In situ performance and potential applications of a thermal bed-load measurement method

Ilgner, H.J.
CSIR, Centre for Mining Innovations, South Africa
Goosen, P.
Paterson & Cooke Consulting Engineers (Pty) Ltd, South Africa
Dumbu, S.
Stoner (Pty) Ltd, South Africa

Abstract

Methods to detect the flow condition at the pipeline invert are reviewed. New results of a small heated plate inserted into a non-metallic pipe are presented. This thermal method is based on mini-heaters and can detect erratic flow behaviour near the transition to the stationary bed. The probe's output correlates well with flow observations and provides a robust threshold to be linked to alarms. Once the mechanical design, installed power levels and their control have been optimised to balance response times and sensitivities with wear allowances and pipeline pressure ratings, the thermal slurry flow sensor can improve overall process control.

1 INTRODUCTION

Instrumentation to detect the transition from fully suspended flow via sliding beds to the existence of stationary beds in pipelines is being developed by a consortium consisting of the CSIR, Paterson & Cooke Consulting Engineers (Pty) Ltd and Stoner (Pty) Ltd. It is based on a thermal slurry flow sensor to detect the bed-load velocity at the pipeline invert. Once it has been fully developed, it will be possible to install the instrumentation and use the method at strategic locations on pipelines to optimise tailings disposal operations. Figure 1 shows the overall integration of an in-line thermal flow probe signal to manipulate the slurry make-up parameters in the upstream thickener and the subsequent pumping operations, thereby reducing water and power consumption.

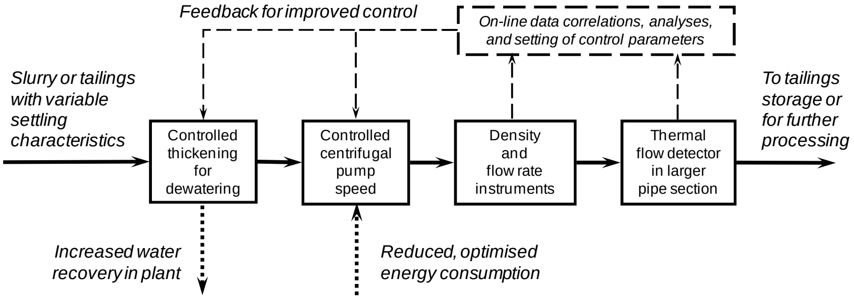

Figure 1: Improved control opportunities with bed-load measurements

This concept of feedback control relies on the ability to detect the onset of sliding or stationary bed conditions without compromising the stable and reliable operation of the slurry pipeline system. The thermal flow detector can be installed directly in the operating pipeline or, alternatively, it can be installed into a short pipe section with a slightly larger internal diameter to indicate near-settling conditions before they occur in the slightly smaller main pipeline sections.

2 BRIEF LITERATURE REVIEW

The relative change in electrical conductivity between various electrodes mounted on the internal pipe wall is often used to calculate the in situ solids concentration. This technique can detect significant changes in the in situ slurry density between the high-density stationary bed conditions and the lower-density medium flowing above it. Evidence has also been provided that the stationary bed in a pipeline does not have a flat, horizontal interface with the slurry flowing above it, although it is often depicted as such in the literature. The four images in Figure 2 from electrical resistance tomography show clearly the transition from an even density distribution at a high mean velocity of 4.5 m/s for pseudo-homogeneous flow conditions to a large stationary bed condition at 1.23 m/s. The sand slurry concentration by volume (Cv) was 18%.

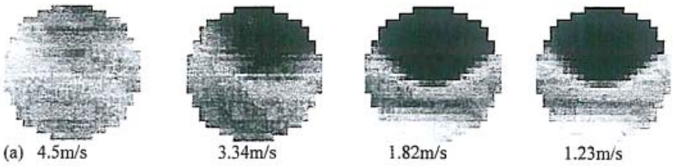

Figure 2: Concentration tomographs for sand slurry, [1]

For most cases, and in particular for large cross-sectional areas, a stationary bed may be inferred from this concentration tomography. However, the existence of a very narrow, erratically sliding bed of, say, 10 mm width and 1 mm thickness at the very invert of the pipe (e.g. the point of onset of deposition) may not be detected by this method.

A method more focused on a narrow point at the pipe invert was presented by Shook et al. [2]. The potential applied was varied to maintain a small controlled alternating current of 0.5 mA at 1 000 Hz between the two field electrode (f) placed along the pipe invert (see Figure 3). The voltage signatures across the two sets of sensing point electrodes (s) were then analysed to determine both the in situ solids concentration and the velocity of the sliding bed. The pipe with the electrode arrangement was rotated to measure point velocities and point concentrations at various angular positions along the inner pipe circumference. As expected, the points with the highest solids concentrations and correspondingly lowest point velocities were recorded at the pipe invert. The point velocities and point concentrations at different angular locations around the inner pipe circumference were correlated with wear rates. The measurements confirmed that there was substantial particle contact and movement directly at the pipe wall. In particular, they confirmed that a higher concentration does not necessarily indicate stationary bed conditions. This phenomenon of particulate, sliding flow along the immediate wall surface is now the basis of the thermal bed-load measurements, which rely on different modes of heat removal directly from their contact face with the slurry to perform best.

