Paste 2018 – RJ Jewell and AB Fourie (eds)

doi:10.36487/ACG_rep/1805_11_Ilgner

Non-invasive sensor network to map stationary bed heights and moving dunes along pipelines larger than NB150

H Ilgner *Council for Scientific and Industrial Research, South Africa*

C Kruger *Council for Scientific and Industrial Research, South Africa*

Abstract

While the presence of stationary beds is generally regarded as an undesired operating condition, the recent monitoring of industrial pipelines with novel instrumentation has now revealed that beds indeed repeatedly developed under certain operating conditions. The smaller beds depleted routinely after process conditions returned to normal. However, as soon as bed heights increased beyond a certain value, pressures and flow rates were insufficient to prevent subsequent pipeline blockages.

This novel instrumentation is now being further enhanced in two ways. Firstly, additional sensors are mounted along the circumference of the pipe so that the actual bed height can be provided as a percentage of the pipe diameter and be used as a single parameter for bed control. Secondly, multiples of these sensor sets can be installed at key locations along the pipeline where settlement is expected. The results from all sensor sets are integrated online for visualisation to provide an instant overview of the actual bed conditions to the operator. In this way the pipeline can intentionally be operated safely with a known bed height. The effects of interventions deployed to change the bed height are immediately available for responsive process control. Based on the experiences from recent field work, the paper concludes with an assessment of trade-offs which were necessary to design a reliable wireless sensor network.

Keywords: *stationary bed control, online visualisation, wireless pipeline monitoring*

1 Introduction

Ever since solid particles have been transported as a slurry through a pipeline, their tendency to settle towards the pipe invert has been a concern to the most meticulous pipeline designers and operators alike. Although academics are advancing the science to model this unavoidable and complex phenomenon, their predictions are often confined to well-specified slurry conditions. Thus even the best results may not be readily applicable to industrial operations. Unfortunately, the multitude of variables and their collective effects, as well as occasional deviations from specified operating envelopes, result in undesired particle settlement, which often leads to pipeline blockages. This paper describes the results of novel instrumentation to measure settlement in industrial pipelines to not only prevent pipeline blockages, but also to minimise water consumption.

2 Sensing technologies

Various ultrasonic sensor techniques were evaluated by Bontha et al. (2010) to monitor settling of mildly radioactive wastes. Various institutions investigated nuclear magnetic resonance imagery, electrical resistance tomography, and electrical capacitance tomography. CiDRA's SANDtrac™ technology is based on sonar array technology. These techniques acquire large amounts of data in the kHz range, which need to be processed with complex algorithms. They don't seem to have a generic calibration, as changes in the slurry properties often require a recalibration. Consequently, only the CiDRA SANDtrac™ is reported to be commercially in use on some Canadian oil sand pipelines.

Thermal flow sensors have been investigated in the past in a number of configurations. Schreib (1984) and Romanet et al. (2005) used non-invasive, rugged arrangements to detect the transition from no flow to the commencement of flow.

Early experiments with thermal sensors in slurry applications were undertaken by Ercolani et al. (1979) and Kazanskij (1979). Ilgner (2005) presented a concept to measure a stationary bed at the pipe invert and even the bed height by using an off-the-shelf thermal flow sensor, protruding through the pipe, but flush with the inner pipe wall. Since then, customised sensors with little meta-oxide-semiconductor field-effect transistor (MOSFET) heaters and Pt100 temperature sensors were designed and mounted with a good thermal coupling at the outside of the pipe wall. This concept creates a hot spot on the inner pipe wall surface. The heat removal rate due to forced convection by the slurry, or the lack thereof when a stationary bed exists, can be sensed and is processed to derive at the prevailing state of flow, or beds in the pipeline. This concept has been implemented in the settled bed detector (SBD) as an industrial instrument on pipe sizes from NB125 to NB400. The SBD provides two online analogue outputs:

1. A 'flow signal' which gives an indication of flow or no flow. It does not provide a flow rate as such.
2. A 'bed signal' which gives an indication of the bed conditions at the pipe invert.

The magnitude of the response of the sensors depends on the overall amount of heat supplied, which can be controlled by pulse-width-modulation to match the pipe wall thickness. Thresholds need to be set to convert the analogue trends to digital states. An example is provided in Section 3.4.

Some inherent limitations of this thermal technology are that short metallic spool pieces are required for high-density polyethylene and rubber-lined pipelines, and that a minimum nominal bore of 150 is required.

3 Data from field installations to measure stationary beds

Two different re-circulating pipe loops (both NB150) and four industrial operations (NB180, NB250, NB350 and NB400) were equipped with the thermal sensing instrumentation on short stainless steel spool pieces with various objectives in mind. Less interesting installations of monitoring a hydrocyclone overflow launder and a conventional tailings pipeline are described in detail by Ilgner (2017). The following case studies present stationary beds detected in a mine backfill operation and in a magnetite product pipeline; as well as erratic sliding bed motion of thickened tailings, two pipeline blockage events and a configuration to measure the actual bed height.

3.1 Cemented backfill operations

Three different cemented mine backfill recipes are used to provide appropriate strengths for different mining applications. A multitude of speculations for the potential reasons for occasional pipeline blockages are readily given by plant and mining personnel. As insufficient data exist to identify the primary cause for these blockages, a SBD was installed underground some 3.5 km downstream from a flow and density meter on-surface. The idea was to merge all instrumentation data to obtain a more objective insight into the actual backfill operations. The backfill distribution system was operated in slack flow mode along the decline, which may result temporarily in a mismatch of flow rate measured on-surface with actual flow rate measured underground until steady state conditions are achieved.

The configuration of the SBD can provide an indication of flow or no flow conditions. A steady output of the 'flow signal' of 12 mA represents no flow, whereas an output lower than 11 mA indicates 'flow'. A stationary bed is indicated when the second output of the SBD, i.e. the 'bed signal', rises above 10 mA.

An inline pressure transducer is located 20 m upstream of the SBD in the underground haulage, providing independent data to complement the data from the SBD as well as from the flow and density meter on-surface. The underground line pressure in Figure 1 indicates the duration of typical backfill sessions, ranging from two to 12 hours. Line pressures above 1 bar associated with a flow sensor output below 12 mA indicate normal backfill operations. Figure 1(a) and (b) provides the sensor outputs which can be used to derive at four typical operational states at the location of the SBD, which are summarised in Table 1.

