Paste 2024 – AB Fourie & D Reid (eds)

doi:10.36487/ACG_repo/2455_34

Monitoring bed formation in a pipeline: a comparative study of two measurement methods

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Abstract

Transport of tailings via pipeline is a common practice between mineral processing sites and a tailings storage facility. To operate these typically turbulent multiphase-flows safely at high solids loadings with minimum energy and water consumption is not a simple task. Monitoring of tailings pipelines is often restricted to pressure drop measurements. Monitoring could be enhanced by effective, non-radiometric instrumentation for solids concentration or concentration profile. Two possible options for such an instrument are electrical resistance tomography (ERT) and thermal bed load detection (BLD). ERT represents a non-intrusive method suitable for monitoring solid-liquid suspension flows. While ERT has shown its capability to generate good qualitative images, it faces challenges including limited spatial resolution, sensitivity to electric noise and the inherent difficulty of calculating concentration distributions. For suspensions with a settled bed, ERT reconstruction projects an incorrect smooth transition at the bed interface and typically underestimates the concentration, with a discrepancy up to 25% (v/v) at the highest bed level. Thermal BLD provides a method of measuring the depth of a settled bed via changes in rate of heat transfer. The BLD consists of multiple sensors around the pipe circumference which combine a heater with a thermocouple to maintain a constant surface temperature. The power required to maintain a set temperature is proportional to the heat lost to the fluid or bed that is in contact with the sensor. The change in rate of heat transfer is then used to infer bed depth. A comparison is made between the results from both methods at laboratory and pilot scales. The data is assessed for its accuracy and the robustness of measurements for field deployment.

Keywords: *solids settling, pipeline transport, electrical resistance tomography, thickened tailings, settled bed*

1 Introduction

Concentrated suspensions are encountered across diverse industrial sectors, including oil and gas drilling, coal slurry, mineral tailings, biological and food industries. The efficient pipeline transportation of these concentrated suspensions requires a comprehensive understanding of suspension behaviour, encompassing flow regimes, deposition velocity and solids settling. During transport, varying conditions can cause particle settling, leading to the formation of either stationary or moving beds within the pipeline. The implications of these bed formations range from a reduction in particle transport to the severe consequence of complete pipe blockage. Understanding the solids settling and bed formation is essential for industry to optimise the design and selection of suitable pump sizes and pipeline configurations.

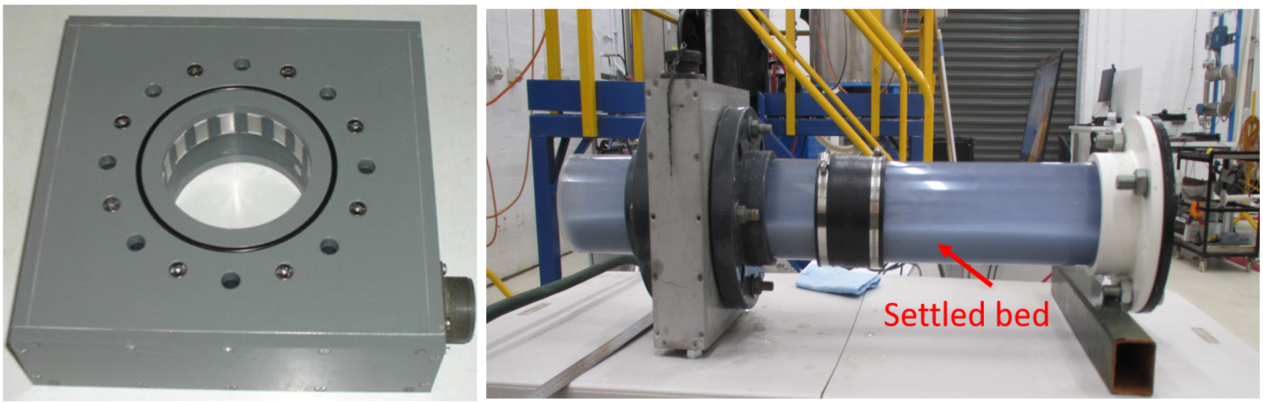
At present, industries predominantly rely on pressure gauges to monitor bed formations within pipelines, using pressure increases as indicators of potential blockages. However, this method lacks precision in control and fails to provide an accurate depiction of the bed's characteristics – whether it remains stationary or moves. A pressure measurement, or the calculated friction loss, is insufficient in isolation to determine which of several causes has produced the increase in pressure drop. Several techniques exist for monitoring suspension flows, such as magnetic resonance imaging and gamma ray densitometry. Each technique has its advantages and limitations, with some only applicable within a dilute range or suitable for non-opaque suspensions, while others necessitate prolonged data acquisition (Silva 2015). Furthermore, gamma ray densitometry techniques involve radiation exposure, raising safety concerns and operational complexity. Additionally, common characterisation techniques such as ultrasonic doppler velocity profiling and particle imaging velocimetry become impractical due to the opaque nature of these mixtures, rendering them ineffective for accurate analysis (Shokri et al. 2017).

