained from the CFD modelling are given in Figure 7. The lubricating fluid supply pressure must be sufficient to exceed the main slurry pipe pressure by enough margin to include the pressure loss through the device at the required lubricant flow rate..

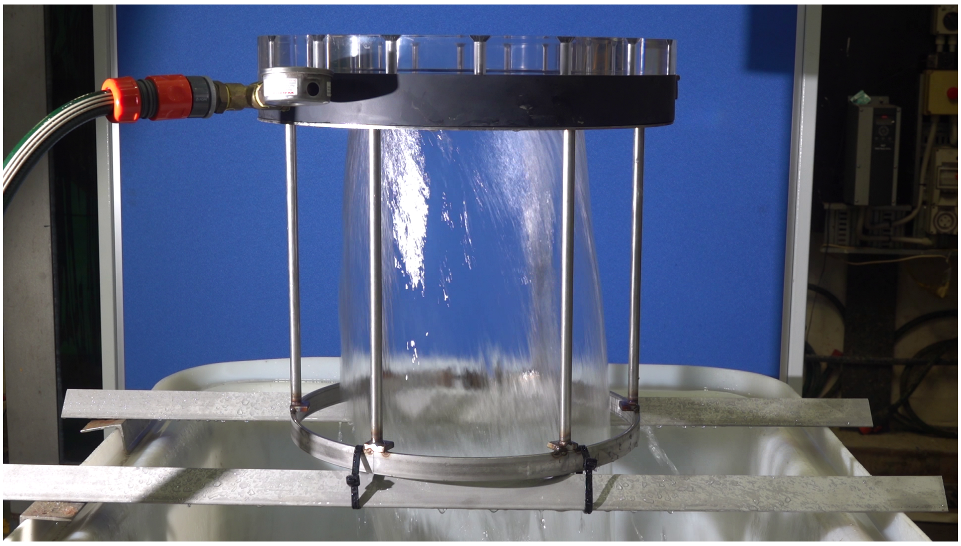

Figure 5 Discharge from NB 250 mm drag reduction technology at 6.8 m^3 h^{-1} (114 L min^{-1})

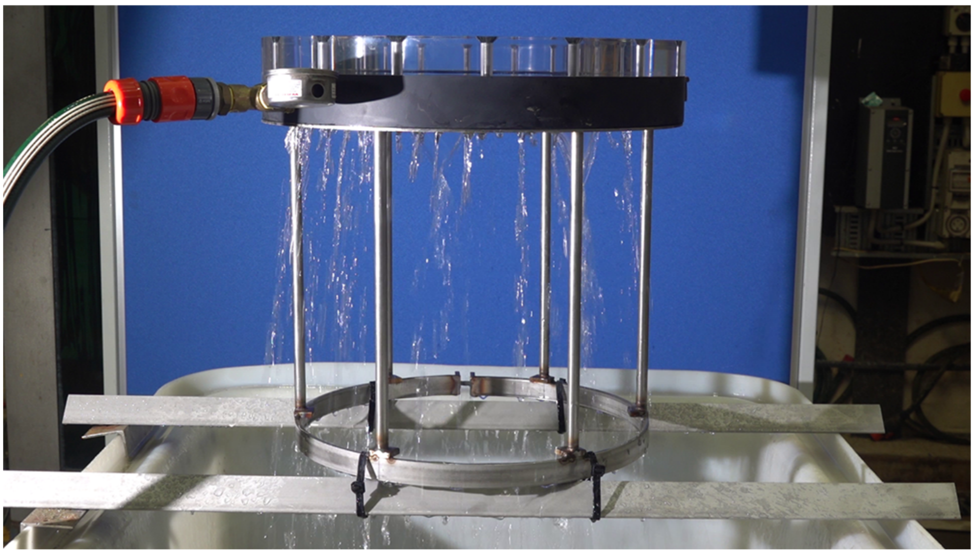

Figure 6 Discharge from NB 250 mm drag reduction technology at 1 m^3 h^{-1} (17 L min^{-1})

