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ARTICLE

A Novel Demonstration of Adhered Material Mobilisation by Hydraulic Transients

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This paper presents results from rigorous laboratory experiments that have investigated mobilisation of pipe-wall adhered material due to hydraulic transients. The controlled, repeatable and systematic physical experiments showed that both valve closing and valve opening transients, accelerating and decelerating dynamic effects, can mobilise adhered material where steady-state hydraulic conditions cannot. These conclusive findings show that mobilisation of adhered material by hydraulic transients can occur. Understanding this process is critical to managing water quality risks in drinking water distribution systems and hence protecting public health and minimising associated economic consequences.

1. Introduction

Understanding the processes and forces that lead to water quality failures in Drinking Water Distribution Systems (DWDS) is crucial. Material associated with poor water quality is mobilised from the pipe wall when its adherence strength is exceeded by imposed hydraulic forces[1]. These hydraulic forces have typically been considered as steady-state based conditions. Emerging research, however, is challenging this steady-state interpretation by demonstrating the persistence of transient events throughout operational networks[2,3]. These findings imply that DWDS should be considered as truly dynamic, with potentially more complex mechanisms for mobilisation.

Dynamic forces induced by transients may provide the hydraulic forces necessary to mobilise adhered particles, such as metals, chemical contaminants, and potentially even pathogens. To date, previous DWDS studies have stated that high intensities of shear stress are generated during transient events, which may cause biofilm sloughing and particle resuspension[4-6]. However, mobilisation was not the focus of these studies, and the statements made are generalised. As an example, "[transients] can generate high intensities of fluid shear and may cause resuspension of settled particles as well as biofilm detachment"[4]. If mobilisation can be caused by transient events, it could explain water quality issues – such as persistent background levels of discolouration customer contacts – not currently accounted for by gradual hydraulic changes. Therefore, it is imperative that deeper insight is gained regarding the impact of transients upon accumulated material within DWDS. It is important to note that much of the material found in active DWDS exhibits cohesive properties, such as biofilms[7]. Consequently, this work will focus on adhered material bound in cohesive layers rather than as sediments with behaviour dominated by gravity/self-weight effects. Biofilms are intricate assemblages of microorganisms bound together that can adhere to the pipe wall in a complex physical, biological and chemical process[8]. They have a varying structure composing of a mix of cells, proteins and carbohydrates, which can entrain metals and other inorganics[9].

Karney and Brunone reported results from closing an automatic control valve in a live DWDS to generate a dynamic transient event[10]. Poor water quality was reported; the water company received discolouration complaints by customers approximately six hours after the transient was induced. This is highly suggestive of the ability for valve closing transients to cause mobilisation, however, uncertainty in the exact operational procedure in the study and a lack of repetition means that this is not conclusive. Physical transient mobilisation trials were performed by Mustonen et al. in a pilot scale DWDS where valves were rapidly closed for 5 seconds before being rapidly opened creating pressure shocks[11]. Aisopou et al. similarly monitored a pump trip (rapid decrease then increase in flow rate) in an operational system[12]. In both these studies, concentrations of materials and turbidity increased after the dynamic events suggesting transient mobilisation. However, no high temporal resolution pressure data was presented to confirm that a transient did occur. Furthermore these studies do not exclude steady-state forces as the cause of particle mobilisation or separate effects due to opening or closing transients.

This study aims to conclusively demonstrate the ability of transient forces to mobilise material adhered to the pipe-wall that cannot be mobilised by steady-state flows at the same initial or final conditions. This research specifically explores material mobilisation due to separate decelerating and accelerating effects.

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2. Methodology

To answer the aim of this work, rigorous experiments were required that provided reliability and repeatability. Laboratory experiments were chosen so that strict control could be placed over the system and a range of transient conditions could be tested using high resolution equipment. Moreover, rigorous experiments could be tested in a carefully designed systematic manner to study subtle phenomena that could be overshadowed by temporal and spatial variability and uncertainty in an operational system.

2.1 Instigating Transients

In operational networks, transients can be produced by a variety of sources, including but not limited to; valve operations, pump trips, flow demand and burst events. Valve operations are the most common instigators of dynamic events[13-16], and the resulting transients are representative of most transients recorded in operational systems. Consequently, valve operations were selected for these laboratory experiments to generate all transients induced. These actions included separate valve openings and valve closings for a variety of initial and final conditions.

