Novel instrumentation to detect sliding and erratic bed load motion

Ilgner, H.J.
CSIR, South Africa

Abstract

Instrumentation was developed to detect the onset of sliding and stationary bed conditions for settling slurries by using non-invasive, external sensing heads. These heads were configured in such a way that suitable data could be obtained and processed online. Tests were conducted at different test facilities with metallic pipes providing internal diameters ranging from 40 to 150 mm, and with various pipe wall thicknesses between 2 and 18 mm.

While the clamp-on sensors were able to detect stationary beds on thick-walled pipes within a minute, only the 2 mm-thin spool pieces were able to detect erratic bed motions due to the sensors' fast response capability. This required additional features to focus the sensing area directly onto the pipe invert. The unique strength of this technique lies in its ability to distinguish between a moving bed, the sudden erratic stick-and-slip motion, and a completely stationary bed right at the pipe invert.

Test results ranged in accordance with volumetric concentrations of 11 to 36% and different particle size distributions. It is shown that when the mean velocity was very slowly reduced, the entire spectrum, including the erratic motion, was clearly recognisable from the data pattern. In fact, the pulsing eddies, recorded optically, coincided with distinct signatures in the data.

The clamp-on sensors can be deployed rapidly onto any pipe diameter without interrupting the pumping operations. As the thermal sensors do not work on rubber-lined pipelines, a novel industrial design was conceptualised to install such instrumentation between the couplings of lined pipelines. Such short, flange-type inserts can be manufactured from superior-quality steel to provide good wear resistance at the exact internal diameter of the lined pipes, and can be as short as 50 mm.

1 INTRODUCTION

The theoretical prediction of the conditions under which solids deposition will or will not occur in slurry pipelines is a critically important part of the pipeline design process and its operating philosophy. This challenge has been the subject of significant amounts of research in the field of slurry flow behaviour for decades. One of the early publications on this subject was by Carleton and Cheng in 1973 (1). Already then they were able to identify 55 different correlations for predicting the deposition velocity, which included rather wide definitions such as sliding bed velocity, saltation velocity, suspending velocity, deposit velocity, velocity corresponding to the minimum of the pressure gradient curve, velocity for homogeneous flow, standard velocity and laminar-turbulent transition velocity.

Since then, the well-known two-layer model has been developed and further refined, with many more theoretical predictions becoming available. However, to be accurate and relevant, they all require the input of the anticipated particle size distribution and the properties of the solids. If the top size of the solids, and more importantly the specific gravity of the solids, are not exactly known, the uncertainty of such theoretical models' ability to predict deposition velocities increases significantly.

A challenging estimation of the critical deposition velocity is being dealt with at the Pacific NorthWest National Laboratory (PNNL) in the US. Mildly radioactive waste has been stored in the Hanford Farm tanks for a considerable time. It now needs to be re-agitated and transferred by pipeline for further processing and storage at other sites. This led to a very comprehensive test programme in 2010, reported by Bamberger *et al.* (2), to evaluate a variety of instrumentation available to detect settlement that may occur during hydraulic transportation of such wastes. The key problem, which no other research organisation faces, was the unavailability of representative slurry test material. Thus, so-called 'simulants' had to be artificially composed, based on estimates of the properties of the re-agitated waste. Thus, particle densities and shapes are rather unpredictable. Unquantifiable chemical reactions may conglomerate constituents or change the flow properties during re-agitation or even during hydraulic transportation. Pipeline blockages with such wastes of the transfer pipelines buried below ground would be highly undesirable. The PNNL test programme identified customised instrumentation to detect settlement of these simulants under specified conditions. Then a gap analysis conducted by Wells *et al.* in 2011 (3) noted the concern as to whether the artificially chosen particle size distribution is "legally defensible". While the simulants, and their envelopes, are the best available options, there remains uncertainty and thus a high risk of blockage. This PNNL example demonstrates the need to detect settlement in pipelines, preferably with simple, cost-effective and robust instrumentation, which does not require calibration with slurries of known characteristics. The slurries used in this paper do not attempt to reconstitute such simulants; they are simply some typical South African waste products.

2 INSTRUMENTATION TO DETECT SETTLEMENT IN PIPES

Some novel instrumentation to detect the transitions from fully suspended flow via sliding beds to the existence of stationary beds in pipelines has been developed by a consortium consisting of the CSIR, Paterson & Cooke Consulting Engineers (Pty) Ltd and Stoner (Pty) Ltd. The South Africa Technology Innovation Agency (TIA) and the CSIR provided financial support to develop the initial prototypes and the processing algorithms. Weir Minerals South Africa provided access to their industrial-scale slurry testing facilities in Alrode, Johannesburg, to complement the pipeloop test work initially done at the test facilities at the CSIR in Pretoria and at Paterson & Cooke in Cape Town.

The instrumentation creates local hot spots at the pipe invert, Goosen *et al.* (2011) (6). A fast moving slurry convects heat away from the hot spot, whereas a stationary bed removes heat only by conduction. The different responses of the sensors to the slurry flow conditions are then processed online with specialised algorithms to derive scalable outputs, which can be used to set thresholds for triggering warnings or alarms. For slurry flow optimisation, the online signals can then be used as inputs for more advanced slurry make-up parameters to optimise the transport concentration, and/or for operating the pipeline at the most economical flow rate without the need for excessive margins to accommodate an estimated deposition velocity.

The basic layout of the test loop and the envisaged applications were described by Ilgner *et al.* in Hydrotransport 18 (4). The current paper presents the latest results achieved since then with various configurations for three different particle size distributions over a large range of slurry relative densities. The external sensors, which can be clamped onto the bottom of the pipeloop, are shown in Figure 1.