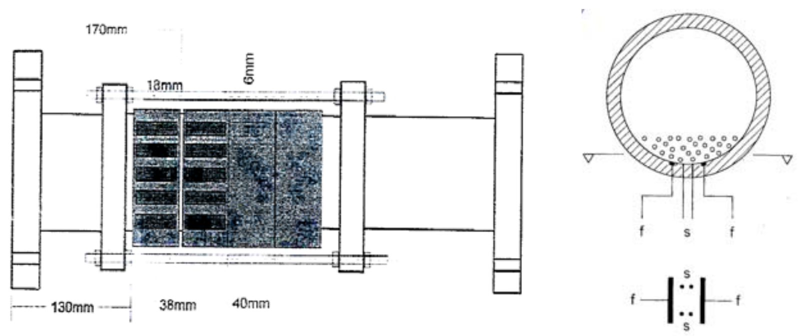

Figure 3: Sensor configurations for tomography and for point velocities, [1] & [2]

Many other techniques have in the past been tried to obtain an electronic signal relating to the local velocity of the bed-load at the invert of pipelines transporting settling slurries [3]. The information obtained was used mainly in R&D organisations to calibrate predictive flow models, including the well-published two-layer model approach. However, many of these detection instruments are rather fragile and require interpretation, and are thus not available commercially.

One commercially available high-tech solution to detecting the onset of sliding and stationary beds is CiDRA’s SandTrac© technology. It is based on a complex sonar array technique and is installed by “wrapping the instrumentation like a blanket around the pipe”. Velocity profiles across the entire pipe diameter can then be calculated and alarms can be raised if thresholds are violated [4]. There are many more benefits obtainable from using the sonar array-based technology on a pipeline than simply the detection of stationary solids at the pipe invert, and therefore the technology is rather expensive. To provide a lower-cost alternative, it was decided to investigate the performance of thermal probes, customised to detect the bed-load motion and stationary bed conditions directly at the pipe invert.

3 THERMAL PROBE CONCEPTS

3.1 Initial configurations

Thermal probes are generally small and thus they can focus on the conditions directly at the pipe invert. Currently available thermal flow probes such as the t-trend from Endress & Hauser and the flow captor from Weber which are intended for use with water or other “clean” fluids have been tested with slurries. They proved that the concept of thermal probes can work well to detect sliding or settled bed conditions at the invert. However, they are not designed to provide a long service life in a harsh slurry environment. Therefore, various new concepts for thermal probes for slurry application were conceptualised and evaluated.

Two fundamentally different configurations of how a thermal probe can interface with slurry at the pipe invert are shown in Figure 4. They are referred to as "counter heat flow" and "point heat exchange" in Table 1. Both types can be manufactured in such a way that their curvature matches exactly the curvature of the internal pipe diameter to avoid any interference with the particles sliding along the pipe invert.

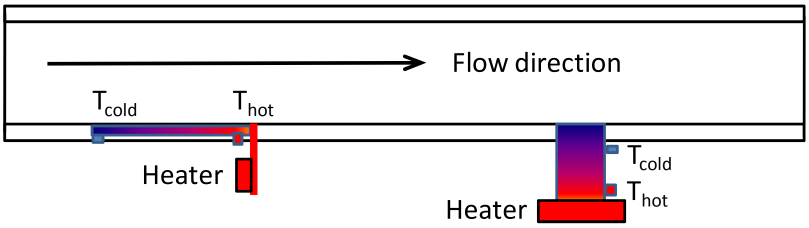

Figure 4: Initial configurations of thermal flow sensors in Perspex piping

There are some significant differences between the two configurations with regard to performance, control and practicality for manufacturing. Some of differences are summarised in Table 1.

Table 1: Comparison of initial configurations

Properties / Considerations	Counter heat flow	Point heat exchange
Heat transfer to slurry	Extensive	Limited
Temperature along contact face	Variable	Constant
Response time to disturbances (settled solids)	Very quick	Delayed
Calibration procedure	Complicated	Simple
Heat losses (offsets)	Low	High
Wear allowance	Poor	Good
Manufacturing aspects	Difficult	Easy

Both configurations require extra care and effort during manufacturing with regard to sealing of the components. The greater the heat difference is between the slurry and the heated components, the better the noise-to-signal ratio will be to detect the slurry's flow behaviour. The effect of a stationary bed on the power consumed to maintain a preset temperature differential must be sufficient that reliable thresholds can be set to enable predictable raising of alarms in the event of a stationary bed condition.