2.2 Analogue for Adhered Material

An important novel component of this research was to design an experimental analogue to replicate pipe-wall adhered material. Such material is a complex assemblage of organics and inorganics, but the important cohesive properties are dominated by the organic biofilm. However, biofilm is extremely variable and time consuming to accumulate and test, thus was not suitable for direct use in this work. Three key features of biofilms were essential in our analogue: adherence force to the pipe surface greater than the material's self-weight, variable adherence strength, and material structure[7,17,18]. It was vital that the analogue could quickly replicate these features with high repeatability and control within a pipeline where fully representative transients could be generated.

An innovative solution was developed. An electromagnet was placed flush against the outside of a short transparent acrylic section of pipeline and magnetic particles placed on the pipe invert, see Figure 1. The electromagnetic attractive force generated simulated adherence forces and could be controlled and quantified by varying the direct current. A high-speed video camera was positioned directly above the particles to track their position. Current was used as a quick, controllable, and repeatable method of quantifying the pipe-wall adhesion force the particles experienced.

2.3 Magnetic Particles

To simulate and gain an understanding of the simplest mobilisation process due to the dynamics of transients a single particle was placed into the magnetic field, this eliminated any effects of particle interactions. These particles were required to be highly consistent and repeatable, therefore spherical ball bearings (φ 500 µm) weighing 0.00051 g were selected[19].

To replicate cohesive layer behaviour closer to that occurring in operational drinking water distribution networks, 35 – 145 µm irregular particles weighing 0.0049 g ± 0.0016 g were used as a powder[20]. The steel alloy grade for the powder was SAF 2507, these particles will be called powder from here on. It is important that this powder provides replication of the forces and behaviour of material layers in operational drinking water distribution systems, derived from biofilms, including particle interaction and interlocking. The powder normally exhibits some degree of such interlocking under its own self-weight. However, when placed in the electromagnetic field, these particles became magnetised and experience additional magnetic bonds between themselves, providing even better replication.

In order to ensure that the adhered material strength was the dominant parameter being investigated the experiments were always performed with some degree of magnetic adherence force. The adherence force of the analogue was in effect additional to the relatively constant particles' self-weight.

2.4 Experimental Methodology

Mobilisation in operational systems occurs when the hydraulic force exceeds the strength of the adhered material. Thus it may seem logical to increase hydraulic forces until mobilisation occurs for a fixed adherence force. However the analogue provided rapid control of the adherence force (current through the electromagnet controlled through computer software) that was quicker than manually adjusting hydraulic conditions. Therefore, hydraulic conditions were established and maintained, then magnetic force slowly reduced until particle mobilisation was observed. The current at which mobilisation occurred for given hydraulic conditions became an effective means of quantifying the mobilisation force. Comparison of these currents for different steady-state and dynamic hydraulic conditions would determine if transient tests could cause mobilisation where steady-state could not.

3. Methods

Laboratory experiments were performed in an experimental pipeline facility at the University of Sheffield, described in detail in previous papers[21,22]. Key properties of the pipeline are as follows: 50 mm internal diameter MDPE of 141 m length. Flow and pressure are representative of DWDS and are operated and monitored with strict control.

3.1 Generating Rapid Transients

A butterfly valve was installed 1.36 m downstream of the electromagnet. Valve operations were performed as rapidly as possible, within 0.2 s, and produced pseudo-instantaneous changes in pressure. Figure 3 shows the range of valve opening and closing transients generated during these experiments. The transients induced were highly repeatable and did not cause cavitation. The facility was continuously run at maximum pressure for three days prior to testing; to ensure air removal and to achieve steady-state with respect to pipe visco-elastic creep and wavespeed variability.

In order to understand if there were any fluid structure interaction effects due to the physical act of operating the transient valve, preliminary tests were run where the valve was struck with a force greater than those to move the valve. This did not cause mobilisation; therefore, fluid structure interactions were unlikely to be a factor in mobilisation.

For valve closing transients, flow transitioned from initial flow rates to zero final flow rate, i.e. decelerating flow. Adherence forces acting upon particles must be able to resist the initial steady-state hydraulic forces. Therefore, any potential mobilisation could only be due to dynamic forces generated during the transients. This is simplest and most convincing case of transient mobilisation, thus valve closing transients were performed first. For valve opening transients, flow transitioned from a zero initial flow rate to a final flow rate, i.e. accelerating flow. These are more complex than the closing transients as there is an inherent increase in steady-state hydraulic force, in addition to any potential dynamic forces. Therefore, to confirm mobilisation due to transient induced forces, it must also be proven that the adherence forces acting upon the particles at which mobilisation occurs was able to resist the final flow rate. Comparison of mobilisation due to the valve opening transients and mobilisation due to steady-state results was therefore required.