Figure 1: Clamp-on sensors at the 150 mm PCCE and the 40 mm CSIR test loops

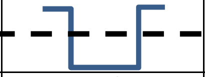
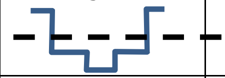
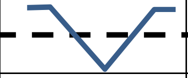
3 TEST PROCEDURE

3.1 Modes to vary the flow rate

In principle, four distinctly different modes were applied to vary the flow rate to study the responses from the instrumentation due to settlement. In itself, the settling of particles depended on the mode chosen, as well as on the rate at which the flow was gradually reduced. A sudden ‘full stop’ of the flow rate did not allow any stratification of solids prior to almost instant settling. However, if sufficient time was provided at flow rates just above the deposition velocity, the coarser particles were able to separate easily and settle out first, while smaller particles remained suspended in the upper pipe section.

Instead of the discrete step changes commonly applied to reduce the flow rate during slurry testing, a continuous ramp-down rate of the flow rate from fully suspended flow to a wide bed was found to be most suitable for characterising the various prototype instruments. The flow rate reduction could be varied at will and depended on the objectives of each test. The four modes and their representative patterns are depicted and briefly described in Table 1. The first three options (Modes A, B and C) include fully-suspended flow regimes at the beginning and end of each test run.

Table 1: Modes to change the flow rate around $V_{bed,}$ shown as dashed reference line

Mode V_{bed}	A ‘FULL STOP’ 	B ‘STEP’ 	C ‘RAMP’ 	D ‘HOVERING’ 
Charac-teristics	Forcing the fastest possible system response.	Sudden, medium bed, followed by full stop.	Ramp-down and ramp-up at various ramp rates.	Hovering around V_{dep}
Advan-tages	Evaluation of wall thickness effect on temperature trends.	Quick assessment of overall functionality and instrumentation ranges.	Shows entire slurry behaviour for settling, as no velocity is absent.	Demonstration of the sensitivity and repeatability to detect $V_{bed.}$
Disad-vantages	V_{bed} is not detected at all.	Sharpness of the transitions and ‘stick-and-slip’ remains unknown.	Thermal system may be too slow to react in time if rate is too fast.	Unknown overall signal-to-noise ratio, potentially large fluctuating signals.
Com-ments	Good for threshold settings and signal output range definition.	V_{bed} needs to be known beforehand, or can be assessed very quickly.	Rate of settling and sensor response improve with slow ramp rates.	Small bed width is required; good for repeatability & setting thresholds.

Viewing sections were used to verify instrumentation output with particle settlement.

For every new configuration of the instrumentation to be evaluated, a fast flow rate reduction was chosen initially to test whether the setting/range of the instrumentation could cover the entire spectrum of operating conditions. Consequently, during that assessment the transition from sliding bed to stationary bed was short and did not allow the particles to segregate freely. Once the instrumentation and data acquisition system had been adjusted and proven to operate satisfactorily, the ramp-down rate was reduced to allow the larger particles to segregate in the lead-in section upstream of the spool piece to provide a more representative transition from sliding motion to a stationary bed.

3.2 Particle size distributions

Three different particle size distributions comprising power station fly ash, cyclone-classified gold tailings and cyclone-classified platinum tailings were tested. The term 'cyclone-classified' refers to the fact that tailings were hydrocycloned at the mines to reduce the ultrafine content during backfill production. The reduction of ultrafines assisted in the settling behaviour and thus in evaluating and comparing the ability of different sensor configurations to detect the onset of pipeline settlement. The three particle size distributions are shown in Figure 2.

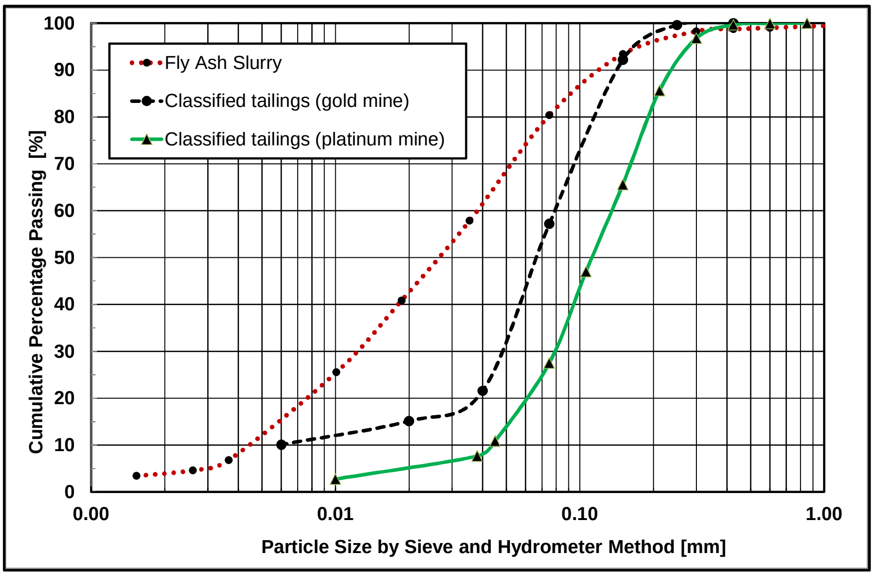


Figure 2: Particle size distributions

4 COMBINATION OF MECHANISMS FOR SETTLING IN PIPELINES

Often, the theoretical predictions for particle settling during pipeline flow are rather narrow in their application in terms of slurry relative density (RD) or slurry concentration. Consequently, the various slurry-specific test results published over the decades by different R&D institutions are often somewhat disconnected in their applicable ranges. In order to cover a wide range of slurry densities, Peter Goosen from Paterson & Cooke Consulting Engineers (PCCE) investigated the three different dominant phenomena, each associated with a particular flow behaviour that can cause settlement. The phenomena are as follows:

1) At low density, turbulent flow deposition is possible when a non-Newtonian carrier fluid exists with a coarse particle fraction, which is the contact-load.

2) At increased density, the transition from turbulent to laminar flow dictates the deposition velocity, and increased velocities are required as soon as the slurry RD increases, e.g. above RD 1.44 (Cv 26%) in his base case shown in Figure 3.