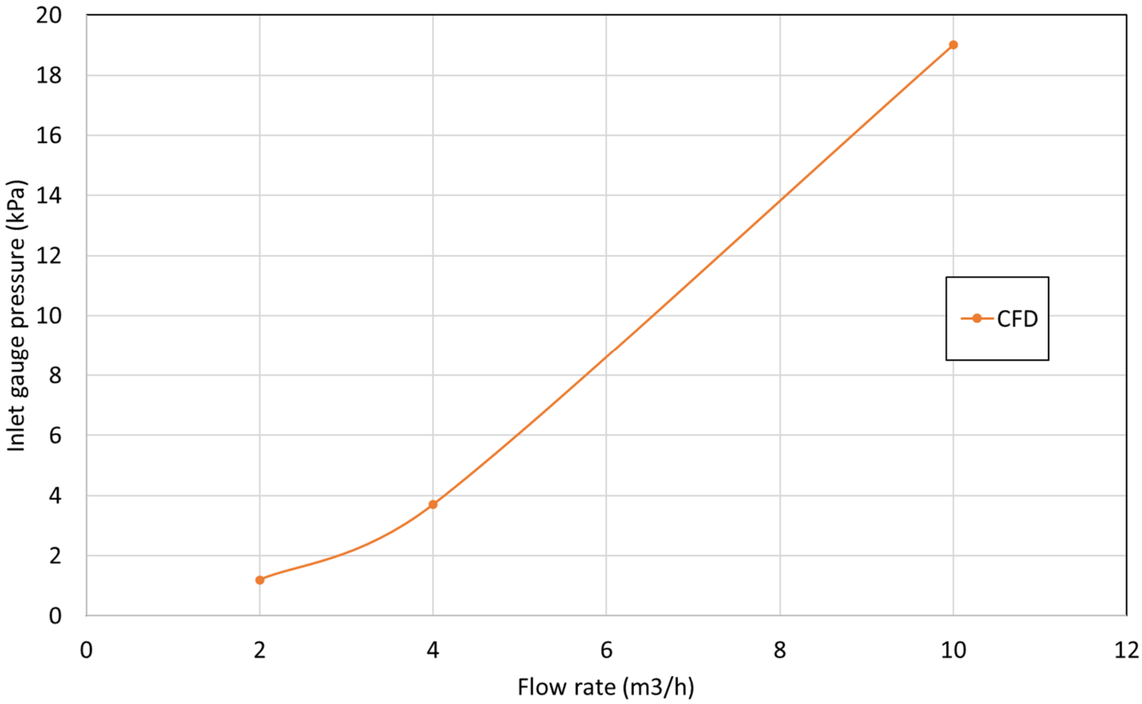

Figure 7 Inlet gauge pressure at drag reduction technology inlet from computational fluid dynamics (CFD) runs for 250 mm NB device assuming atmospheric pressure at the outlet

Figure 8 shows laboratory data for a 50 mm NB pipe 10 m long (200 pipe diameter) fitted with a DRT system. The slurry was a kaolin/water slurry with a yield stress of 80 Pa. The lubricating flow was 1.5% w/w of the main slurry flow. The test data shows the drag reduction effect when the lubrication was turned on was approximately 60%.