3.2 Controlled temperature differential

With the development of ever-smaller platinum heaters which offer footprints of only a few square millimetres, it is now possible to integrate small heated plates into a non-metallic pipe wall. The heater can be power-controlled to ensure that the metallic interface with the slurry has a sufficient heat differential to initiate forced convection. Once solids have settled on the heated plate, less power is required to maintain the same temperature differential, as the heat transfer is slowed down. The convective heat losses now become less dominant because the stationary bed acts as an insulator. As the bed thickness increases, the heat flow through the bed decreases. More heat is now dissipated into the surrounding pipe wall and into the bed itself. Once the bed is about 15 mm thick, the sensor becomes insensitive to flow rate changes.

Figure 5 shows such a “heated, metallic plate”, curved to match the pipe internal diameter and integrated into a Perspex pipe. The heated plate was 7 mm in diameter and had a small thickness of 1 mm to provide an effective geometry for maximising desired convective heat losses into the slurry and for minimising undesired conductive heat losses into the pipe wall. The metallic plate was equipped with a mini-heater (footprint of 9 mm^2) and a high-resolution temperature sensor. The control method is based on a temperature differential between the heated plate and the slurry.

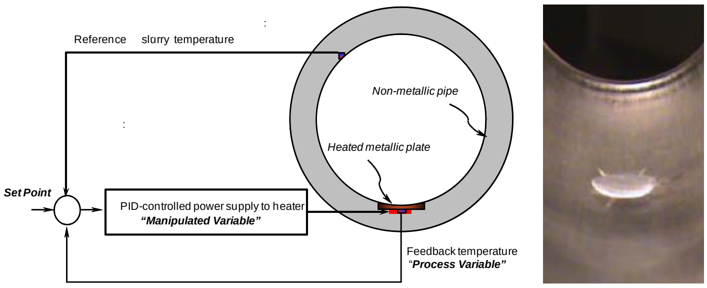

Figure 5: Heated plate with controlled temperature differential

3.3 Comparison of concepts

The initial, simple configurations proved the concept of thermal heat flow sensing in a slurry environment in principle. However, the components were relatively large, which delayed the response times. Nevertheless, various control approaches were evaluated and control parameters and temperature ranges for effective signal creation were established.

The major challenge was to select heaters with suitable response rates and power ratings. Appropriate drivers and high-resolution temperature sensors were required to balance the control methods with the dynamic behaviour of each mechanical layout.

There is no ideal thermal probe for all measurements and detection purposes. The dynamic transitions near the critical deposition velocity could be detected only with a very small fast-acting sensor. Although copper and aluminium interfaces offer fast response times due to their high thermal conductivity, such sensors would not last in abrasive conditions. When the sensor face is manufactured from stainless steel, the sensor’s response time and thus its sensitivity are significantly reduced. In addition, increasing the sensor face thickness to a few millimetres further delays the response times, but can be compensated for by using more sensitive temperature sensors.

4 EXPERIMENTATION

4.1 Laboratory tests

Initial tests to evaluate various concepts and control approaches were conducted in an NB40 test loop at the CSIR. The rig comprises a flat-bottomed mechanically agitated mixing tank, a variable speed progressive cavity pump, as well as density and flow rate instrumentation. On this small scale, particle size distributions can be varied quickly and a wide range of slurry concentrations can be tested within a short period of time. Coarser sand fractions can be added at any ratio and can then be removed via a wet screen arrangement.

Once a new development stage has been tested successfully in the laboratory, larger test spools are manufactured and tested in an NB150 pipe section. At the time of writing, some very interesting developments are being finalised and it is hoped to include these results in the presentation at Hydrotransport 18.

4.2 Full-scale tests

Paterson & Cooke's large NB150 slurry test loop at Weir Minerals in Alrode, South Africa was used to quantify the performance of thermal sensors for different slurry properties and various operating conditions. Thermal sensors were installed in two transparent uPVC test spools with 150 and 153 mm internal diameters to enable correlation of observed flow behaviour with the sensor signals. The idea of the two different internal diameters was to use the larger section as an early-warning indicator to detect settlement in the larger section before settlement occurred in the remaining sections of the pipe loop. When the flow rate was controlled within a small range, it was possible to have stationary bed conditions in the larger pipe section, while there was still fully suspended flow in the smaller section. This particular situation is shown in Figure 6.

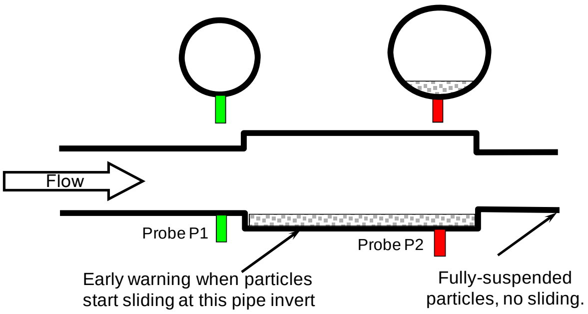

Figure 6: Concept for early settlement detection in larger pipe section

The two test sections with the probes installed at the pipe invert are shown in Figure 7. Additional probe holders are provided along the pipe circumference to obtain velocity distributions at the pipe wall at angular positions other than the invert.