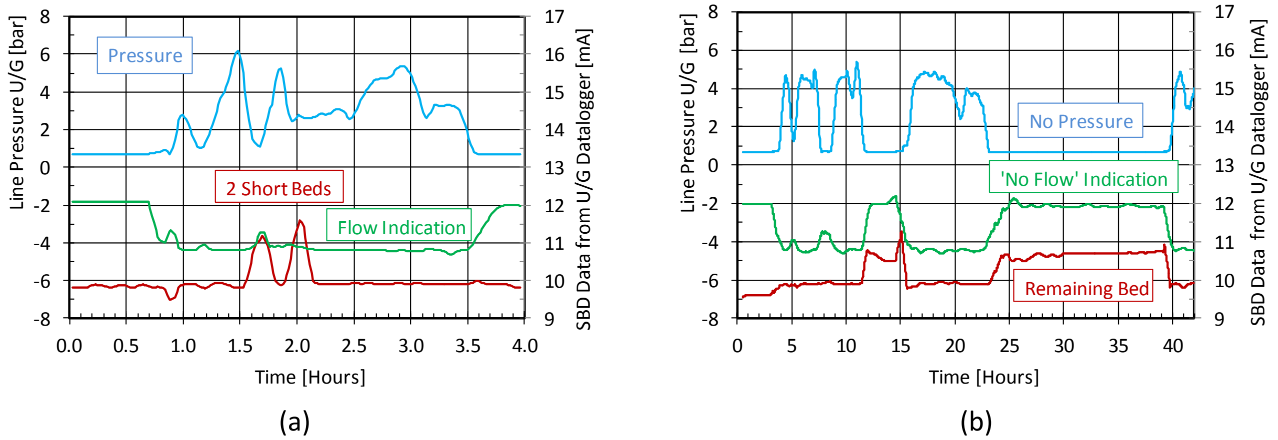


Figure 1 **(a) Two stationary bed events during flow; and, (b) Stationary beds remaining in the pipeline for up to 16 hours during a no flow period**

Table 1 **Derived states of the cemented backfill pipeline from sensor data at the location of the SBD**

State	Condition in backfill pipeline	Inline pressure	Flow signal	Bed signal
1	No flow, completely empty pipe	<1 bar	>11 mA	<10 mA
2	Flow with no stationary bed	>1 bar	<11 mA	<10 mA
3	Stationary bed during flow	>1 bar	<11 mA	>10 mA
4	Stationary bed during no flow	<1 bar	>11 mA	>10 mA

Note: The analogue signal for flow indication is high during no flow, and low during flow.

It is intended to integrate the various instrumentation outputs into an embedded intelligent system. The state of the backfill pipeline is then presented in a more user-friendly format rather than in analogue traces or as multiple digital states. Such unambiguous display of information will ensure effective intervention when required.

Figure 1(a) shows two stationary beds within half an hour in close sequence during a backfill session. The cause is most likely a combination of interdependent backfill properties, e.g. a coarser particle size distribution will promote settling, or a higher backfill density will increase the inline pressure and affect the flow rate. In this gravity-fed backfill distribution system with slack flow characteristics, more data will be required to identify individual causes of each sedimentation event.

An example of a backfill session temporarily interrupted within minutes of its commencement has resulted in a short-lived stationary bed during the no flow period. The sequence of event was reconstructed as follows and is shown in Figure 2.

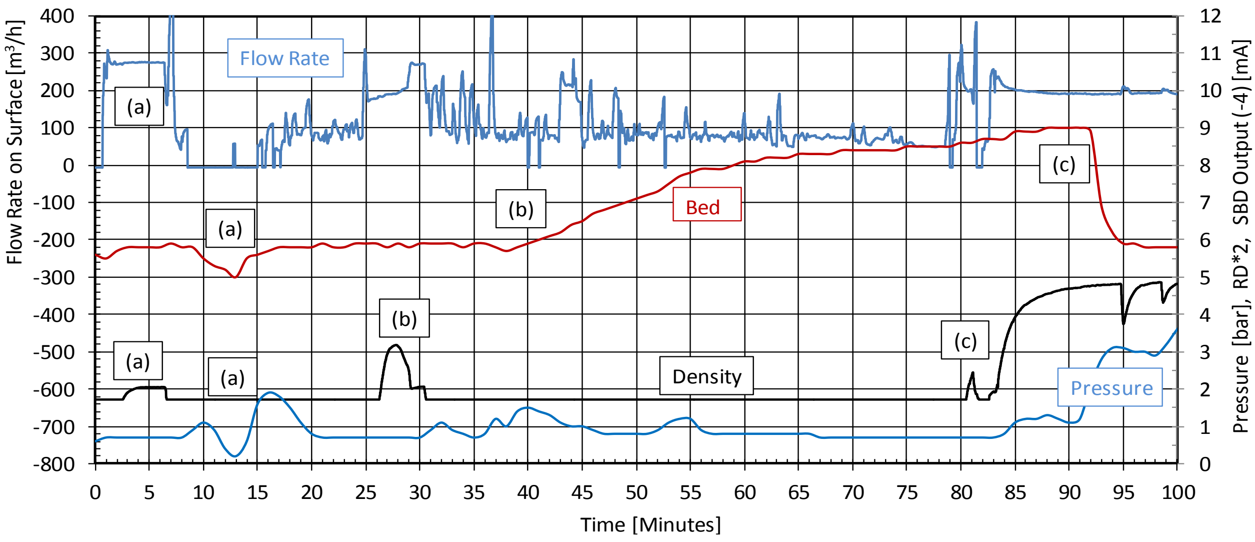


Figure 2 Interrupted backfill sequence resulting in a stationary bed (slurry relative density was multiplied by two)

The density meter and flow meter on-surface clearly indicate a water pre-flush. With a 10 minute long time lag between the instruments on-surface and underground, both the underground pressure sensor and the SBD reacted to the limited water batch being released into the pipeline (a). Only a limited backfill volume flowed for about two minutes, as indicated by a short rise of the density (b) on-surface. Without an effective post-flush, this backfill batch settled at the location of the SBD some 10 minutes later (b) in the underground haulage on route to the stope. An hour later, the backfill flow recommenced with the high backfill density (c), removing the stationary bed with ease (c). This entire sequence is shown in Figure 2.

Note that the mA data for the bed signal had to be reduced by 4 mA to provide more clarity of the four trends in Figure 2. Thus, the 6 mA level actually equals the 10 mA level in Figure 1.

Although there is a systematic time lag between the surface and underground events, the data analysis improves the understanding of the dynamic system behaviour in terms of time delay and typical sequences. Overall, the outputs from the SBD contributed to the reconstruction of events associated with a backfill session start-up failure.