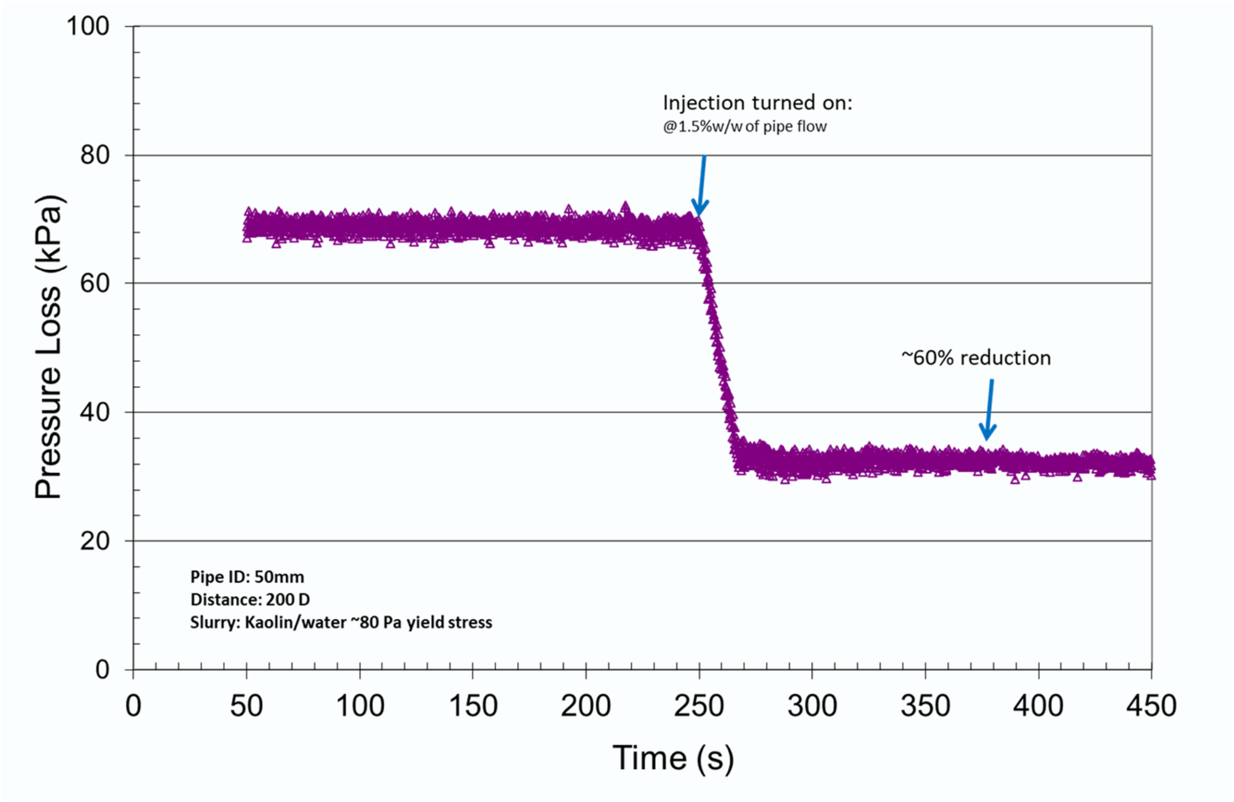

Figure 8 Drag reduction test data from a 50 mm diameter pipe at CSIRO

4 Installation considerations

The DRT is only effective in laminar slurry flow where the diffusion of the lubricant into the slurry is minimised as long as possible. Thus, it is important to understand the operating envelope of the pipe system in question. By way of an example, the operating envelope is calculated for a pipe system. An important input into these calculations is the expected rheology range of the slurry. For the present purposes, it is assumed that the slurry can be modelled by a Bingham plastic rheology model:

$$\tau = \tau_y + k\dot{\gamma} \quad (1)$$

where:

τ = shear stress

τ_y = yield stress

$\dot{\gamma}$ = shear rate

k = plastic viscosity.

Ideally, rheology data covering the range of expected slurry properties should be obtained. For the present exercise, an assumed range of slurry rheology has been developed as given in Table 1 where the yield stress and slurry density have been assumed to change.

Slurry pipe calculations were performed using the method described by Wilson & Thomas (1985) for turbulent flow and an analytical expression for the laminar flow regime such that the laminar/turbulent transition is determined at the intersection of the two curves.

Table 1 Rheology parameters for slurry pipe calculations

Nominal concentration (%)	Yield stress, τ_y, (Pa)	k (Pa s)	Density (kg/m^3)
25	5	0.063	1,197
30	17	0.063	1,247
35	50	0.063	1,301
40	150	0.063	1,359

The resultant flow curves for NB 250 mm pipe are shown in Figure 9 on a flow rate/pressure gradient basis. The transition from laminar to turbulent flow can then be extracted from the flow curves to yield the chart in Figure 10 which gives the operating regime defined as the region below the curve denoted as the laminar regime. Thus, the DRT would be effective to reduce pipe friction and pump load in that regime allowing flow rates to be maintained as slurry rheology increases because of desired higher solids concentration.