3) As less and less liquid volume remains available within the carrying vehicle to enable eddies to suspend particles at RDs above 1.68 (Cv 40%), the inter-particle contact becomes increasingly dominant and pipeline pressure losses increase rapidly, with further increases in density. As soon as the friction loss is greater than about 1.5 kPa/m, then it becomes the dominant property to governing and preventing stationary deposition. Particles are now pushed by inter-particle contact along the invert of the pipe, reducing the deposition velocity to almost zero.

The mathematical calculations for deriving the unique profile (thick dashed line) shown in Figure 3 are based on Goosen's approach, with links to Sanders *et al.* (5).

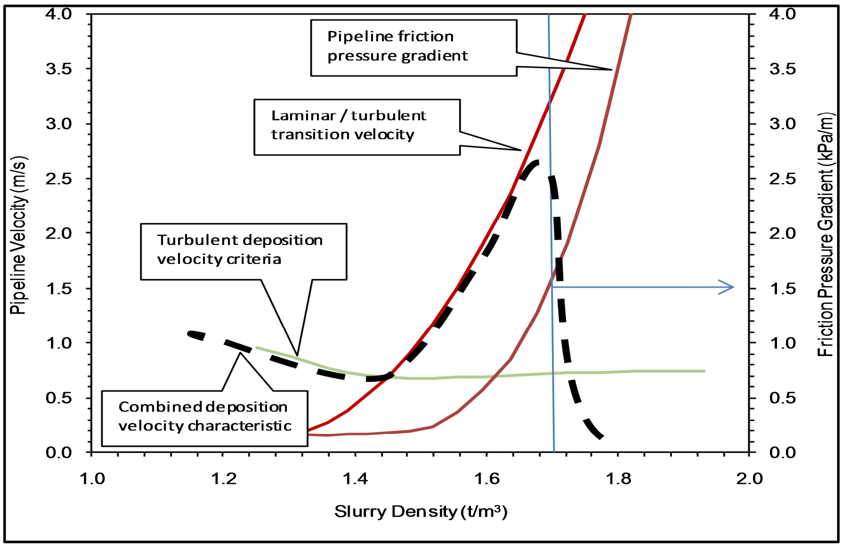


Figure 3: Three dominant settling mechanisms, depending on slurry relative density (Goosen *et al.*, 2011) (6), corresponding Cv scale: 0 to 58%

The combination of all three governing influences to cover such a wide RD spectrum was described in more detail and presented by Goosen *et al.* in 2011 (6). The existence and the extent of the peak at an RD of about 1.67 (Cv 39%) in this evaluation is significant as it is associated with a much higher deposition velocity when compared with both lower and higher slurry RDs.

The novel instrumentation with the clamp-on heads was tested over a similarly wide range of RDs and produced the same characteristic peak for all three slurry types. The solids density varied from 2 050 kg/m^3 for fly ash to 3 100 kg/m^3 for platinum tailings.

5 TEST RESULTS

5.1 Small NB40 mm loop with initial clamp-on sensor

In order to detect the entire transition from fully suspended particle flow to the development of a stationary bed, the flow rate was reduced gradually and continuously. The responses of the instrumentation for seven slurry densities are shown in Figure 4.

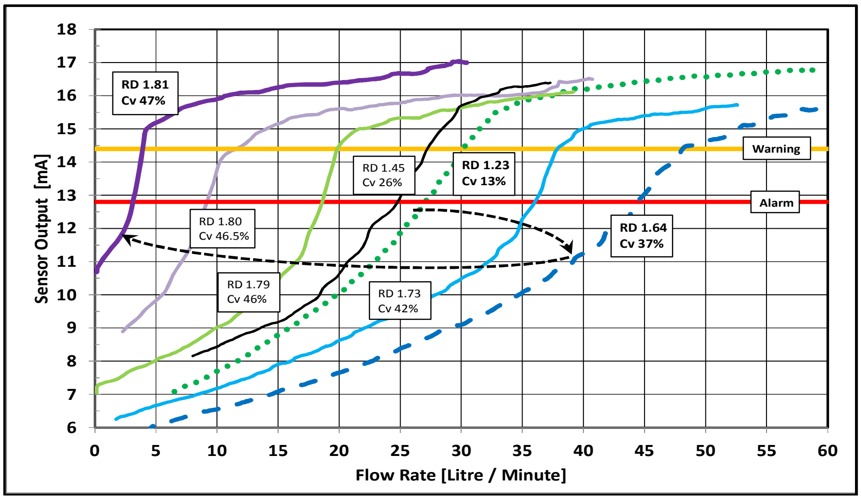


Figure 4: Indications from the instrumentation on 34 mm ID piping for classified tailings from a gold mine

The response at the lowest density of 1.23 kg/litre (Cv 13%) is in the middle of the array of data sets on the chart. The maximum deposition velocity was observed at a slurry RD of 1.64 kg/litre (Cv 37%) in the 34 mm ID pipeloop. Further increases in the slurry density then resulted in a significant reduction of the deposition velocity, mainly due to increased inter-particle contact.

A very sharp transition of the profile is evident at the highest slurry RD of 1.81 (Cv 47%). This indicates the abrupt stoppage of the high-density bed. The other curves still had a somewhat fuzzy transition towards stationary bed conditions. This was also due to the simple data processing in 2011. Further development to sharpen the transition with online data processing is currently under way and is showing excellent results.

Most curves show a gradual flattening at velocities far in excess of the deposition velocity. This resulted from a lack of sensitivity of the instrumentation at high flow rates due to the limited heating power provided. The latest prototypes provide higher heating power.

The solids material-specific and the slurry density-dependent deposition velocities for the small 34 mm ID pipeline are compared in Figure 5 for a wide range of slurry densities. The data points for the curves were derived from the same ‘alarm’ threshold setting (i.e. 12.8 mA in Figure 4) during the volumetric ramp-down tests shown in the previous figure. Additional test results for fly ash and platinum tailings can be found in Goosen *et al.* (2011) (6).