When more robust instrumentation is required, two potential options are electrical resistance tomography (ERT) and a thermal bed load detection (BLD) system. ERT emerges as a relatively cost-effective and non-intrusive method for dynamically mapping the internal distribution of solids during flow. This technique applies electric current to a circumferential electrode array encircling the vessel or pipe cross-section of interest, measures resulting voltages, and reconstructs a conductivity-based image. The inherent advantage of tomography techniques makes ERT suitable for opaque mixtures. Alternatively, the thermal BLD provides a method for assessing settled bed depth by monitoring changes in heat transfer rates. Comprising multiple sensors around the pipe circumference, this thermal system combines a heater with a thermocouple to maintain a consistent surface temperature. The power required to maintain this temperature reflects the heat dissipation to the fluid or bed in contact with the sensor, allowing an estimation of bed depth. This thermal-based system is less affected by environmental conditions or electrical noise, making it adaptable for onsite deployment. To assess the efficacy of both methods, a comparative analysis is conducted at laboratory and pilot scales, evaluating data accuracy and measurement robustness for potential field deployment.

2 Inline devices

2.1 Electrical resistance tomography

ERT employs electric current applied to electrodes encircling the area of interest within a vessel or pipe, measuring resulting voltages to form a two-dimensional graph of conductivity. An example of the electrode array is shown in Figure 1. The concentration of each phase can then be calculated based on the known conductivity of each phase, producing a concentration map.



(a) (b)

Figure 1 (a) Electrical resistance tomography electrodes; (b) Mounted in a section of pipe for static test

ERT offers an affordable and non-intrusive means of assessing the dynamic distribution of internal solids during flow. It has proven effective in generating qualitative images of suspension flows (Sharifi & Young 2013). It should be noted that the ERT requires an electrically isolated array with no lining between its electrodes and the process fluid, otherwise its output is largely independent of pipe material of construction. However, ERT encounters challenges such as limited spatial resolution, susceptibility to electrical interference, and difficulties in quickly and accurately solving the complex mathematics problem involved (i.e. the forward and inverse problem) to accurately map conductivity. Regularisation methods are required to transform the ill-posed problem into a well-posed one. Regularisation techniques offer various options, for example, choosing an edge-sensitive spatial Laplacian filter for Gauss–Newton (GN) one-step reconstruction smooths the reconstruction while penalising sharp edges. Alternatively, using 'total variation' (TV) regularisation allows for discontinuities, aiding in detecting abrupt conductivity changes.

These circumstances make an *a priori* knowledge of material and expected flow conditions necessary for quantitative evaluation. Additional details on ERT and reconstruction algorithms can be found in (Polydorides 2002). Presently, ERT is primarily used in controlled laboratory settings due to hardware and software limitations, making quantitative analysis challenging in industrial applications, especially with mixtures possessing significantly higher conductivity than those tested in labs, leading to increased electrical noise and reduced accuracy. Hashemi et al. (2021) studied the impact of surface-active clays in real tailings on accurate ERT-based solids concentration measurement, noting ERT's sensitivity to clay concentration and its improved accuracy at lower clay concentrations and higher coarse solids (sand) concentrations.

2.2 Bed load detector

The BLD has been developed as an instrument to monitor the nature and height of a settled bed. A settled bed can be classed as static, sliding (motion at the particle–pipe wall interface) or sheared. The BLD is an annular spool constructed of a low thermal conductivity material, flanged into the pipeline and contains several sensors consisting of a thermocouple and heater around its lower circumference and a single thermocouple at the top, as shown in Figure 2. To maintain a constant resolution, the number of sensors is proportional to pipe circumference.

The BLD operates on the principle of heat transfer, as settled solids will conduct heat at a slower rate than the fluid will via forced convection, acting as a blanket. The turbulent flow of fluid past the sensor will remove heat at the highest rate (proportional to fluid Reynolds number) and a static bed the lowest. A sliding or sheared bed will be somewhere between the extremes. The single thermocouple at the top of the BLD measures the ambient fluid temperature as a reference, and the lower heaters are set to maintain a constant temperature difference above the ambient temperature. The use of relative temperatures makes the BLD largely independent of environmental conditions. The power used by each of the lower heaters to maintain this differential is proportional to the heat flux of that sensor. Therefore, if the power consumed is lower than for the reference condition (pure fluid without solids), then the sensor is partially or fully covered. Given each sensor is at a different height, data from each can be combined to determine the height of the bed. The data from the BLD is processed within the instrument and converted to operator understandable information such as bed height and rate of height change.