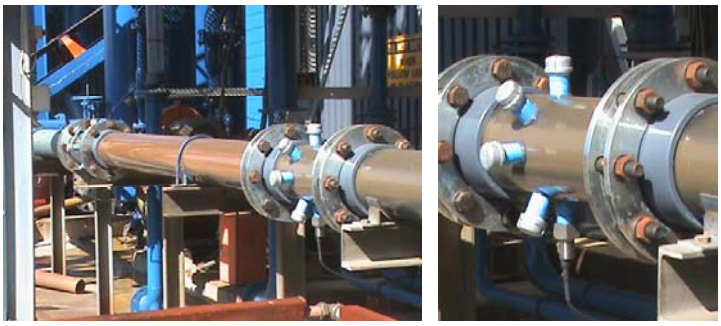

Figure 7: NB150 spool pieces with probes at invert at the Weir Minerals test site

The very small difference in diameter of 3 mm (IDs of 153 and 150 mm) was sufficient to create a stationary bed in the larger diameter section, while the flow in the smaller diameter section remained suspended. To demonstrate this sensitivity of the thermal probes in detecting such minute differences in the settling characteristics, the following procedure was adopted.

1) Adjust and maintain the flow rate as low as possible so that both probes are indicating suspended flow.
2) Decrease the solids concentration until settling takes place in the larger pipe section without changing the flow rate.
3) Further decrease the solids concentration until both probes are covered.
4) Increase the flow rate to remove stationary beds from covered probes.

4.3 Particle size distributions

The particle size distributions for both laboratory and full-scale tests were semi-hydrocyclone-classified gold plant tailings with a particle density of 2.7 t/m^3. They originated from different processing sites and their differences are shown in the distributions in Figure 8.

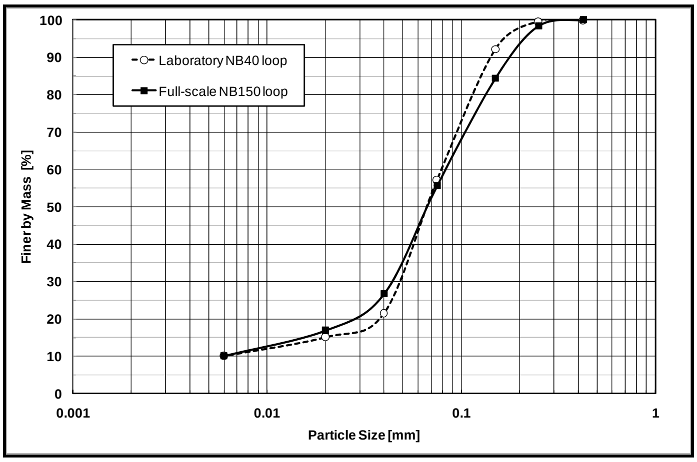

Figure 8: Particle size distributions of different tailings in the two test loops

A third slurry type was used during comparison of the probe's signal with direct observation of settlement in the Paterson & Cooke laboratory, as shown Figure 10. The particle size distribution of this sample can be described as a coarse crushed ore product with 2 mm top size.

5 RESULTS

5.1 Detection of settlement due to water addition

Once the flow rate in the NB150 pipe loop had been adjusted and maintained at around 20 litres/s, which was just above the critical deposition velocity for the tailings at a concentration by volume of 22.4%, water was added very slowly. Figure 9 shows the timeline of adding water twice and the response of the thermal flow probes in the two pipe sections of different internal diameters. Five zones (A to E) are of interest and are characterised as follows:

Zone A: Cv = 22.4%: Both probes are indicating flow without settlement.
Zone B: Output of both probes increased slightly while water was being added.
Zone C: Cv is reduced to 21.4%: Probe 2 in larger pipe section is now covered with solids, while probe 1 in the smaller pipe section is indicating erratic sliding.
Zone D: Further addition of water to dilute the tailings to 20.7%.
Zone E: Probe 1 is gradually being covered with stationary solids, while the thickness of the stationary bed above probe 2 has further increased.