As shown in Figure 5, all three slurries tested follow an initially relatively flat trend where settling is governed by deposition under turbulent flow conditions at low RDs. The second region, that of steeply increasing deposition velocity with increasing slurry density, is associated with the onset of laminar flow conditions, as described earlier. A significant peak of the deposition velocities is visible for all three slurry types. At these slurry-specific densities the potential for particle settling is greatest.

In the third region, the deposition velocity decreases with increasing density. This is the region in which stationary deposition is governed, or prevented, by the friction pressure gradient criterion of a minimum of 1 to 2 kPa/m. This flow is typically characterised by a high-density sliding bed, sometimes associated with erratic stoppages. Deposition to the right of the peak velocity is associated with completely laminar flow conditions but ever-increasing pressure losses.

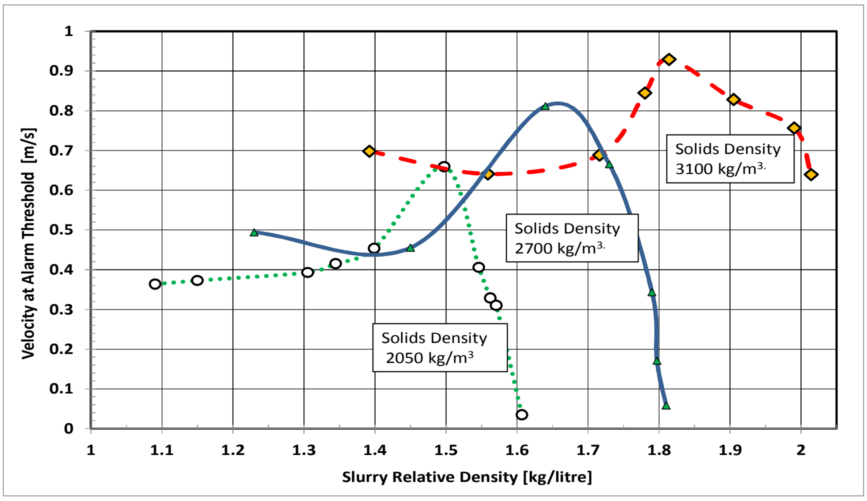


Figure 5: Deposition velocities for three slurry types in 34 mm ID spool piece

Strictly speaking, the Y-axes in Figures 4 and 5 are the ‘threshold velocities’ rather than the deposition velocities at which the instrumentation triggered the alarm. Thus the indicated velocities in m/s in this figure are slightly lower than the real V_{dep}, at which the very first particle became completely stationary. But the establishment of patterns and the detection of the peaks was the key intent in this assessment of the instrumentation.

5.2 Improvements to instrumentation

Two major changes were implemented to increase the sensing capabilities. The thermal heating power was doubled so that it would also be able to sense at mean velocities far in excess of the deposition velocity. The reference sensor and the overall data processing were reconfigured by adding a so-called ‘compensation feature’ to make the instrumentation independent of actual slurry thermal properties. This feature is complex and not covered in this paper.

A minor change was made in the data presentation. Whereas the previous output (Figure 4) from the instrumentation dropped when particles started to settle, the modified clamp-on sensors now have a baseline at 0% of full-scale output. Consequently, as soon as a stationary bed exists, the output will suddenly increase drastically.

5.3 Large NB150 mm spool piece with modified clamp-on sensor

The modified, more powerful sensing heads could now also be tested on thicker steel pipe walls. In order to measure the effect of different pipe wall thicknesses on the response of the instrumentation, a 2 m-long spool piece with an inside diameter of 132 mm was modified by reducing the outside diameter to obtain various wall thicknesses. Because the inside diameter remained the same along the entire spool piece, the sensors on the different wall thicknesses were sensing exactly the same settling behaviour. The nominal bore NB150 Schedule 160 ASTM 106 pipe was machined to six pre-selected wall thicknesses, i.e. 4, 6, 9, 12, 15 and 18 mm. Dimensions are provided in Figure 6.

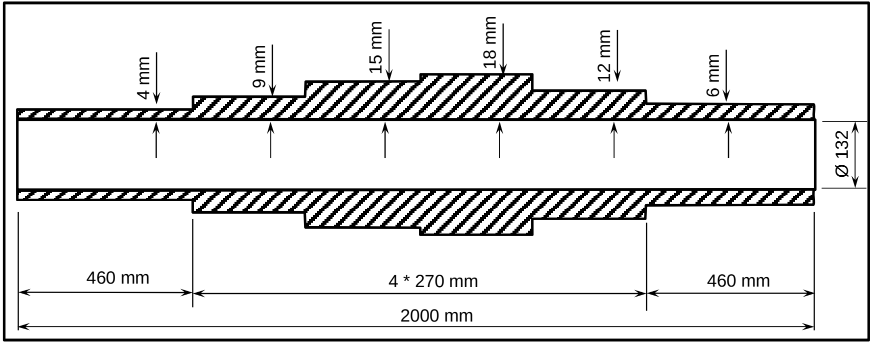


Figure 6: Dimensions of 'stepped' pipe spool piece for clamp-on heads

A large step change in the flow rate was chosen to obtain directly comparable responses from three sensors to quantify the influence of different pipe wall thicknesses. The response to a sudden stationary bed for three wall thicknesses is shown in Figure 7.