3.2 Erratic bed load motion of thickened tailings

The pipe wall thickness and the heating levels dictate the dynamic response of the externally mounted sensors to the varying flow conditions at the inside in the pipe wall. In order to measure stick-and-slip motion of an erratically sliding bed, a pipe spool piece with a very fast response time was manufactured. The multiple sensing points consisted of small pockets, i.e. recesses into the pipe wall to provide a 2 mm thin pipe wall section to ensure the fastest possible response. This geometry of seven recesses, symmetrically distributed across the pipe invert is shown in Figure 3. Unfortunately, the thermal hot spots were too close to each other and this created undesired thermal interference. To eliminate this thermal cross-talk, only the sensor at the pipe invert and the outermost side sensor were thermally excited and their temperature sensed. The gap between the 4 mm wide pockets was as narrow as 3.5 mm. Figure 3 shows the geometry, the as-built sensors and the thermal cross-talk when all seven heaters were powered up.

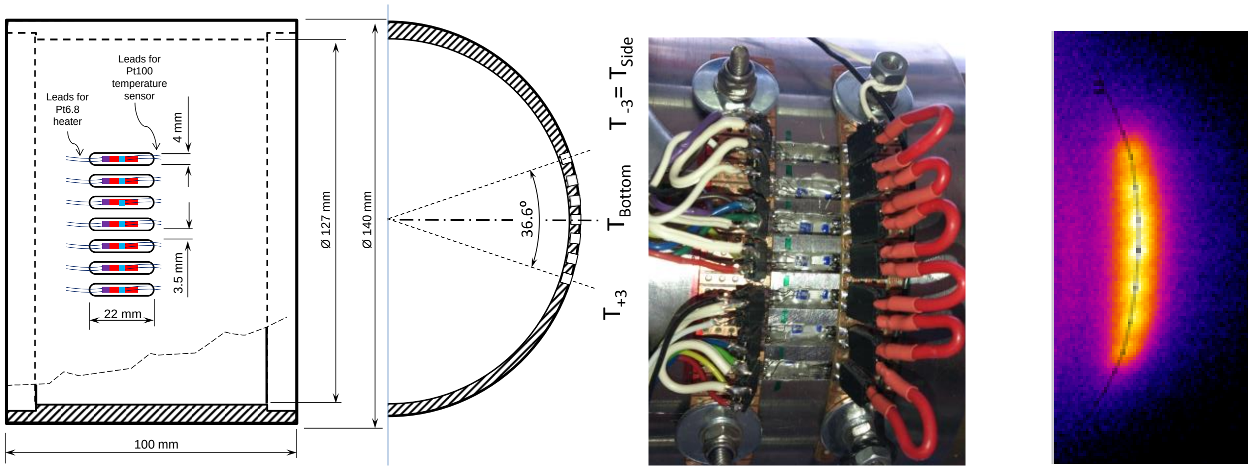


Figure 3 Spool piece with seven recessed sensor pockets across the invert to measure sliding bed motion

The flow rate of the thickened gold tailings was continuously reduced at a rate of 0.1 m/s per minute to capture the onset and changes of the sliding bed motion. Thus, the charts presented in Figure 4 relate to a 12 minute time span. This method created analogue signatures from both the bottom and the side sensor to describe the concentration-dependant bed motion prevailing at different mean velocity ranges. The dotted lines in Figure 4 represent typical constructs for the tailings at a low concentration at which particles would settle suddenly without an erratic stick-and-slip motion. The area between the black dashed and dotted lines define the effect of the higher tailings concentration. Smooth particle sliding occurred at mean velocities between 1.7 and 1.9 m/s, and was characterised by a slightly elevated temperature when compared to the dotted reference line. A further reduction of the velocity to 1.5 m/s introduced occasional stoppages of the moving bed, associated with a temperature increase of about three degrees. While the velocity was decreasing even further, the frequency of the stoppages increased, as observed in the viewing sections adjacent to the metallic spool piece. Eventually, at mean velocities below 1.4 m/s, the bed became completely stationary, resulting in a significant temperature increase due to the absence of heat removal by a moving bed.

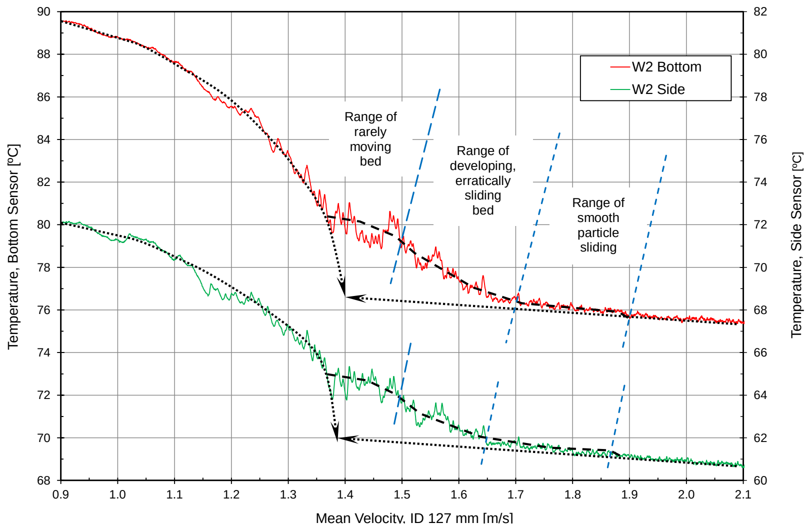


Figure 4 Ranges of bed motion for thickened tailings during gradual reduction of flow rate

The thin sensor wall provided interesting insights to advance the understanding of the transition from fully suspended flow to a sliding bed state and eventually to a stationary bed. Thicker pipe walls would still be able to distinguish between sliding and stationary beds, but individual, short-lived stick-and-slip events will not be detectable. Response times for 18 mm thick pipe walls (NB150 schedule 160) to detect stationary beds were quantified to be in the order of one minute (Ilgner 2014).