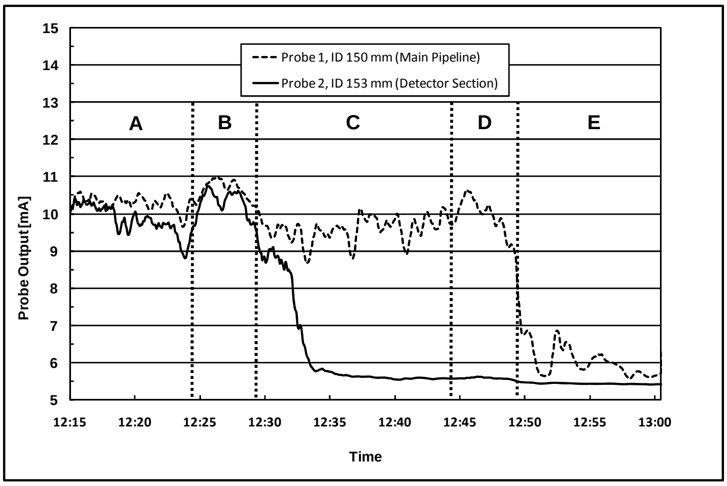

Figure 9: Detection of stationary bed conditions in sections with different pipe diameters

The initial water addition starting at about 12:25 briefly increased the flow rate from 20 to 21 litres/s. As soon as the flow rate had been controlled back to the set point of 20 litres/s, the particles started to settle out in the larger diameter pipe section due to the increase in deposition velocity for this slurry associated with the lower concentration. Thus, the output from probe 2 was drastically reduced to less than 6 mA, indicating the presence of a settled bed. Probe 2 was now covered with a thin layer of stationary bed, as shown in Figure 6. For this reason the initial "noise" associated with the transition range above the critical deposition velocity had also disappeared.

Probe 1 is in the smaller diameter pipe section and there are still a lot of dynamic transitions evident in the unsteady output, but there is as yet no stationary bed in this pipe section. This exact condition, when the output of probe 2 is "low" while the output of probe 1 is still "high", relates to the operating condition with minimal pressure losses in the main pipeline.

The further reduction in the slurry concentration starting at about 12:45, from a concentration by volume of 21.4 to 20.7%, again resulted briefly in a small increase in the flow rate. As soon as the flow rate was readjusted to 20 litres/s, solids also settled in the smaller diameter pipe section. Probe 1 was now also covered with a thin layer of stationary solids. Both probes were now "low", whereas initially they were both "high". The signal change was large enough to allocate a threshold anywhere between 6 and 9 mA to trigger alarms.

If the probe threshold is set at 7 mA, the probe's signal can be readily processed to provide any of the three following conditions to initiate, if desired, corrective actions:

1) Both probes above 7 mA: "high-high" →Reduce flow rate (and increase density if necessary to maintain mass balance).
2) Both probes below 7 mA: "low-low" →Increase flow rate.
3) Probe 1 "high" and Probe 2 "low" → Pipeline operates at or close to optimum in terms of energy consumption per unit mass of solids transported.

Thus the instrumentation can provide a straightforward means to manipulate the flow rate and to operate a pipeline safely at reduced pipeline pressure losses, closer to the deposition velocity.

5.2 Comparison of the probe signal with flow observations

Further test work was conducted at Paterson & Cooke's Westlake Facilities in Cape Town in another NB150 test loop to determine the correlation between the deposition velocity, observed by skilful and experienced test personnel, and the output of the thermal probe.

The flow loop tests were conducted with coarse material over a wide range of slurry densities. The mean velocity at which observed deposition occurred was recorded independently from the probe's output signal and was only compared with the observation afterwards to eliminate bias. For this slurry type and test configuration, an initial threshold of 3 V was selected (NB: the mA output signal from the probe was converted to a voltage drop for data logging in this case) to define stationary bed conditions. The correlation between the mean velocity relating to the observed deposition conditions and the mean velocity at which the output signal of the probe passed the 3 V threshold is shown in Figure 10 for a wide range of slurry densities.

A second threshold of 1.7 V is also plotted in Figure 10. Both thresholds confirm that indeed the output of the thermal probe relates to deposition velocities very similar to those recorded by visual observation. Furthermore, both thresholds clearly indicate the same trend of reduced deposition velocity for this slurry type as the density is increased over a wide range. It must be mentioned that the thermal probe head used for these tests was 20 mm wide and had not yet been optimised in terms of matching the pipe curvature.

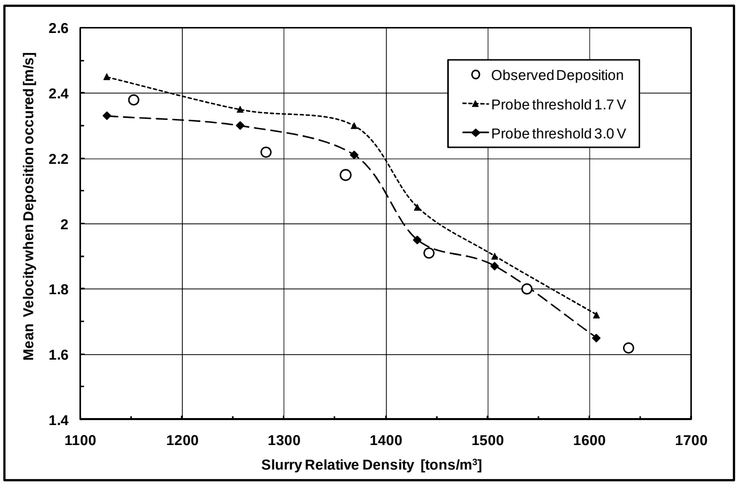

Figure 10: Correlation between observed and measured deposition velocities

5.3 Detection of unsteady conditions at near-deposition velocity

Fast-acting thermal probes have also been used in vertical slurry bubble-columns [5]. When an air bubble passes the thermal sensor, heat losses are lower than when water passes the sensor. Not only the frequency of passing bubbles, but even the relative size of the bubble can be detected from the responses of the thermal sensor. The same approach is applied to detect unsteady flow conditions at the pipe invert for settling slurry.