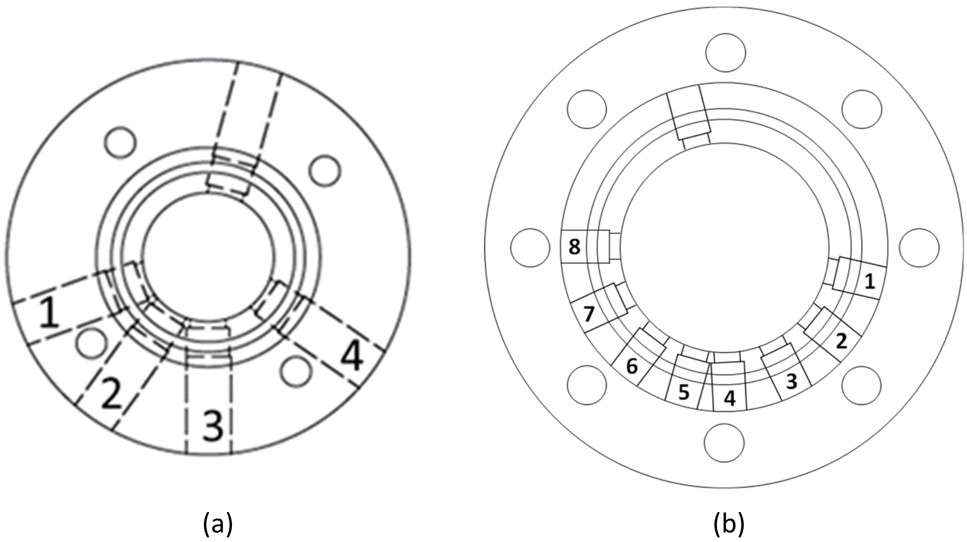


Figure 2 Bed load detector showing position of sensors. (a) 44 mm; (b) 100 mm. Not to scale

3 Suspension experiments in a pipe loop

3.1 Electrical resistance tomography set up

Both static and dynamic suspensions with physically sensible flow scenarios were established to assess the ERT performance in monitoring bed formation. The suspension was set up utilising a saline solution as the suspending medium. Glass spheres, B1 (mono-sized, $d_p = 3mm$) and B2 ($d_p = 650 - 800\ \mu m$) were used in this study. These glass beads were sourced from Burwell Technologies in Australia.

For the case of static suspensions, stationary bed levels were established by immersing glass beads within the saline solution, varying the bed levels between one-quarter and one-half of the pipe diameter. For dynamic suspensions, a recirculating pipe loop was used. A diagram of the pipe loop is shown in Figure 3. This loop includes a 700 L feed tank, a centrifugal pump with a variable speed drive and a 44 mm inner diameter pipeline system. The horizontal pipe section's length is 6 m. The pipe loop integrates an ERT ring with 16 electrodes connected to the Industrial Tomography Systems (ITS) ERT system (Industrial Tomography Systems 2009). A Coriolis mass flow meter was employed to measure mass flow rates and inline concentration (inferred from density). Measurements were recorded every five seconds through an automated data acquisition system. The mean solids concentration C_v was in the range of 0.10–0.22. Flow rates were varied to obtain different flow regimes from heterogeneous flow with no visible bed to a moving bed at the pipe invert.

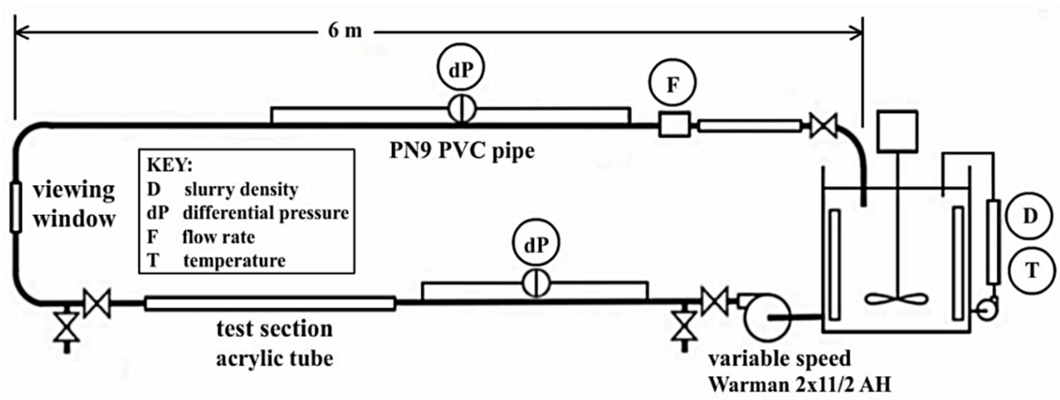


Figure 3 Diagram of the 44 mm internal diameter experimental pipe loop. Electrical resistance tomography and bed load detector spools are immediately upstream of the acrylic viewing section

Regarding the ERT processing, it was conducted using both an ITS p2+ and p2000 unit supplied by ITS (http://www.itoms.com/). The ERT spool piece comprises a cylindrical flange constructed from rigid non-conductive polyvinyl chloride. The electrode ring contains 16 stainless steel electrodes evenly distributed around the pipe's inner circumference. ERT data was collected at a current injection frequency of 9,600 Hz, and 200 frames were averaged to produce the final image. The ITS-developed software employs an online linear back-projection (LBP) reconstruction algorithm, providing near real-time tomographic images. Other reconstructions utilise the open-source tool Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS 3.10).