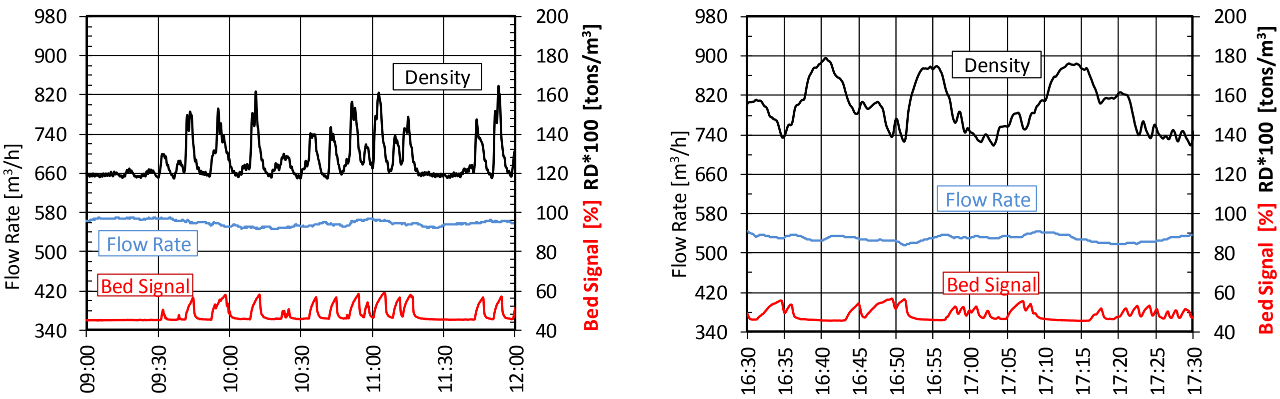
3.3 Effect of relative density changes of a magnetite slurry

Dry granular magnetite material (specific gravity 4.2) is reclaimed from a surface storage facility by a dozer and mixed with process water for wet processing. The inconsistent feed preparation and very limited pump control instrumentation creates a wide range of flow and density fluctuations in the centrifugal transfer pump system for the NB250 pipeline. The mine endeavours to maximise the slurry relative density, as the magnetite needs to be dried in evaporation ponds prior to further shipment. An SBD with wireless communication was installed at a strategic location to quantify the incidences and extents of stationary or sliding beds. This monitoring instrumentation will assist ultimately with the implementation of a more controlled high-density pumping operation not only to save water but also to improve turn-around-times at the evaporation ponds.

Additional process data to improve the understanding of the system behaviour are provided by a CiDRA sonar array flow meter and a nuclear densitometer, as shown in Figure 5. They are installed some 30 m upstream of the SBD in close proximity to the pump station.

Figure 5 Flow meter, inclined density meter, control unit and installed short spool piece

Some interesting correlations between the relative density of the magnetite slurry and the stationary bed conditions were identified. Small temporary increases of the slurry relative density (RD) above RD 1.4 created short-lived stationary beds while the flow rate was relatively stable, as shown in Figure 6(a). However, temporary increases to an RD of 1.70 and higher resulted in higher shear rates which consequently removed the stationary beds established at lower RD with ease (Figure 6(b)). Similar effects of reduced deposition velocities with increasing density up to a paste consistency were detected with fly ash slurries, as presented and analysed by Goosen et al. (2011). Note that in Figure 6 the density value was multiplied by 100 to fit onto the same axis as the other signals.



(a) (b)

Figure 6 Relationships of short-lived stationary/sliding beds with slurry density fluctuations; (a) Stationary beds were initiated when density increased above RD 1.4, whereas (b) Stationary/sliding beds were removed when density increased to 1.70 and higher, even at a slightly reduced flow rate

More data, preferably taken with a stationary bed during no flow conditions, are required to calibrate the instrumentation to be able to distinguish confidently between a stationary and a sliding bed condition.

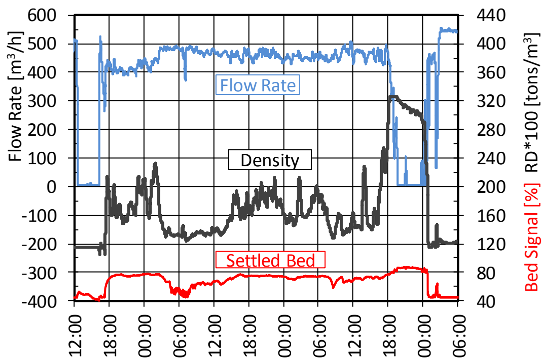
3.4 Pipeline blockage events

The magnetite product pipeline experienced a complete blockage when the flow rate ceased after a stationary bed existed for longer than two days. Figure 7(a) shows that even after the inclined densitometer (Figure 5) saturated at RD 3.25, the cross-sectional area available for flow was still large enough for the centrifugal pumps to maintain a limited, but gradually decreasing flow rate above the settled bed for about 1.5 hours. The flow rate only reduced drastically thereafter from 200 m^3/hr to zero within the last 10 minutes prior to the shutdown. Although the bed signal indicated a lasting stationary bed, the SBD could not sense the actual height of the bed which would have been useful to identify that very bed height, above which the flow rate ceased.

Figure 7(b) shows the overall flow rate, the flow signal and bed signal from the SBD for a NB400 phosphate tailings pipeline, before and after a blockage event. Cyclic temperature fluctuations are evident between the upper and the lower sensing head due to the daily sunshine onto the upper pipe section, even though the sensors themselves were covered, due to the heat being conducted into the short spool piece predominantly through the upper pipe section. The cyclic temperature effects are shown in Figure 7(b). During pumping conditions, the flow signal changed only slightly around noon, whereas for the standing condition, the flow signal dropped significantly due to a lack of cooling by the slurry flow.

The dashed lines in Figure 7(b) indicate the allocated threshold levels required to either trigger a warning of a stationary bed, or a no flow condition. Essentially, once calibrated they convert the analogue output signals into digital states of either flow or no flow, and to either bed or no bed conditions, respectively.

The tailings pipeline, like the magnetite pipeline, did not block suddenly, but after a stationary bed was present for some time. Interestingly, the trends in Figure 7(b) indicate that when the flow rate increased twice to about 470 m^3/hr for a limited period, the stationary bed could be cleared with ease, as indicated by the bed signal going below the threshold of 17% for this particular set-up.



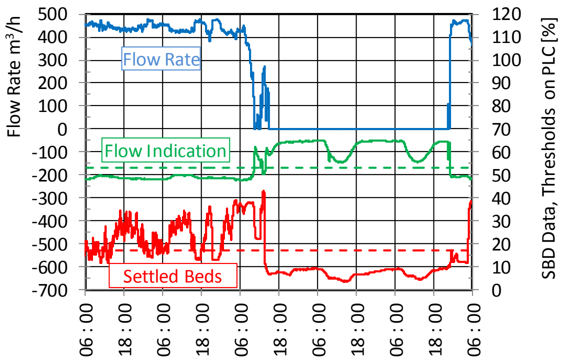


Figure 7 Build-up towards pipeline blockages; (a) Magnetite slurry; and, (b) Phosphate tailings

In both installations, the sensors located at the pipe invert could only sense the existence of a bed in the hours before the blockage events, but could not raise a warning before the blockages became imminent.