In order to detect the unsteady flow conditions associated with the erratic development of sliding beds, the power to the heater was kept constant to eliminate any possibility of temperature variations due to controller actions. The power level was adjusted to yield a difference of 15 ^{o}C in temperature between the heated plate and the slurry during fully suspended flow conditions at a flow rate of 60 litres/s.

The flow rate was then reduced linearly to obtain a continuous profile of the probe's response while the slurry behaviour at Cv 18% changed from fully suspended flow to stationary bed. At the end of the test run, about 50% of the 34 mm internal diameter pipe was filled with the stationary bed. The flow rate was decreased slowly to enable the full development of erratic bed motions at the transition from a sliding to a stationary bed.

Figure 11 shows the response of the fast-acting probe for three slurry flow conditions, e.g. fully suspended flow, erratic sliding, and stationary bed with increasing thickness.

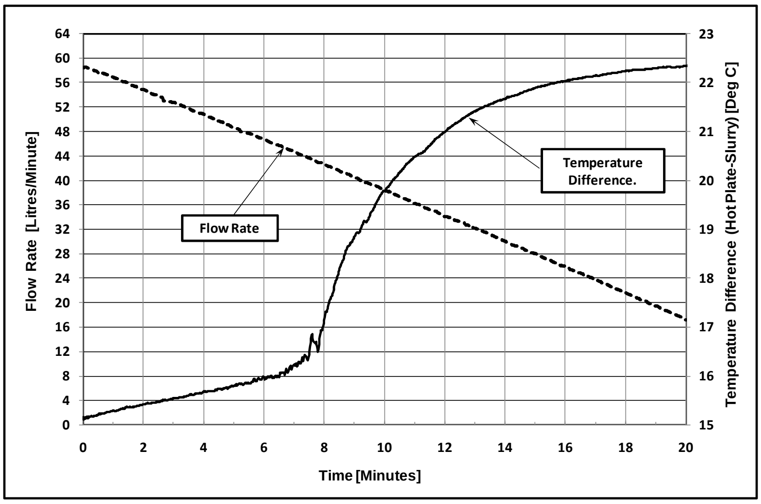

Figure 11: Detection of unsteady flow conditions

As the flow rate decreases, less heat is removed from the heated plate. Thus the temperature of the heated plate increases proportionally to the flow rate decrease, because of the constant power input. As soon as a sliding bed moves erratically over the heated plate, these flow dynamics can be detected from the temperature changes. As soon as the probe is covered over its entire 7 mm diameter, there is considerable heat build-up. Heat is then dissipated into and through the stationary bed before it is removed by slurry flowing above the stationary bed. As the bed thickness increases, the rate of temperature increase slows down until the temperature difference from the slurry temperature stabilises between 22 and 23 ^{o}C, as shown in Figure 11.

The constant-power configuration is ideal for identifying flow variations, but its response time is slow due to heating and subsequent cooling processes. For industrial designs, the heated plate would contain more mass and would be made from stainless steel with low thermal conductivity, which can both be compensated by appropriate power-input control methods.

5.4 Heat transfer coefficient with power-controlled heater

To improve response times, the temperature sensor mounted on the heated plate was used as feedback for a fast-acting controller, which now maintained a constant temperature difference to the slurry, as shown in Figure 5. The target temperature difference was controlled at 15 ^{o}C above the slurry reference temperature. With such a meaningful temperature differential, the temperature distribution across the 7 mm diameter heated plate can, for first-order estimates, be assumed to be even. This then enables the calculation of the average heat transfer coefficient between the heated plate and the slurry.

Figure 12 shows the change in the heat transfer coefficient due to the development of a stationary bed for two different slurry concentrations, as well as for water as reference.