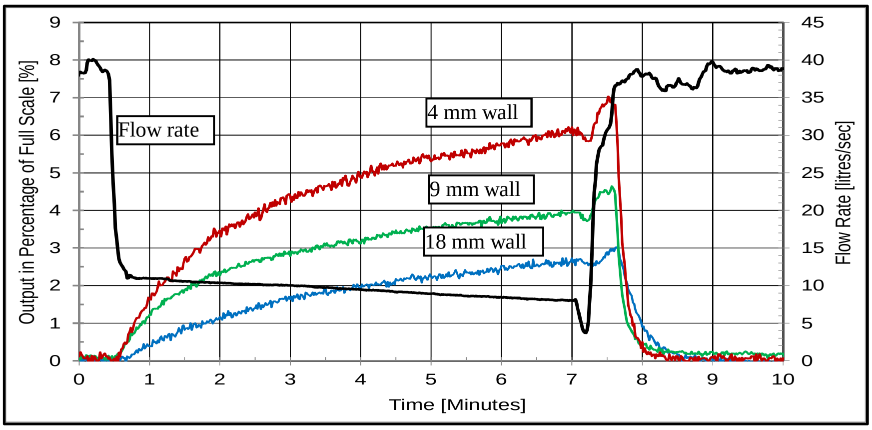


Figure 7: Responses to sudden settling above three different pipe wall thicknesses, RD 1.41, Cv 24%

The small fluctuation in the three signals after settlement is general noise from the unfiltered data from the instrumentation. The results indicate that, even with a pipewall 18 mm thick, the instrumentation was able to detect the existence of a stationary bed within one minute. More importantly, the modified data processing now provides a more distinct response to settling, as well to the removal of the stationary bed as soon as the flow rate increases again. This assists in setting more accurate triggers for warnings for further control responses without the need for calibration during installation on site.

The next modification to the sensing configuration was aimed at the detection of unsteady 'stick-and-slip' motion at the pipe invert. In this configuration, the signals were closer to the 100% limit and do not have the horizontal baseline shown in Figure 7.

5.4 Fast-response spool piece with recessed sensor on 2 mm-thin wall

The heating power capabilities were further increased to provide a better response to unsteady slurry bed motion. In addition, the interface between the sensor and the slurry (i.e. the effective wall thickness) was reduced to 2 mm to minimise thermal capacity and the associated thermal delay which would mask any sudden and erratic bed motions.

To increase the number of discrete sensors across the invert, seven recesses were machined from the outside into a stainless steel spool piece. Micro-heaters and temperature sensors were mounted into the recesses. The spool piece layout is shown in Figure 8.

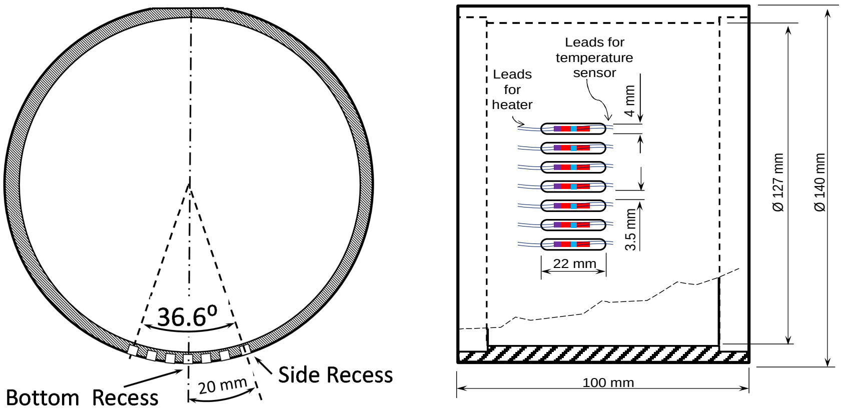


Figure 8: Layout of multi-recess spool piece

The individual cabling to the sensors with separate connectors, as well as the installation of the spool piece between two perspex viewing sections, and downstream of a long lead-in pipe loop section, are shown in Figure 9.

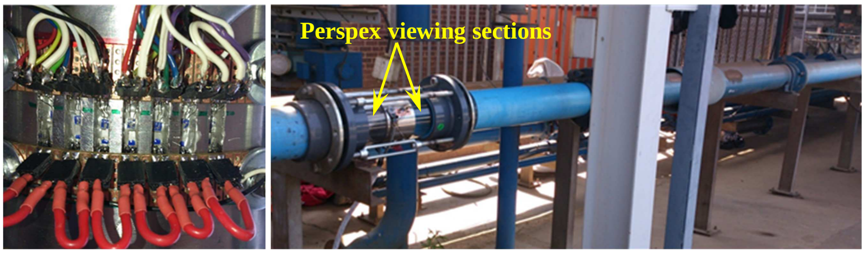


Figure 9: Multi-recesses and spool piece installed in NB150 mm pipe loop

The flow rate was changed in many different ways as shown in Table 1 to evaluate a broad spectrum of possible slurry settling conditions, in order to simulate as closely as possible those that could be expected in the field. Only the bottom sensor and far right sensor (i.e. side sensor) were used initially. Heating power was adjusted and the sensor signals were processed to derive the results presented below.

5.4.1 Delay between the responses of the bottom and side sensors

The side sensor was located about 20 mm away from the bottom sensor, which was located at the invert. Consequently, when the flow rate was ramped down gradually, the bottom sensor at the invert was covered with a sliding or stationary bed before the side sensor was covered. This delay was about 15 seconds in the 127 mm internal diameter spool piece, when the flow rate was reduced at about 0.13 m/s per minute. This shift between the two signals is clearly shown in Figure 10.

The ranges of the side and bottom sensors are separated vertically by 14% of their full scale, which enables good visualisation in Excel by using the same abscissa. This was necessary to include the mean velocity on the second abscissa.