3.2 Bed load detector set up

Testing was conducted using the 44 mm diameter pipe loop described in Section 3.1 with a BLD spool inline. Different combinations of solid particles and carrier fluids were used, as seen in Table 1. To replicate the effects of a carrier fluid with a yield stress a 0.1 wt% Carbopol solution (a non-Newtonian fluid) was used. The slurries either had a narrow particle size distribution crushed glass or additional coarse particles added (mixed crushed glass). Trials were conducted using a 5, 10 or 20°C temperature differential at flowrates from 2.6 to 100 L/min. Power consumption for each sensor was monitored as a function of flow rate and compared to video images as a measure of bed depth.

Assessing the data for different differential settings showed that sensor power increased linearly with increasing temperature differential, indicating that heat flux was constant at given flowrates and fluid compositions.

Table 1 Suspensions used for bed load detector testing

Suspension name	Carrier fluid	Particle
GWS	Water	Crushed glass
MWS	Water	Mixed crushed glass
GCS	Carbopol solution	Crushed glass
MCS	Carbopol solution	Mixed crushed glass

3.3 Simultaneous measurements

In this section of work both units (ERT and BLD) were operated simultaneously in the pipe loop as described in Sections 3.1 and 3.2. A water and glass spheres slurry (BWS) was transported in the 44 mm pipe. The glass beads B2 ($d_p = 600{\sim}850\ \mu m$) with a design solids volumetric concentration $C_v = 0.15$ were added. The deposition velocity was estimated to be of 1.4 m/s according to Oroskar & Turian (1980). Flow rates were varied between 0.9–3.0 m/s to obtain different flow regimes from heterogeneous flow with no visible bed to a moving bed at the pipe invert.

4 Experimental results and discussion

4.1 Electrical resistance tomography results

A comparative evaluation of different algorithms for reconstruction was undertaken. Figure 4 exhibits reconstructed concentration images using the LBP, GN Laplace and TV algorithms for stationary bed configurations consisting of a mixture of two glass beads. The LBP and GN Laplace algorithms depict a smooth transition at the bed interface, while the TV algorithm represents reality better by detecting sharp concentration gradients. The LBP algorithm tends to spread concentration beyond the bed area, predicting a slightly higher bed than actual. In cases of significant bed volume, both the LBP and GN Laplace algorithms lack information in the center, as depicted in Figure 4b. Although the TV algorithm captures sharp concentration changes, artifacts are noticeable at the bed interface.

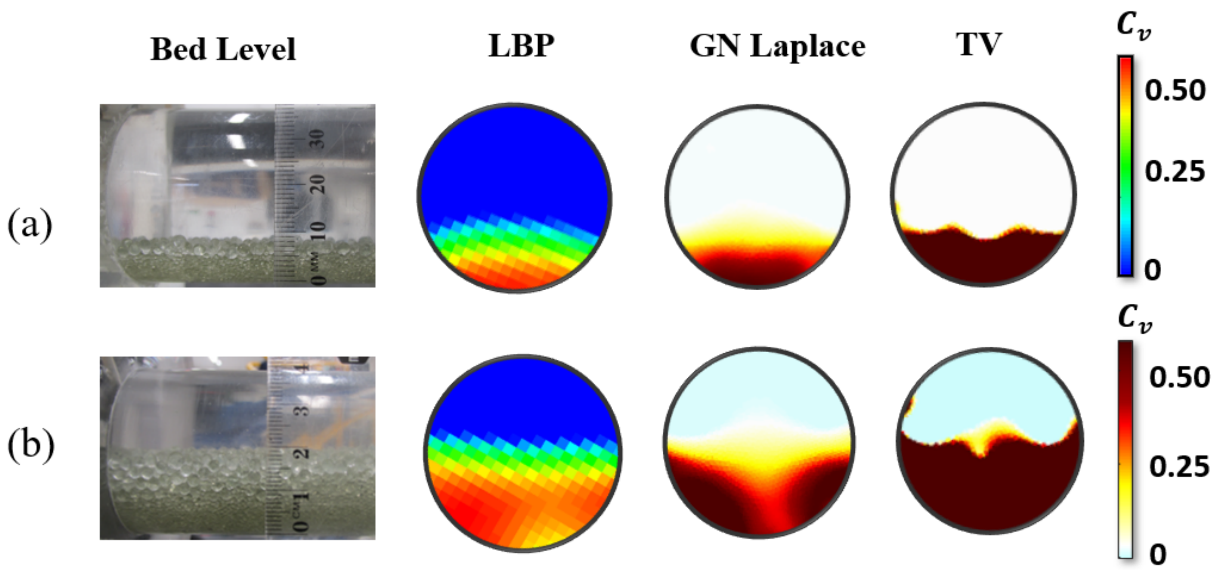


Figure 4 Reconstructed concentration images based on LBP, GN Laplace and TV algorithm for (a) low bed level and (b) high bed level

The two-dimensional (2D) algorithm is time efficient and suitable for real-time imaging. However, 2D images based on LBP and GN Laplace would generate misleading information at the center of the pipe, particularly when there is a significant bed. The ERT reconstruction is commonly based on a 2D method due to its computational efficiency. A potentially more accurate method to reconstruct the ERT images inside a pipe geometry is the 2.5D approach. The 2.5D reconstruction sets up a 3D model for the forward problem and uses a 2D model for the inverse problem. The 2.5D reconstruction provides good predictions on the interface sharpness, as shown in the chord-averaged concentration profile in the pipe cross-section in Figure 5. This method, however, takes more computational effort. Despite it not being applicable for real-time imaging, it would be applicable for processes if time scales are long enough.