3.5 Bed height sensing with additional sensors

A stainless steel spool piece, installed between two Perspex viewing sections with an internal diameter of 127 mm was prepared to accommodate additional sensors to detect the rising level of a progressively growing stationary bed (Ilgner 2016). To minimise thermal interference, the sensor positions were located as far apart from each other as possible (Figure 8).

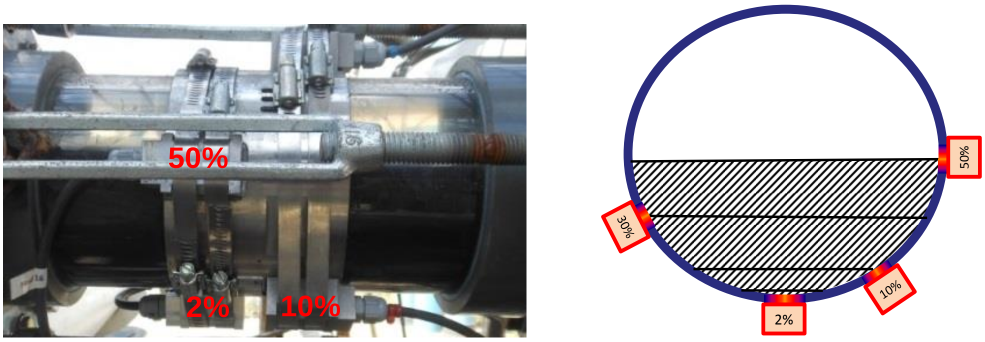
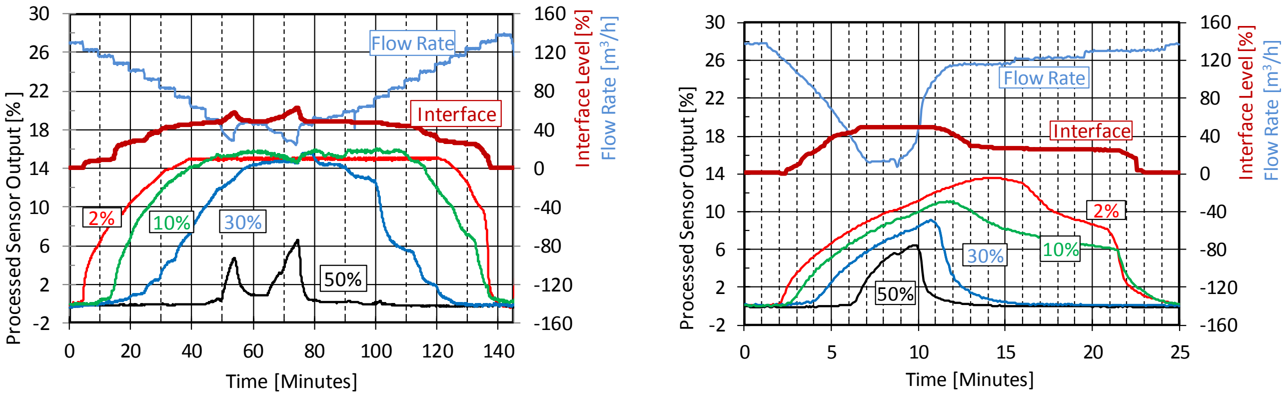


Figure 8 Arrangement of thermal sensors and two viewing sections to measure and observe bed heights

The flow rate was reduced in small steps every five minutes to identify those flow rates at which the individual sensors detected the transition of the rising bed. Special algorithms were developed to calculate the exact level of the interface between the moving slurry and the stationary bed. The two hour test duration with the responses of the sensors and with the calculated interface level in response to the individual steps is shown in Figure 9(a). It was difficult to maintain a stable low flow rate when settlement became substantial along the pipe loop.

A much shorter, second test with a continuously reducing flow rate is shown in Figure 9(b). After the side sensor, located at 50% of the pipe diameter, was completely covered with a stationary bed, the flow rate was increased rapidly to avoid the development of unstable flow conditions.



(a) (b)

Figure 9 Sensor outputs and derived interface levels during (a) Step-wise flow rate reduction; and, (b) Continuous flow rate reduction

Irrespective of the method of flow rate changes, the sensors located at the side of the pipe responded in the expected sequence. The derived interface levels corresponded with the observations through the two viewing sections.

4 Analyses and review of in-field performances

4.1 Sensor response time

For industrial control purposes, the response time of the thermal sensors should be in the order of a few minutes, whereas for research and development purposes, a faster response is often required to better characterise the variable bed motion. The field data have indicated that both requirements can be met by customising the frontend-sensing geometry. However, if a high pressure rating is required, e.g. for a long-distance paste pipeline, the thicker pipe wall will delay the response time, which was quantified to be within five minutes for 18 mm thick piping (Ilgner 2014). For industrial use, data acquisition may be as fast as every 10 seconds when timeous intervention is critical, but even 10 minute intervals have been found to be sufficient for ongoing monitoring of slow-changing processes.

The data have also quantified the extent of the hysteresis associated with the thermal sensor's response. While the onset of a stationary bed creates a rapid and distinct temperature increase, the removal of the bed and the subsequent cooling down of the sensing area generally takes longer than the heating up.

4.2 Noise-to-signal ratio

Compared to other technologies to sense settlement in industrial pipelines, the straightforward analogue outputs do not require complex processing or interpretation to make sense as they are readily available to be integrated with a mine programmable logic controller (PLC). If desired, the noise-to-signal ratio can be improved by adding more heating power to the thermal sensors to compensate for additional conductive heat losses along a thicker pipe wall. Upscaling to larger pipe diameters does not affect the noise-to-signal ratio, as the sensor's focused zone of influence is independent of pipe diameter.

4.3 Integration with mine programmable logic controller

The analogue outputs from the SBD have been integrated with a mine PLC to trigger an online warning which needs to be acknowledged by the operator (Ilgner & Pienaar 2016). Such triggers can be time-delayed to avoid unnecessary warnings due to minor and short-lived beds. The sensitivity of warnings or alarms must be customised to the site-specific response options within the scope of acceptable interventions. The setting of realistic and sustainable thresholds and alarm notifications is imperative to minimise false alarms while at the same time ensuring that critical developments are not ignored (Ilgner et al. 2015). Additional process data, like pressure, flow rate, power draw or slurry density should be included in the online assessment of the prevailing condition inside the pipeline.

4.4 Thermal interference between sensors

The need for localised heat generation to be able to sense both flow and settled bed conditions creates a risk that the individual temperature readings will be affected by near-by heated sensors (Figure 3). This poses a challenge for small pipe diameters, i.e. less than 100 mm, and particularly when multiple sensors are located too near to each other across the pipe invert to detect small increments of the bed height. To alleviate this interference, sensors at different levels may be staggered parallel to the pipe axis to widen the physical gap between them.