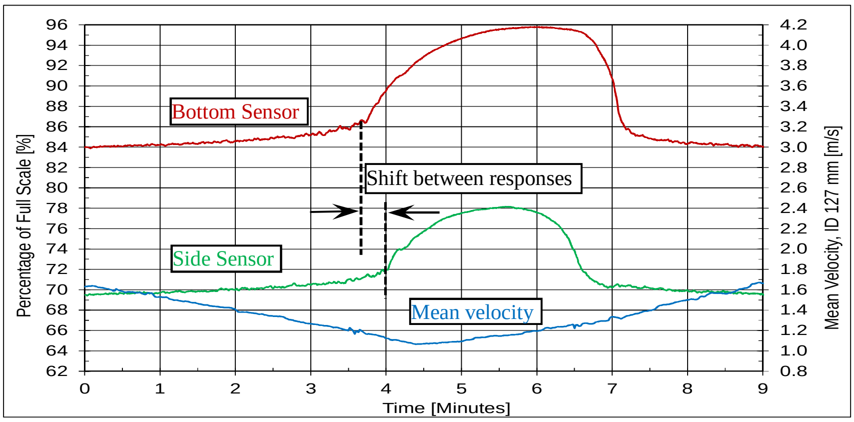


Figure 10: Responses of and shifts between both sensors, RD 1.43, Cv 26%

Both sensors indicate a gradual increase in unsteadiness due to sliding bed motion before the signals increase rapidly. At this point the uneven motion of the sliding bed changes to a stationary bed, which is clearly visible in both curves.

5.4.2 Effect of ramp-down rate on bottom sensor at RD 1.58, Cv 34%

The responses of the bottom sensor to three different, arbitrarily selected ramp-down rates, as well as to a sudden stop of the flow rate, are shown for comparison in Figure 11. The different rates are referred to as ‘fast’, ‘medium’, ‘slow’. This rate relates to the change of the reference speed for the variable speed drive of the centrifugal pump, which was gradually reduced to create a gradually and linearly reducing flow rate.

For clarity, only the responses of the bottom sensor are shown for a slurry with an RD of 1.58, Cv 34%. The durations of flow rate reduction from the initial velocity of 1.5 m/s to the left end of each curve are provided with the graphs as they dictate the settling behaviour in the pipeline and consequently the detailed response of the sensor.

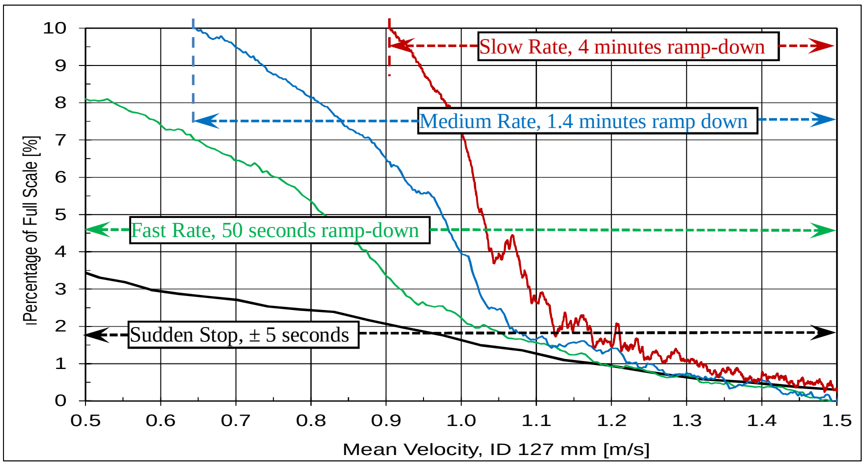


Figure 11: Effect of ramp-down rate on bottom sensor output, RD 1.58, Cv 34%

The results indicated that when the flow was reduced almost suddenly or at the fast rate, there was no time for the development of a sliding bed with its typical 'stick-and-slip' motion. Thus, during the 'sudden stop' test, when the flow meter already indicated a slow velocity of 0.5 m/s, the particles had not yet settled sufficiently to be detected. Thus the response for the sudden stop is almost a straight line in Figure 11.

As the rate of flow rate reduction was lowered in the above tests, there was more time available for the particles to segregate and settle, thereby establishing some sliding beds. These were formed predominantly by the coarser particles. The random motion of sliding beds was evident in the fluctuations shown for the test with the slow rate in Figure 11. To enable the curves to be distinguished, the results from the side sensor, which were very similar to those from the bottom sensor, are not shown.

5.4.3 Effect of slurry relative density on bottom sensor

Another important parameter affecting the settlement of particles during pipeline flow near the deposition velocity is the slurry RD. For this evaluation, the ramp-down rate was kept the same at about 0.15 m/s per minute, while the RDs were varied. The results for four test runs are shown in Figure 12.

All curves initially display a gradual increase, which rises progressively as the sliding bed slows down. The start of a sudden, strong rise indicates the velocity at which the bed eventually becomes stationary. The vertical arrows in Figure 12 indicate the exact mean velocities (i.e. 1.04, 1.28 and 1.47 m/s) at which the bed is completely stationary for the lower slurry RDs.

At the high slurry RD of 1.63 (Cv 67%) some erratic 'stick-and-slip" bed motion occurred over a considerably wide velocity range. Close to the deposition velocity, some occasional slip motion still re-occurred due to the high shear forces above the bed, before the bed became completely stationary.

In terms of time scale, it took about 10 minutes to reduce the flow rate gradually from 2.3 to 0.9 m/s in Figure 12. This custom instrumentation clearly detected the density-dependence of the critical deposition velocity and associated, erratically sliding bed motion.