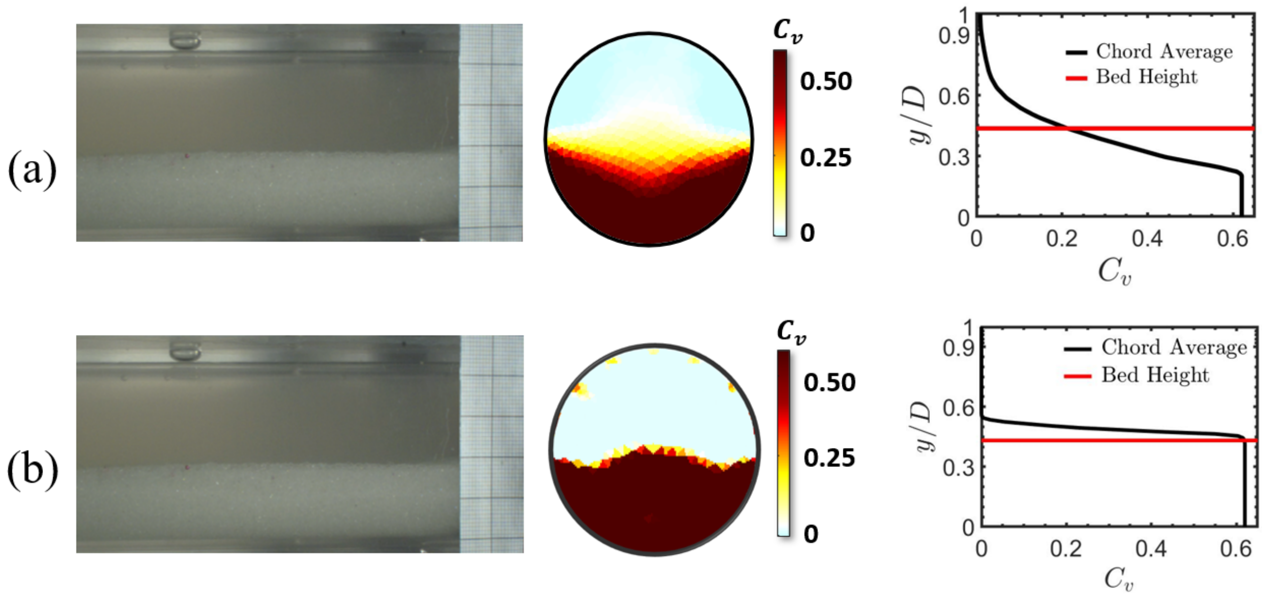


Figure 5 Reconstructed concentration image for a settled bed based on (a) 2D GN Laplace algorithm (b) 2.5D GN Laplace algorithm

In a dynamic case, for flows with no significant sliding or stationary bed at the pipe invert, the chord-averaged vertical distribution of particles in a pipe undergoing turbulent flow can be approximated using a one-dimensional Rouse–Schmidt model (Gillies & Shook 1994). The standard turbulent-diffusion equation using hindered-settling velocity, together with the particle diffusivity proposed by Eskin (2012), have proved to be successful in predicting concentration profiles in both dilute and concentrated suspensions. Figure 6 compares chord-averaged concentration profiles between ERT measurements and predictions derived from the Eskin model, utilising the GN Laplace algorithm for real-time measurements. It is a water glass beads slurry in a 44 mm pipe with a designed solids concentration of $C_v = 0.15$. The ERT-predicted profile exhibits similar trends to Eskin's model, albeit with a slight underestimation of solids concentration, especially near the invert section where particles predominantly gather.

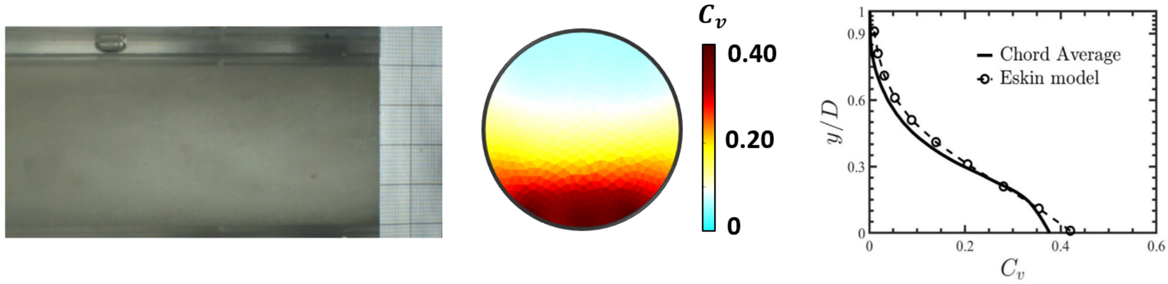


Figure 6 Reconstructed concentration image for a water glass beads slurry in a 44 mm pipe, 15% v/v

4.2 Bed load detector results

The power output for the BLD sensors is shown in Figure 7 for the MCS suspension (dilute carbopol solution as carrier). The orientation of sensors 1–4 is shown in Figure 2 (sensor 3 is the invert). The power output can be seen to plateau at high flowrates (fully suspended solids) and low flowrates (static bed). The different graphic symbols indicate the type of flow regime present as determined from the video recordings. Sensor 3 stays covered at a higher flow rate that the others, as would be expected.