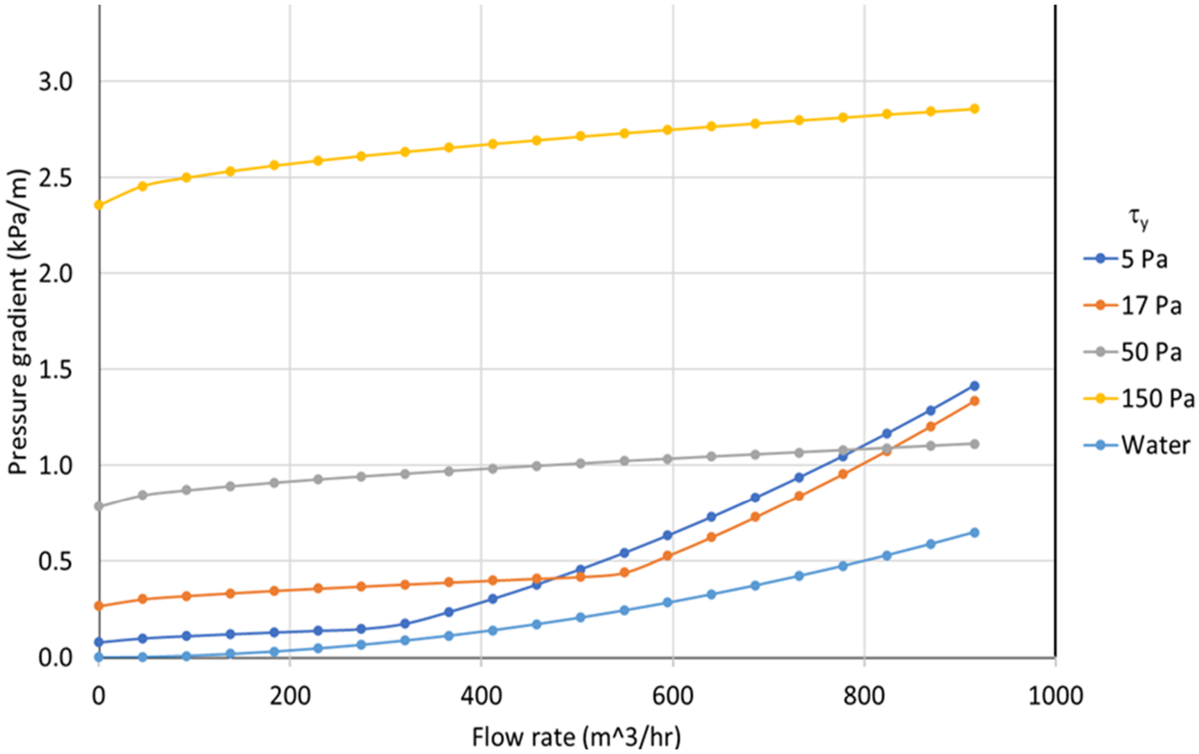

Figure 9 Flow curves based on slurry flow rate and pressure gradient

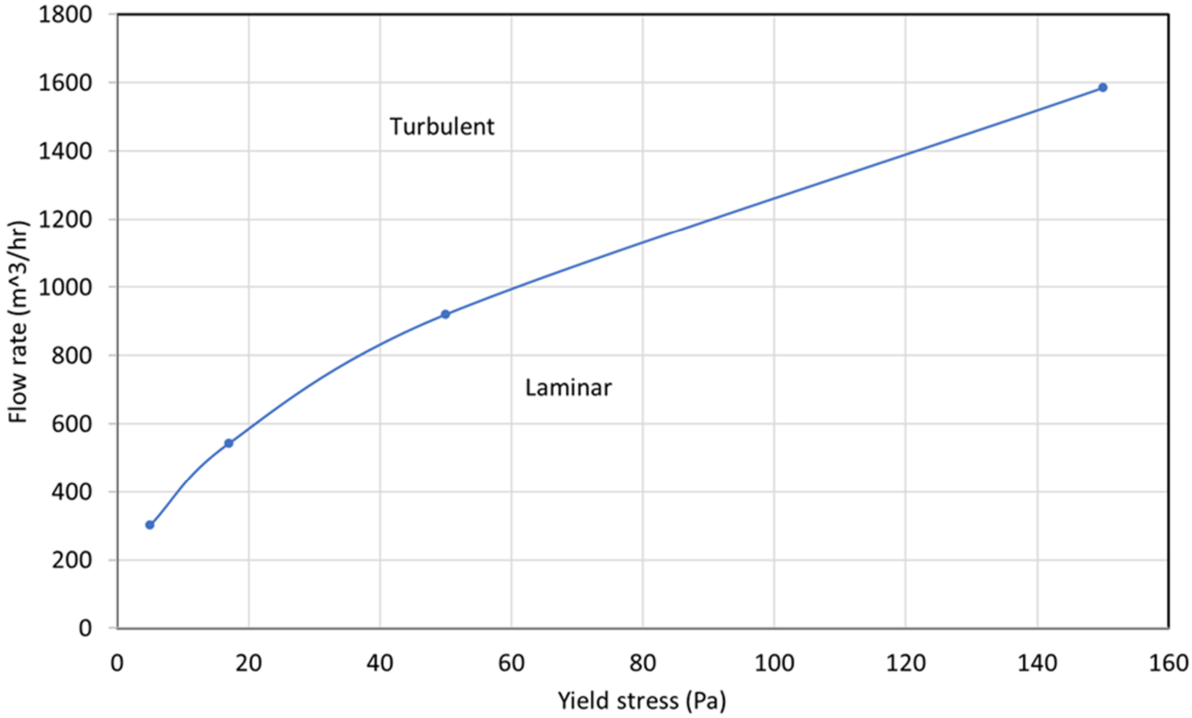

Figure 10 Chart showing the laminar and turbulent operating regimes of the example NB 250 mm pipe system

5 Site experience update and further directions

Some site experience in terms of friction reduction has been presented in previous work (Wu et al. 2020), however, with the original installation at Murrin Murrin Operation (MMO) now having been in place for eight years at the time of writing, it is worth revisiting the site factors.