Currently, the contact area of the clamp-on sensors is 22 mm wide and 40 mm long to ensure meaningful heat transfer from the sensor into the pipe wall. This relatively large size was suitable for industrial pipe sizes from about 150 mm upwards, but it cannot be used readily without modifications for smaller pipe sizes.

4.5 Limited sensing depth

The settled beds prevent heat removal from the heated contact area on the inner pipe wall. Consequently, the sensed temperature will always rise until the equilibrium is reached between heat supply and heat removal. However, if the stationary bed thickness is below 20 mm, the rise of the temperature is limited as it is controlled by the flow above the bed. However, if the bed exceeds 20 mm, the temperature will settle at a level independent of the actual bed height. A thicker pipe wall will further reduce the effective depth to sense flow conditions through a stationery bed. In essence, the output of a single sensor is related to some extent to the bed height, but other influences, like duration of the bed, will also influence the final output. However, the limited sensing depth is also a positive feature as it limits the sensing area by focusing only on the near-wall effects.

4.6 Communication provisions to set up the field instrument

Sensors can be retrofitted onto operational, unlined steel pipelines irrespective of the actual flow conditions. Alternatively, for rubber-lined pipelines, sensors can be attached to short, unlined spool pieces which can be installed at a later stage during a shutdown period. The quality of the thermal coupling between the heated sensors and the pipe wall after installation, as well as the pipe wall thickness itself, necessitate a fine-tuning during fully suspended slurry flow conditions.

An auto-configuration function is currently being developed, which can trigger itself to start-up when a fully suspended pipe flow pattern is detected based on the original factory setting. However, until then, it is important to have convenient, wireless access to the control unit for uploading historical start-up data for analysis to enable fine-tuning of thresholds for the alarm triggers.

The existing microcontroller of the SBD is resource-constrained which prevented the implementation of complex communication functions. A compact internet data format architecture, i.e. concise binary object representation (CBOR), was critically reviewed by Kalvoda (2015) for remote monitoring with limited resources. The platform was implemented as an Android application to operate via Bluetooth as well as an Ethernet transmission control protocol (TCP) for communication via a laptop. This connectivity gives the operator an instant overview of the current settings, live data and flow conditions (Figure 10). Unfortunately, the microcontroller's constraints prevented further development (Ilgner & Pienaar 2016).

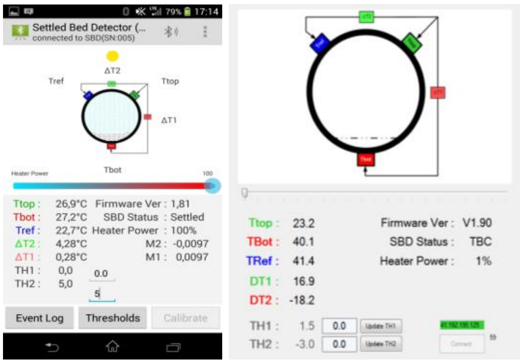


Figure 10 Bluetooth connectivity for smart phone application and Ethernet communication to collect event logs and to adjust the thresholds

4.7 Required enhancements

The recent measuring successes in real-world operations warranted the development of new features to the SBD. After a critical technical review to identify existing limitations, a gradual migration towards the digital Industry 4.0 standard is being implemented with the upgrades. The following major enhancements are being implemented:

1. The resource-constrained microcontroller should be replaced with a mini PLC with expandable features as required for different applications. The data communication must follow a proven industrial protocol, i.e. Modbus TCP and wireless transfer from remote areas to a control room for integration into a holistic control philosophy to optimise hydrotransport operations. This protocol must also handle large data volumes from multiple sensors to enable fine-tuning via the internet. Ongoing collection of operational data will be used to define the auto-configuration and self-calibration algorithms over time.

2. The heating power should be increased further to improve the sensitivity to detect flow behaviour and sliding bed motion even through thicker pipe walls. Heating levels need to be controllable to reduce thermal interference, which was evident on smaller diameter pipelines.

3. Instead of sensing settlement only at the pipe invert, additional sensors should be provided along the pipe circumference to enable the determination of the interface level between the stationary bed and the flow above it. This online output can readily be used to deliberately control the bed height by operating the pipeline at a predetermined stationary bed level. In this way, the pipeline invert is protected from wear due to abrasive particle sliding. Furthermore, acceptable maximum levels of bed heights can be defined based on the actual characteristic of the pump systems and its control philosophy. When only a limited tonnage is available, the pipeline can be operated with confidence at a reduced throughput rate. This eliminates the need to add unnecessary amounts of dilution water to comply with minimal flow rate specifications.
4. A sensing network should be established to not only sense at one location of the pipeline, but at all critical locations along the entire pipeline where settlement is expected to occur. This sensor network will be of particular interest for those applications where the settling properties of the slurry change while being in the pipeline, e.g. in the oil sands industries. It is also anticipated to use such a sensor network to monitor the movement of localised dunes, or when beds remain in the pipeline even after a water flushing cycle. Such a sensor network could then provide anything between 50 and 100 live data points describing collectively the condition inside the pipeline at numerous locations.
5. The large number of data from the sensor network should be compiled into a single colour-coded pixel map. Such a map offers an instant identification of critical areas and their severity. Furthermore, such pixel maps can be played back as a video to assist with the post-analysis of recorded anomalies, or even to analyse the circumstances in a pipeline which might have led to the development of a pipeline blockage incident.

The details of this visualisation approach are described in the next section.

5 Visualisation concept

5.1 System layout

A prototype is being developed with six sensors being located across the pipe invert to sense at distinct points, i.e. at the invert itself, and at chord levels of 6, 12, 18, 24 and 30% of the internal pipe diameter. Two additional reference sensors are located along the upper half of the pipeline (Figure 11). This set of eight sensors feeds the algorithms to calculate the following conditions:

1. Flow or no flow in the pipeline at this location.
2. Existence of stationary solids at the different chord levels.
3. Interface level between 0 and 30% of internal pipe diameter, if a bed exists.
4. Sliding bed or variable bed conditions at the different chord levels, when data vary rapidly.

The online visualisation derived from the various sensor outputs, as well as the calculated interface value, i.e. 4.3% for a small or sliding bed, or 16.4% for a substantial bed are shown as an example in Figure 11. The text within the chord areas is used as an online explanation to the user in addition to the colour code to depict optically the prevailing flow conditions.