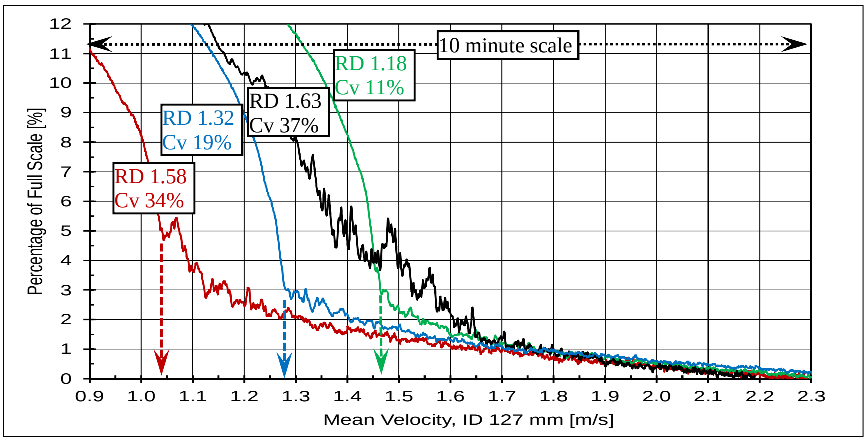


Figure 12: Effect of slurry relative densities on bottom sensor, slow rate

5.4.4 Effect of very slow ramp-down rate at high relative densities

With an even slower ramp-down rate of 0.02 m/s per minute both the bottom and the side sensor detected three different flow regimes. Little differentiation was possible between the bottom and the side sensor as the large size of the erratically moving lumps covered both sensors. At velocities above 1.85 m/s, the signals from both sensors were smooth and indicated no sliding bed. With decreasing velocity, the contact of sliding solids at the pipe invert increases, which causes the visible fluctuations of the signal. Just before the critical deposition velocity was reached, the bottom sensor signal reacted rather violently at 1.58 m/s due to the erratic motion of the sliding bed, as shown in Figure 13.

Once the bed is established and completely stationary, the signals become smooth again, e.g. below 1.5 m/s for the bottom sensor and below 1.35 m/s for the side sensor. It took about 37 minutes to reduce the velocity gradually from 1.93 to 1.25 m/s.

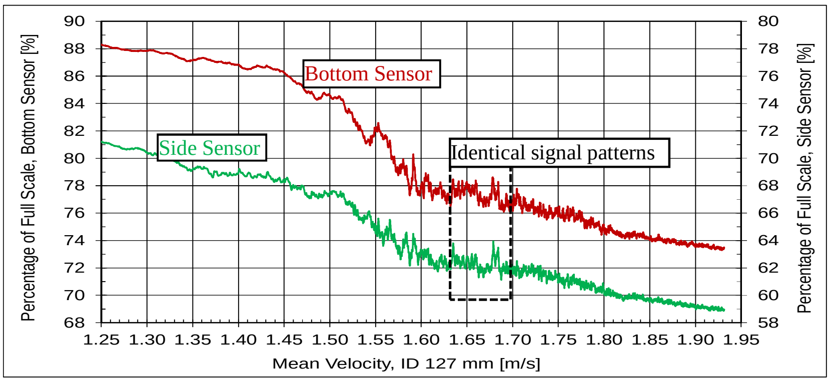


Figure 13: Indicated sliding bed, RD 1.61, Cv 35%

The dashed rectangle in Figure 13 above indicates unexpectedly high similarity between the actual patterns of the signals from the bottom and side sensors, which are only 20 mm apart on the pipe circumference. At that point both sensors measured exactly the same ‘stick-and-slip’ motion, between a mean velocity range of 1.62 and 1.69 m/s respectively, as the bed was wide enough to cover both sensors simultaneously.

The highest practical slurry RD was 1.63 (Cv 37%). It was tested at a ramp-down rate of 0.02 m/s per minute. As expected, this combination of test parameters created the most pronounced transition profile from fully suspended to fully stationary bed conditions, as shown in Figure 14.

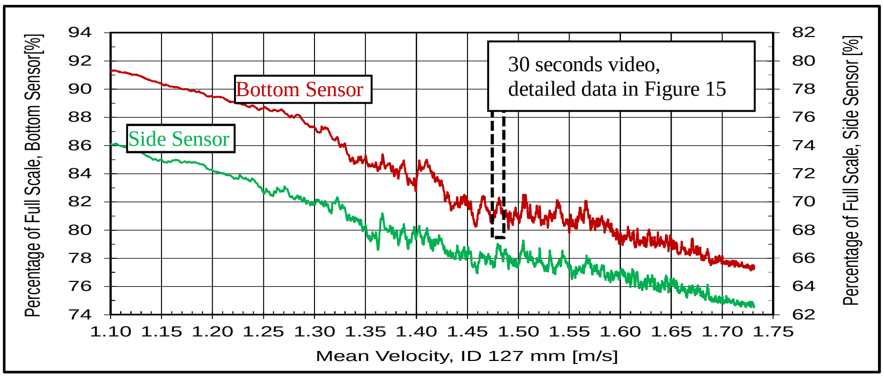


Figure 14: Measured erratic motion, RD 1.63, Cv 36.5%, 31 minutes duration

Unfortunately, no data exist for velocities above 1.73 m/s. The dotted rectangle in Figure 14 above indicates the part of the signal during which a 30-second video was taken of the sliding bed motion through the viewing section adjacent to the metallic spool piece, compare layout with Figure 9. The video shows distinctly the high-velocity eddies that appeared on average at intervals of 3 seconds, while the sliding bed moved steadily but very slowly. The occurrences of eddies synchronised exactly with the response of the sensor. This was verified with the time stamp of the data and the time recorded on a watch placed next to the viewing section.

A detailed 35-second window of the signal from the bottom sensor (sampled at 4 Hz) is provided in Figure 15. Local peaks represent relatively slower bed motion, whereas local minima coincide with the faster-moving eddies.