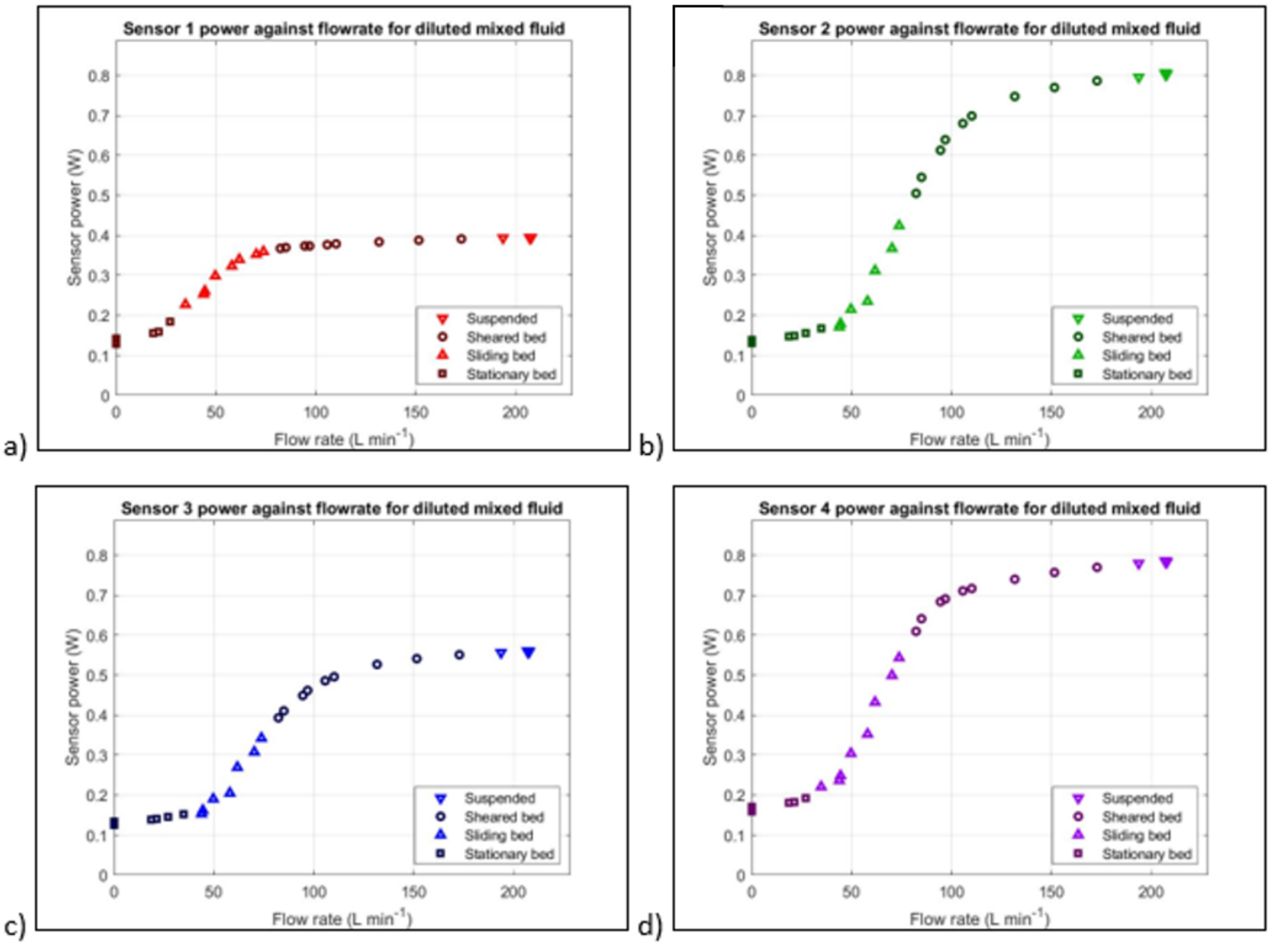


Figure 7 Bed load detector power output as a function of flow rate for MCS suspension

Different responses can be seen in Figure 8 for water as a carrier fluid. The transition between plateaus is more abrupt in the absence of a yield stress, and goes from static to fully suspended over a short range of flowrates. All sensors change at approximately the same flow rate. Again, different responses can be seen in Figure 9 for a more concentrated carbopol solution as a carrier fluid. The lower plateau is absent and a smooth transition to fully suspended flow occurs with no sliding bed detected. Note that power is expressed as a normalised Nusselt number in Figure 9, so the values vary between 0 and 1. This allows the data collected at different differential temperature settings (5, 10 or 20°C) to be shown on the same graph. It was seen that sensor power increased linearly with increasing temperature differential and measurements were unaffected by the different conditions.