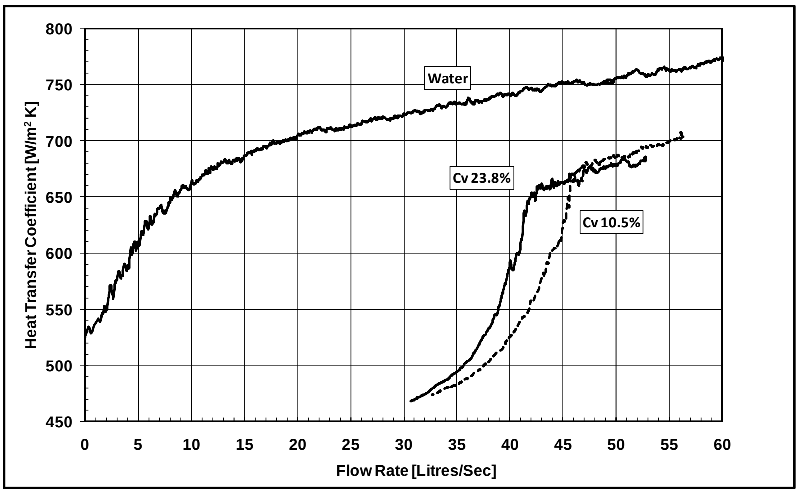

Figure 12: Clear indication of transition to stationary bed condition

The water curve is significantly higher as the heat removal of the slurry is lower than that of water only. The heat transfer coefficient for water flow is essentially linear and proportional to the flow in the range of practical flow rates. Both slurry curves display a typical sudden drop when the sensor face is covered with a stationary bed layer. The noise-to-signal ratio is very good for this probe, thus the threshold to raise an alarm can be set at around 600 W/m^2K for this particular slurry type and sensor configuration.

The configuration for controlling the power to the heater to maintain a given temperature differential can be scaled up to industrial pipe sizes with considerable wall thickness. However, the thermal properties of a specific slurry type need to be known to be able to design and build reliable thermal flow sensors to operate in an abrasive environment.

5.5 Wear considerations

Initial trials with commercial probes (intended for use with water or clean fluids) provide a slightly convex contact area at the sensing face, which is in direct contact with the abrasive slurry bed-load to be measured. When used with very abrasive slurry with particle sizes in excess of 1 mm and at mean velocities above 4 m/s, these probes showed considerable abrasive wear in a matter of hours. Even a thin titanium-ceramic coating did not provide adequate wear resistance. Other than the electrical and thermal operation of the probe, R&D work has also been focussed on designing an appropriate interface with the slurry to address the wear issues associated with operation in a slurry pipeline.

6 POTENTIAL APPLICATIONS

There are various possibilities for providing insight into the flow behaviour immediately at the pipe invert. Unfortunately, none of them can even compete with the interpretation ability of the brain of a skilled human observer using a transparent viewing section to characterise the changes in flow behaviour. However, for optimised process control, industrial instruments do not have to provide such complex information about the slurry flow condition at their interface. They simply have to be reliable, repeatable and be robust enough to operate in the slurry environment. As there is an ever-increasing tendency for process control and optimisation to include the less optimal process of tailings thickening and disposal operations, some feedback information from the invert of the pipe, even if it is just a basic “flow” or “no flow“ condition, would be useful.

6.1 Integration with metallurgical plant optimisation

A review paper by Hodouin et al. [6] about the “State of the art and challenges in the mineral processing industry” concludes that there is still a lack of sensors in mineral processing plants. Furthermore, there is a significant gap between available tools and actual exploitation of available data. With the variability of mineral ores and with improved ability to sense the actual process conditions, there is constant room for fine-tuning which must include the slurry make-up parameters and the pipeline operating conditions.

Once a sufficient database regarding the performance envelope and the variability of certain processes has been established and is accessible for control optimisation, more predictive monitoring strategies should be implemented to provide an early warning of abnormal situations, which may arise if no corrective action is taken within a sufficient warning period [7].

6.2 Early-warning device

For long pipelines in which settlement should under no circumstances take place, but which yet should be operated at pressure losses as low as possible, the thermal flow sensor should be placed at the pipe invert of a short pipe section with an internal diameter slightly larger than the diameter of the main pipeline. This is because any sliding bed conditions will occur there first before settlement takes place in the main pipeline.

6.3 Pipeline blockage detection

In its simplest application, the processed signal from a thermal sensor could be used to prevent pipeline blockages by raising an alarm as soon as the sensor is covered with a stationary bed layer. This would be a typical application for short transfer pipelines within plants. If required, the extent of the blockage can be quantified by equipping the spool piece with a few more sensors around one half of the pipe circumference, as shown in principle in Figure 7.

6.4 Slack flow

Under certain circumstances, pipelines may operate under slack flow conditions. This phenomenon can occur in a gravity-assisted backfill distribution system and can lead to excessive wear. Small thermal sensors installed at the invert, as well as in the upper part of the pipeline, can be configured to communicate the flow differential between the two sensors to a control room.

6.5 Energy and water savings

In the most advanced application, thermal flow sensors could be integrated with a control strategy that considers the region-specific costs of water or of electrical power. Based on those costs and historical data, the control methodology would manipulate the slurry pumping operation either to maximise water savings – even if it meant using more energy – or to operate the system to minimise power consumption – even if it resulted in an increase of water consumption.

7 FUTURE DEVELOPMENTS

The development of a thermal flow sensor for slurries which will eventually be suitable for industrial applications still requires further work and refinement.