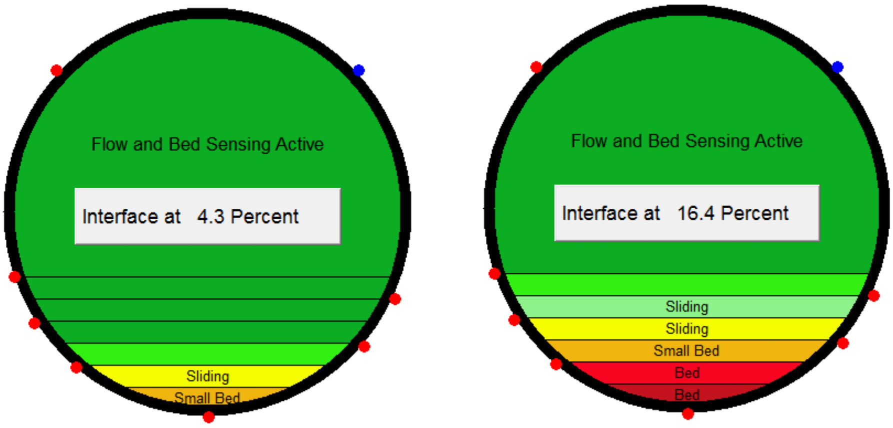


Figure 11 Simulated display of processed sensor data and calculated interface level

Another advantage of the colour coding is the ability to build an entire pixel map from multiple sets of sensors which are envisaged to be installed along the pipeline.

5.2 Data integration from sensor network along pipe route

The following animation of the output of a sensor network is based on having 11 sets of sensors installed at 500 m intervals along a 5 km long pipeline. In this example, the number of pixels for each location was also increased to 12 to extend the vertical sensing of the actual bed heights even when they exceed half of the pipe diameter. This is in response to the monitored pipeline blockage, during which the bed height was so high that even the output of the inclined densitometer saturated at an RD of 3.25 (Figure 7(a)). Essentially, the pixel map depicts relative differences in the velocities sensed at the pipe wall, similar to an infrared image of surface temperatures. The gradual colour changes are more suitable to communicate effectively the prevailing state than text or charts.

In order to decrease the apparent graininess due to insufficient pixels, additional pixels can be created, based on interpolation between the discrete datasets from the known locations. This improves the user experience during the playback of a pixel video for event analysis. For this approach to be valid, it is assumed that a typical bed formation will extend beyond two or three sensing locations to justify such interpolation. However, a slow-moving dune, or even a local, stationary bed, with a length less than the spacing of the sensors, e.g. 200 m, might exist. This short bed won't be depicted, as the interpolation would incorrectly indicate that no bed exists. The advantage of the interpolation outweighs the risk of missing a relatively insignificant bed.

An animated pixel map showing a stationary bed with a limited bed height along the entire pipeline length is shown as an example (Figure 12).

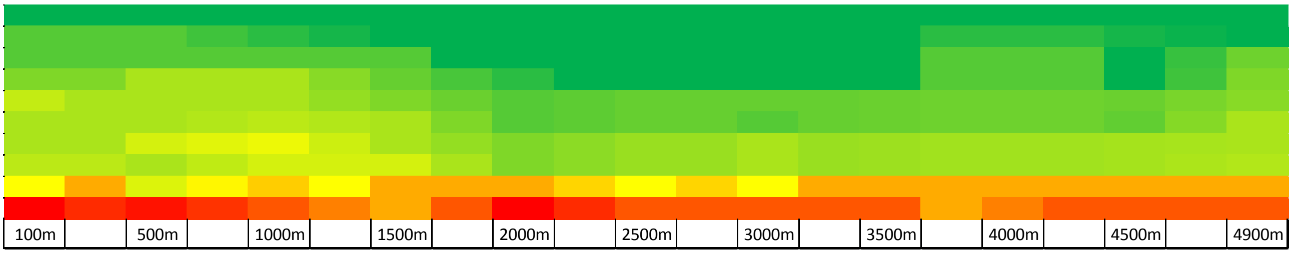


Figure 12 Animated results showing a stationary bed evenly distributed along the pipeline length. Note that the calculated interface level is not shown in this animation

A different scenario, in which a significantly large formation of a stationary bed is sensed at the start of the pipeline, with a smaller, localised bed further down the pipeline is shown in Figure 13.

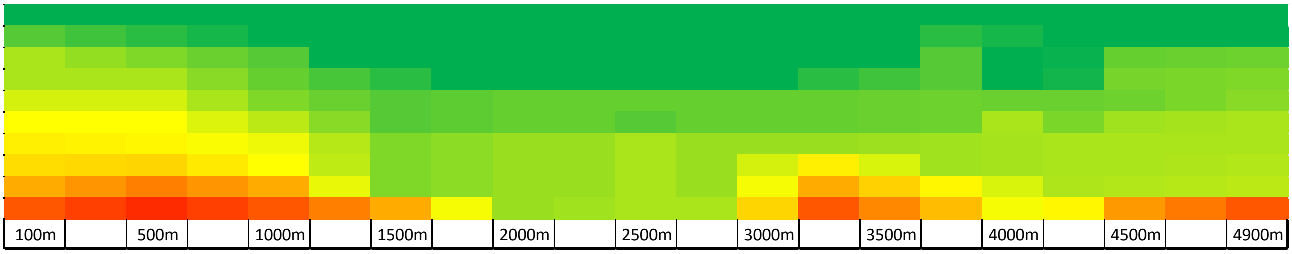


Figure 13 Localised sedimentation from animated results of a sensor network

So far, there are no real-world data available to substantiate the animation results shown above due to the following reasons:

1. Conventional temperature sensing and associated data processing equipment is too expensive when considering a sensor network of up to 100 data points for a single pipeline.
2. The distributed nature of the many sensor sets along the pipeline in often harsh terrains requires competent wireless data communication to synchronise all data into one pixel map and to provide that to a centralised control room in real time.

The issues relating to the current development of this wireless sensor network to create the online pixel map are described in the next section.

6 Industrial wireless sensor network

An industrial grade wireless sensor network (IWSN) will be required to implement the proposed enhancements to the SBD listed in Section 4.7. Key challenges in deploying the IWSN are listed as follows:

- The sensors are located sequentially along a pipeline which is in contrast to the multiple point-to-point and star-based topology of traditional WSN deployments.
- The system needs to implement redundancy against data loss due to single sensor failure as well as show robustness to variable sources of radio frequency (RF) interference.
- The technical complexity of the IWSN needs to remain out of sight from the end-user and be self-configuring in order to reduce set up, maintenance cost and thus accelerate user acceptance.
- The IWSN needs to be based on a well-defined standard which can be easily integrated into the existing supervisory control and data acquisition (SCADA) systems.