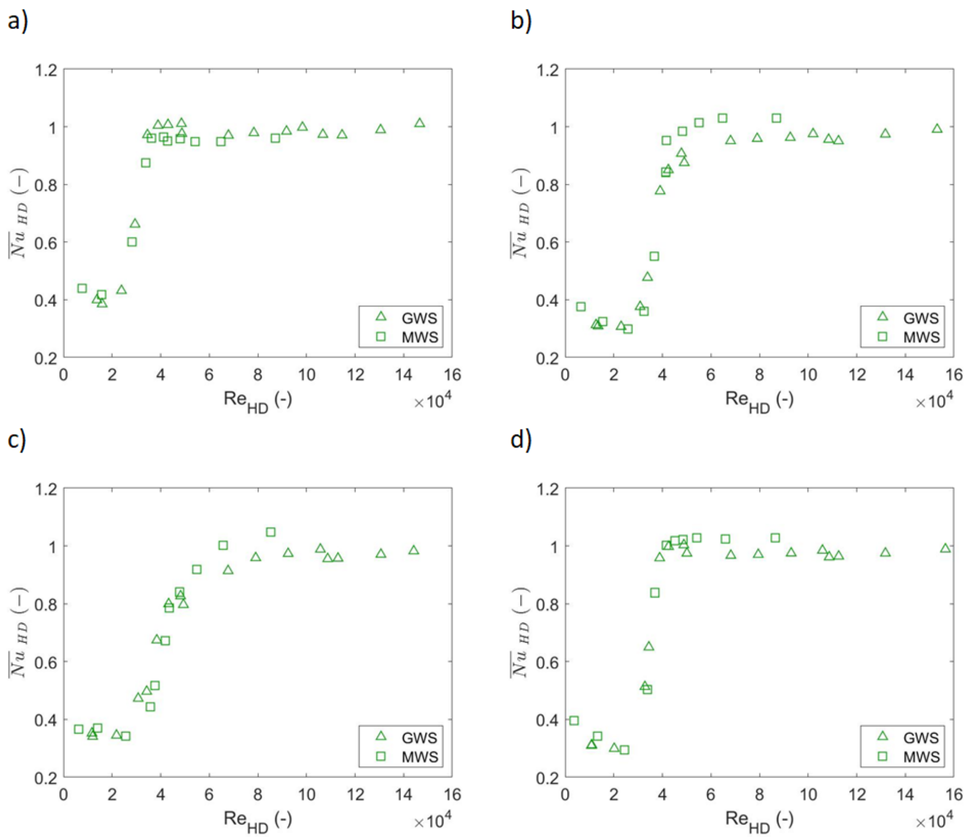


Figure 8 Bed load detector power output expressed as normalised Nusselt number (the ratio of convective to conductive heat transfer) versus hydraulic diameter Reynolds number (-), for glass water slurries and mixed glass water slurries. a) Sensor 1; b) Sensor 2; c) Sensor 3; d) Sensor 4

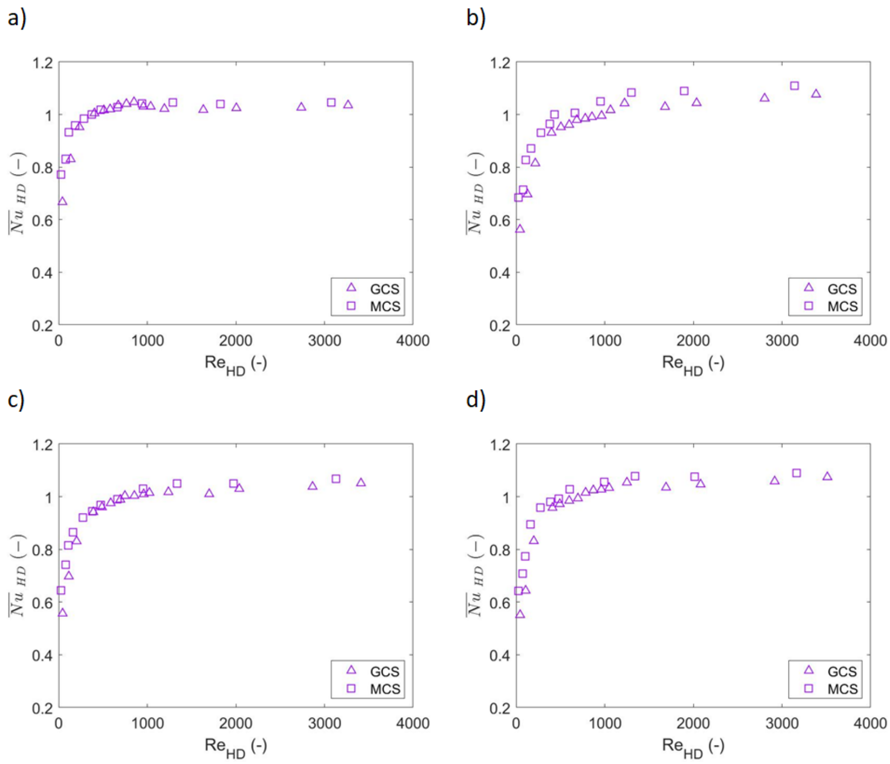
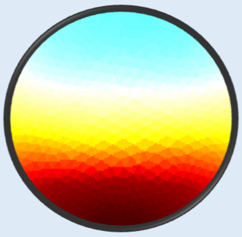
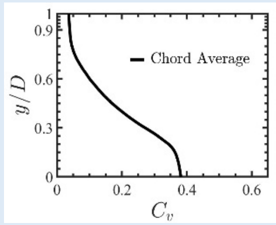
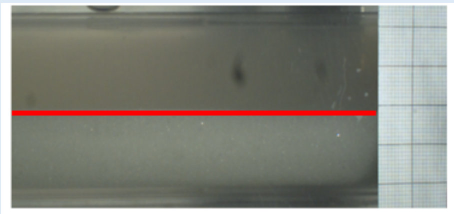
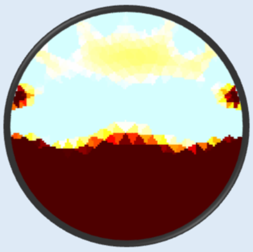
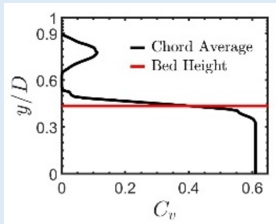