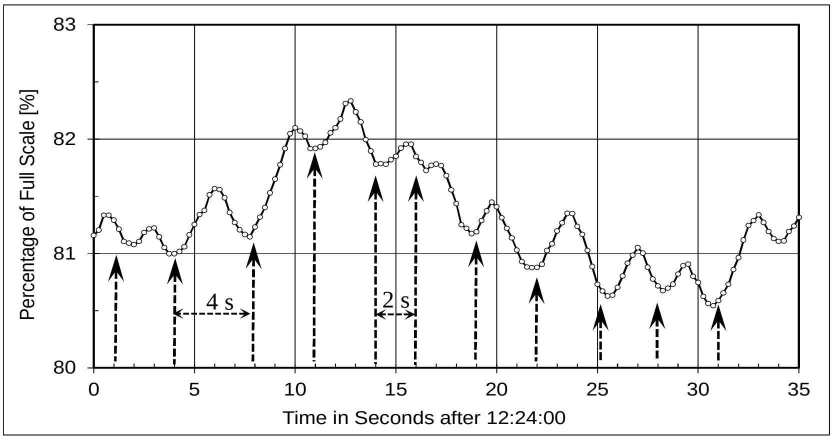


Figure 15: Observed 'eddies' and measured 'slips', RD 1.63, Cv 37%, mean velocity 1.48 m/s

Good correlation between the observed and measured eddies is evident. The fact that the two intervals, namely the 4-second and 2-second intervals shown in Figure 15, also correlated with the video footage confirmed that the video and data patterns refer to exactly the same time window.

6 PROPOSED INDUSTRIAL DESIGN

During the trials, it became clear that to achieve good thermal coupling of the clamp-on heads requires special care during installation. The other sensing option with small recesses on the outer pipe wall is also not a simple solution for retrofitting the instrumentation to industrial operations. The major limitation of this instrumentation, however, is that it does not work on rubber-lined pipes, as it requires a metallic interface between the sensor and the slurry.

To alleviate the above disadvantages, while harnessing the benefits of controlled recesses, a proposed solution (alternative spool piece) was developed and is illustrated in Figure 16. Due to its short length, it is still cost-effective even if it has to be manufactured from more expensive, wear-resistant metallic material while providing the required thermal conductivity between sensor and slurry. Being a custom-designed item, its internal diameter can be matched to that of a rubber-lined pipeline.

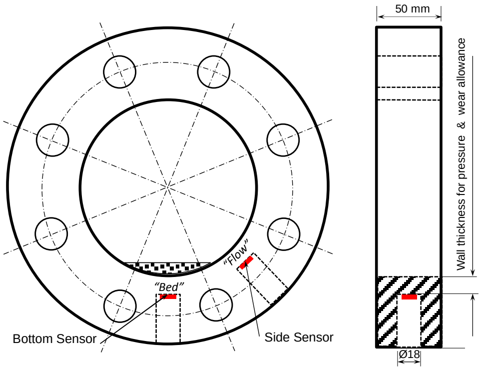


Figure 16: Proposed short spool piece for lined pipelines with two sensors

The side sensor can be used to sense the height of a stationary bed in those applications where a stationary bed is desired, but its extent needs to be limited to a preset and acceptable level. With regard to Figure 16, an alarm would be raised only if the side sensor detects a change from "flow" to 'bed" conditions.

7 CONCLUSIONS

Simple thermal clamp-on sensing heads and their data processing methods were developed, which can detect the density-dependent changes of the critical deposition velocity for different solids densities and particle size distributions over a wide range of slurry relative densities. The maximum wall thickness tested to date of 18 mm delayed the response time when compared with the 4 mm-thin wall. However, the signal-to-noise ratio was still very good and settlement was clearly identified within one minute in the thick-walled pipe.

Small sensors built into customised recesses to provide a 2 mm-thin interface with the slurry were able to detect the erratic stick-and-slip motion at the pipe invert. This configuration provided documentable insight into the dynamic transitions over the entire spectrum from fully suspended flow to a completely stationary bed.

This instrumentation cannot detect the very first onset of individual, stationary particles. Thus it cannot replace the value of human observations which can interpret the complex mechanisms involved in and during unsteady bed motion at the pipe invert, in addition to identifying the precise deposition velocity. The sensor, however, provides a unique signature describing the behaviour at the pipe invert over the entire velocity range.

The need to have a metallic interface between the slurry and the instrumentation does constitute a limitation. To enable installation on rubber-lined pipelines, short spool pieces of about 50 mm in length, made from wear-resistant material and having an internal diameter matching the internal diameter of the lined pipe, are recommended.

8 ACKNOWLEDGEMENTS

This R&D project was financially supported by the CSIR and the South African Department of Science and Technology (DST) through its Technology Innovation Agency (TIA). The valuable contributions from many colleagues are much appreciated and acknowledged. Weir Minerals South Africa is thanked for allowing extensive access to their slurry test facility in Alrode.

9 REFERENCES

(1) CARLETON, A.J. and CHENG, D.C., 1974. Design velocities for hydraulic conveying of settling suspensions. *Third International Conference on the Hydraulic Transport of Solids in Pipes,* pp. E5-57.

(2) BAMBERGER, J.A., BONTHA, J.R., ADKINS, H.E. et al., 2010. *Proposal: Hanford tank farms waste certification flow loop test plan for instrument evaluation.* U.S. Department of Energy, Pacific Northwest National Laboratory Report, PNNL-18936.

(3) WELLS, B.E., KURATH, D.E. and MAHONEY, L.A., 2011. *Hanford waste physical and rheological properties: Data and gaps.* U.S. Department of Energy, Pacific Northwest National Laboratory PNNL, Report PNNL 20646.

(4) ILGNER, H.J., GOOSEN, P. and DUMBU, S., 2010. In situ performance and potential applications of a thermal bed-load measurement method. *Proc. Hydrotransport 18, 18th International. Conference on Slurry Handling and Pipeline Transport,* Rio De Janeiro, Brazil, pp. 129-142.

(5) SANDERS, R.S., SUN, R., GILLIES, R.G., MCKIBBEN, M.J., LITZENBERGER, C. and SHOOK, C.A., 2004. Deposition velocities for particles of intermediate size in turbulent flow. *Proc. Hydrotransport 16, 16th International Conference,* Vol. 2, Santiago, Chile, pp. 429-442.

(6) GOOSEN, P., ILGNER, H.J. and DUMBU, S., 2011. Settlement in backfill pipelines: Its causes and a novel online detection method. *Proc. MINEFILL2011 Conference,* Cape Town, South Africa, pp. 187-195.