These key requirements were taken into consideration during an evaluation of currently available technologies. Nixon (2012) provides a comprehensive review of wireless technologies. Table 2 describes the outcome of an investigation into possible connectivity solutions conducted to date.

Table 2 Assessment of technology options for remote monitoring of pipelines

Option	Connectivity standards	Advantages	Disadvantages
1	Cellular (3G) connectivity	The connectivity is managed and maintained by the cellular provider	High operating cost. Limited availability in remote areas
2	WirelessHART	Well-defined standard. Proven field deployments. Mainly used in process control applications	No IPv6 connectivity for internet protocol based automation
3	Wi-Fi (802.11.4)	Low implementation cost	No built-in mechanism to deal with interference or to provide redundancy
4	ISA100.11a	Robust algorithms to deal with redundancy and RF interference. Built-in methods to provide quality of service	Limited range between sensors. Technically complex
5	LoRa	Long range up to a few kilometres in ideal conditions. Relatively simple	Uses a shared spectrum and has no quality of service guarantee

The ISA100.11a standard was identified as the most suitable technology for implementing the wireless communication defined in Section 4.7. This standard makes use of mesh networking technology to implement redundant communication paths in the network as well as radio frequency channel hopping to mitigate interference from other RF sources. The difficulties originating from the sequential network topology along a pipeline can be addressed by deploying multiple gateway devices along the pipeline which are connected to each other using a wired fibre optic based backbone allowing deployments of up to 10 km between gateways. The technical complexity of the ISA100.11a standard is quite high, but most of the technical complexity is hidden by the gateway device. Several manufacturers offer now ready-to-deploy gateways and end-node devices which are interoperable with any other device supporting the standard. In addition, ISA100.11a provides excellent security measures, ensuring the integrity of devices and that the data being transmitted are of a reliable high quality.

7 Conclusion

The field trials have proven the concept of non-invasive thermal sensors for the detection of sliding or stationary beds. Sensing geometries were evaluated to either sense erratic bed motion of thickened tailings with a very thin-walled spool piece, or to document frequency and extent of re-occurring stationary beds in commercial pipelines. The capability of the field instrumentation has been enhanced with additional sensors placed across the pipe invert to provide the height of stationary beds. Although such configuration is based on discrete sensors, it was shown that the gradual rise of the bed level, i.e. the rising interface, can be derived from these measurements. This interface value is a single parameter which can be used to control a deliberate bed height, or to simply monitor it in relation to other operating parameters.

The biggest advantage of the relatively simple thermal sensor technology is believed to be in the potential to develop a sensor network to monitor the prevailing bed conditions along the entire pipeline, even though at discrete locations. By compiling the sensor network results, the condition of the pipeline can be visualised live as a colour-coded pixel map. This map provides instant insight and locations of potential problems and thus enables better interventions, either manually or by integrating the online results with the pump control system.

Recent advances in wireless data transmission technologies were assessed, resulting in the selection of the ISA100.11a standard. While the complexity and limited range may be challenging, its robust algorithms are a key advantage to ensuring reliable and interference-free operation in harsh conditions.

Acknowledgements

The financial support from the Council for Scientific and Industrial Research's industrialisation initiative for Industry 4.0 is gratefully acknowledged. The assistance from Dino Singh from Shorrock Automation to provide an effective system configuration during prototyping is greatly appreciated.

References

Bontha, JR, Adkins, HE, Denslow, KM, Jenks JJ, Burns, CA, Schonewill, PP & Wilcox, WA 2010, *Test Loop Demonstration and Evaluation of Slurry Transfer Line Critical Velocity Measurement Instruments*, PNNL-Report 19441 Rev 0, Pacific Northwest National Laboratory, Richland.

Ercolani, D, Ferrini, F & Arrigori, V 1979, 'Electric and thermic probes for measuring the limit deposition velocity', in HS Stephens (ed.), *Proceedings of the 6th International Conference on the Hydraulic Transport of Solids in Pipes*, BHR Group, Cranfield, pp. 27–42.

Goosen, P, Ilgner HJ & Dumbu, S 2011, 'Settlement in backfill pipelines: its causes and a novel online detection method', in HG Ilgner (ed.), *Proceedings of the 10th International Symposium on Mining with Backfill*, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 187–195.

Ilgner, HJ 2005, 'Advances in the race between paste and other backfill types', in RJ Jewell and S Barrera (eds), *Proceedings of the International Seminar on Paste and Thickened Tailings*, Addendum to the Seminar Proceedings, Australian Centre for Geomechanics, Perth, pp. 39–58.

Ilgner, HJ 2014, 'Novel instrumentation to detect sliding and erratic bed load motion', *Proceedings of the 19th International Conference on Hydrotransport*, BHR Group, Cranfield, pp. 163–178.

Ilgner, HJ 2016, 'Detection of bed height for settling slurries', *Proceedings of the 10th North American Conference on Multiphase Flow*, BHR Group, Cranfield, pp. 117–131.

Ilgner, HJ 2017, 'Non-invasive detection of sedimentation and its removal in industrial pipelines', *Proceedings of the 18th International Conference on Transportation & Sedimentation of Solid Particles*, Institute of Hydrodynamics CAS, Prague, pp. 121–128.

Ilgner, HJ, Brink, VZ & Brink, S, 2015, 'From data mining to decision making in the South African mining industry', in P Perna (ed.), *Proceedings of the 15th Industrial Conference on Data Mining*, Springer International Publishing, Cham, pp. 71–82.

Ilgner, HJ & Pienaar, S 2016, 'Implementing a compact data format for Bluetooth and 3G communication to monitor remote pipelines', *Proceedings of the 2016 International Conference on Advances in Computing and Communication Engineering*, Institute of Electrical and Electronics Engineers, New Jersey, pp. 45–50.

Kalvoda, P 2015, *Implementation and Evaluation of the CBOR protocol*, bachelor thesis, Charles University, Prague.

Kazanskij, IB 1979, 'Critical velocity of depositions for fine slurries – new results', *Proceedings of the 6th International Conference on the Hydraulic Transport of Solids in Pipes*, BHR Group, Cranfield, pp. 43–56.

Nixon, M 2012, *A Comparison of WirelessHART™ and ISA100.11a*, Emerson Process Equipment, Round Rock.

Romanet, T, Volle, J & Reber JD 2005, *Method and Device for Detecting Deposit in A Conduit*, US Patent 6 886 393 B1.

Schreib, SF 1984, *Ultrasensitive Apparatus and Method for Detecting Changes in Fluid Flow Conditions in Relief Flow Lines Associated With a Chemical or Refinery Complex*, US Patent 4 434 418.