Figure 9 Bed load detector power output 15 Nusselt number (-) versus hydraulic diameter Reynolds number (-), for carbopol slurries. a) Sensor 1; b) Sensor 2; c) Sensor 3; d) Sensor 4

4.3 Simultaneous measurement results

The results for simultaneous measurements on ERT and BLD for BWS in the 44 mm pipe loop are shown in Table 2 and Figure 10. The first row of Table 2 shows a largely suspended particle flow according to the ERT, but with a distinct concentration gradient and possible bed. The corresponding BLD measurements in the early section of Figure 10 indicate a sliding bed at a ratio of bed height to pipe diameter (y/D) of 0.19. The second row of Table 2 indicates a static bed, which corresponds to the later section of Figure 10. Both instruments indicate a static bed with y/D of ≈0.47.

Table 2 Comparative measurement data BWS

Video	ERT (2D GN Laplace)		BLD
			y/D=0.19
			y/D=0.47

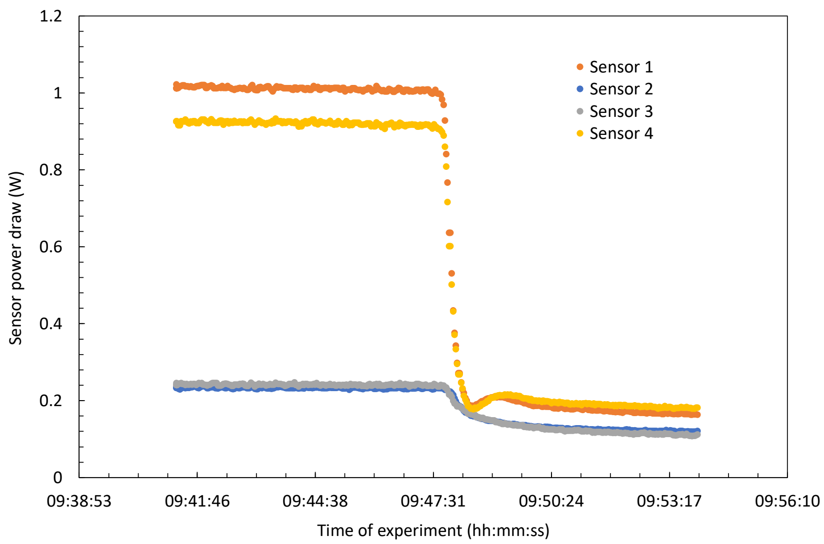


Figure 10 Bed load detector power output for BWS corresponding to Table 2 (red line indicates bed level)

5 Conclusion

At present, the application of ERT is predominantly confined to well-controlled laboratory settings. When imaging suspension flows, different algorithms exhibit varying performance. Notably, for settled bed suspensions, rapid real-time reconstruction methods like LBP or GN Laplace algorithms often lack detailed information at the central region of the pipe, leading to a general underestimation of concentration by up to 25% (v/v). Challenges stemming from hardware and software limitations pose significant hurdles in achieving quantitative analysis of ERT images for monitoring industrial suspension transport. Industrially relevant slurries, such as mineral tailings, frequently exhibit considerably higher conductivity compared to those evaluated in laboratory settings. Suspension flows with a high conductivity level are notably susceptible to electrical noise, resulting in a diminished signal-to-noise ratio. This situation might necessitate injection currents beyond the current range of an ERT instrument. By contrast, the BLD lacks the detailed description of concentration distribution provided by the ERT, but is a robust method of detecting bed levels and providing pertinent information about the condition of the bed, such as whether it is static, sliding etc. As such, the BLD may provide a relatively simple means of pipeline bed level monitoring.

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