It is understood from the initial site that the initial DRT device operated for five years without any cleaning or other maintenance. A performance reduction was noticed and it was taken out of service and found to have some blockage of the internal passages. After cleaning and reconditioning, it was placed back into service. A spare device was also ordered so that a changeover system could be used whenever the installed unit needed service to minimise downtime.

Maintenance of the lubricating fluid supply system is also critical to prevent backflow of slurry into the DRT and consequent blockage. It has been found that even when the drag reduction effect is not required, it is good practice to maintain a minimal lubrication flow to prevent backflow. Suitable non-return valves can also be installed in the lubrication supply line as a preventative measure. A related issue is that it is preferable to have the lubrication flow inlet at the underside of the pipe (if it is horizontal) such that any settled solids can be more readily flushed than if the inlet was at the pipe top.

Minor imperfections in the pipe such as weld joints and flange joints did not significantly impair the operation of the DRT at MMO.

MMO use the DRT to help pump viscous slurry from their paste thickener systems in place of dilution of the slurry as was previous practice to keep the pump load within acceptable limits. Tests on site showed that the DRT only uses ~5 m^3/hr water, compared with the previous ~20 m^3/hr water dilution required to maintain the same production flow (~500 m^3/hr).

Some design changes were necessary on the second device installed at a different site in New Caledonia, largely due to the dimensional restrictions at the proposed installation location and a requirement to fit the standard flanges in use at the site. A change to the internal design of the DRT was developed to allow a more compact device which was subsequently modelled and tested at CSIRO. This device has now been successfully commissioned and is operating.

One of the future options for research at CSIRO is improving the prediction of the friction loss for a given main slurry flow and related to that point, the maximum pipe length which the lubrication is effective for a particular slurry. At present, these predictions rely on testwork carried out in a pipe rig. Development of a predictive model is proceeding at CSIRO.

6 General applications and constraints

The DRT, as implemented by CSIRO, has thus far had site applications associated with reactor feeds. There are other potential applications where the concept can be used which may provide benefits for slurry pipe flows. Some of these have already been tested in the laboratory at CSIRO.

The applications include:

- Centrifugal pump suction difficulties, e.g. a long suction line out of a paste thickener. Lubrication of the pipe on the suction side of the pump led to a significant increase in pump performance for a high yield stress slurry. This aspect has been tested successfully at CSIRO but not as yet on a site.
- Short distance horizontal cemented backfill lines, e.g. from a surface paste plant to a borehole. A challenge here is the structural design as the pressures are very high. The lubrication added will also have to accounted for in the backfill composition in order to maintain the required strength.
- Protective layer chemical injection, e.g. scale suppression. The concept is to inject anti-scalants or other chemicals adjacent to the pipe wall rather than dispersing them throughout the slurry. This application has been modelled at CSIRO and can also be used for lower viscosity slurries provided that the pipe length is not so long as the injected fluid will disperse into the slurry. A plant trial of this concept was scheduled and a device manufactured, but as yet has not proceeded.

The present constraints are that CSIRO has found that the lubrication was effective up to approximately 1,000 pipe diameters downstream of the injection location. Longer pipes may need multiple injection locations or the development of additives to maintain the lubrication film for longer distances. Another constraint is that the downstream equipment (e.g. holding tank or reaction vessel) must be capable of accommodating the increased possible solids concentrations due to the use of DRT.

7 Conclusion

CFD modelling has been utilised to develop and validate the design of the internal passages of the DRT. The models have been validated against the experimental tests showing that the uniformity of the lubricating flow could be well predicted by CFD.

This outcome leads to confidence in the design of the DRT device to suit required flow rates and operating conditions to allow for increased solids concentration in reaction vessels, thus leading to improved process efficiency. Other applications of the technology are possible such as pump suction difficulties, paste backfill and chemical injection and await site trial opportunities.

Further work on improving prediction of friction loss with lubrication is under development.

Acknowledgement

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