7.1 Optimisation for response time, sensitivity and wear characteristics

As mentioned above, the noise-to-signal ratio of the thermal flow sensor is critical to provide a reliable signal as fast as possible. A thin and narrow sensing area at the invert would be fast and focused, yet a thick pipe wall may be necessary to provide the required wear and pressure ratings. Thus, thermal slurry flow sensors will have to be designed around that compromise. The sensors only have to be as accurate as necessary, and they can be as slow as the overall control philosophy can tolerate.

7.2 Thermal sensor flow modelling

In order to balance the mechanical design considerations for a thermal slurry flow sensor with the thermal heat flow dissipated into the slurry for various flow and no-flow conditions, it is advisable to do some numerical simulations. The model can be calibrated with data obtained from the laboratory spool pieces. Various material combinations, power levels, slurry types and flow scenarios can be simulated to arrive at optimal designs and performances for various duties.

7.3 Industrial trials

Once a robust thermal slurry flow sensor is available, it will be tested in industrial field trials. Each application will require integration with existing control methodologies to maximise the benefits. It is envisaged that in the long term, the simplicity of the thermal sensor measuring method will promote its multiple installation along pipelines as part of the standard design procedure to provide an effective pipeline monitoring and operating protocol.

8 CONCLUSIONS

Some concepts for using thermal probes to detect the flow conditions at the pipe invert have been presented. The response times to changes in the flow regime depend on the thermal inertia of the interface between the heating element and the slurry. While sensors with fast response times are able to detect dynamic transitions between sliding beds and stationary conditions within seconds, industrial sensors with higher pressure ratings and sufficient wear allowance require very precise temperature sensors and appropriate control methods to compensate for the increased thermal inertia of a thicker interface.

Although human observation and interpretation is still the simplest and most reliable method for characterising the dynamic transition from a sliding bed to fully stationary condition, this is only practical in the laboratory. For applications in industrial slurry systems a thermal flow sensor can provide a robust, repeatable signal that can be integrated into a process control philosophy. Compared with the more complex methods using sophisticated interpretations, thermal flow sensors are relatively simple and can be installed at many strategic locations to guard against undesired settlement in pipelines.

In view of increasing awareness of the need to optimise tailings disposal operations, the knowledge of the actual flow condition at the pipe invert can be exploited in many possible ways. The cost and complexity of methods to obtain this knowledge have to be balanced with the consequences of poor control and lack of detection.

9 ACKNOWLEDGEMENTS

This R&D project is financially supported by the South African Department of Science and Technology through its Innovation Fund. The valuable contributions from Joe Felix and many colleagues are much appreciated and acknowledged, particularly those from, Rob Cooke, Fritz van Sittert, Alan Rosewall, William Sebolai, Bethuel Nemakhavhani and Gideon van Zyl. Weir Minerals is thanked for allowing access to their slurry test facility. Endress & Hauser of South Africa provided the latest electromagnetic slurry flow meters for both the laboratory and full-scale test facilities.

10 REFERENCES

[1] PACHOWKO, A.D., POOLE, C., WANG, M. & RHODES, D. 2004. "Measurement of slurry density profiles in horizontal pipes by using electrical resistance tomography", *Proceedings, Hydrotransport 16*, 16th International Conference on Hydraulic Transport of Solids, BHR Group, pp. 481-495.

[2] SHOOK, C.A., MCKIBBEN, M. and SMALL, M., 1990. Experimental investigation of some hydrodynamic factors affecting slurry pipeline wall erosion. *Canadian Journal of Chemical Engineering*, 68(1), 17-23.

[3] ILGNER, H.J., 2004. Innovative flow control philosophy, based on novel in situ measurements to reduce energy consumption for tailings pipelines. *Proceedings, Hydrotransport 16*, 16th International Conference on Hydraulic Transport of Solids, BHR Group, 497-511.

[4] MARON, R.J., FERNALD, M., O'KEEFE, C., VIEGA, J., BAILEY, T. 2008. New applications of sonar-based technology in the minerals processing industry: Velocity profile measurement and pipe wall wear monitoring in hydrotransport lines. V International Mining and Plant Maintenance Meeting, *MAPLA 2008, Santiago, Chile*.

[5] JHAWAR, A.K. and PRAKASH, A., 2007. Analysis of local heat transfer and hydrodynamics in a bubble column using fast response probes. *Chemical Engineering Science*, 62(24): 7274-7281.

[6] HODOUIN, D., JÄMSÄ-JOUNELA, S.-L., CARVALHO, M.T. and BERGH, L., 2001. State of the art and challenges in mineral processing control. *Control Engineering Practice*, 9(9): 995-1005.

[7] JURICEK, B.C., SEBORG, D.E. and LARIMORE, W.E., 2001. Predictive monitoring for abnormal situation management. *Journal of Process Control*, 11(2): 111-128.