3.2 Determination of Mobilisation

Mobilisation in this work was defined by the particles surpassing a distance-based threshold in the streamwise direction. To determine if mobilisation occurred during testing, videos were recorded by a high-speed camera at 400 frames per second. The videos were then analysed by isolating the particles in each frame, locating the centroid and tracking this point through the video to create a streamwise location-time series. Figures 4 and 5 present examples of a ball bearing particle tracked through valve closing and valve opening transients, respectively. In the images, flow travels from the top of the image to the bottom, thus this direction is taken as positive.

The threshold for mobilisation required a length that clearly distinguishes a mobilisation event from other streamwise movements. Preliminary testing observed small particle oscillations occurred whilst under flowing conditions that smaller than a particle diameter[21]. For valve closing transients, a highly conservative threshold distance of 1 mm upstream in the direction of the decelerating flow was selected. This was significantly greater than the initial oscillations (see Figure 4, up to 0.475s). This threshold could be robustly and repeatedly applied to the ball bearing experiments, however the multiple particles of the powder structure meant that clear mobilisation could not be determined for the powder experiments, i.e. some of the particles surpassed the threshold, while others had not. Hence conclusive valve closing transient mobilisation experiments could only be conducted with ball bearings. Further details of the estimation and application of the threshold distance can be found in Weston et al.[21]. For steady-state and valve opening transients, the threshold distance was selected as out of the field of view downstream in the direction of the accelerating flow. This could be conclusively applied across ball bearing and powder analogues.

3.3 Experimental Testing

To insert the particles into the electromagnetic field without draining the full pipe line, a small valve installed in the acrylic pipe was opened to temporarily depressurise a defined section of the system. The particles were pipetted into the same point on the pipe invert to ensure consistent location within the magnetic field and hence subject to a consistent imposed adherence force. To avoid any potential disturbance from this position during establishing testing conditions, the electromagnet was set at maximum current of 425 mA (i.e. maximum resistance force) and the small valve was closed to repressurise the system. Initial hydraulic conditions of flow and pressure were established by adjusting system pump and valves. For steady-state experiments, the hydraulic conditions remained constant whilst the current was slowly decreased in 1 mA steps until particles mobilised past the distance threshold. For transient experiments, the initial hydraulic conditions were set with the butterfly valve at the appropriate location; for valve closing transients it was at the ‘open’ position, for valve opening transients it was at the ‘closed’ position. The valve was then rapidly changed to the alternate position to generate the respective transient. If the particle did not meet the criteria for mobilisation, the butterfly valve was slowly turned to the original position to “reset” the initial conditions. The current was decreased by 1 mA and the process repeated until the particle passed the mobilisation threshold. Once this occurred, the current at which mobilisation occurred was recorded for that particular hydraulic condition.

Preliminary steady-state testing aimed to determine the flow rate capable of mobilising a ball bearing held at maximum current. The resulting flow rate of 1.48 l/s consequently became the upper limit of the flow rates tested. The lower limit was 0.1 l/s, the lowest flow rate controllable by the system. Pressure conditions ranged from 24.7 m to 46.9 m. These hydraulic conditions were defined by the electromagnet’s range of magnetic force and system capability, and are representative of typical operational DWDS in the UK.

4. Results

4.1 Ball Bearing Steady-State

Steady-state experiments were performed to create a base line to compare to dynamic results. Currents at which mobilisation occurred produced a positive linear relationship with steady-state flow rate, which is presented in Figure 6. The region below this relationship indicates mobilisation would always occur due to steady-state forces. Experimental control and repeatability of the ball bearing particles within the electromagnetic system was demonstrated by the exceptionally low variation between repeats, while this and the strength of the linear relationship is evident in the high coefficient of determination, 0.996. During subsequent experiments, additional repeats were periodically performed to ensure the stability of this relationship, at least one additional repeat for each of the five steady-state flow rates tested. These values for the additional repeats did not exhibit any variation from the primary relationship.

4.2 Ball Bearing Valve Closing Transients

Particles were initially held by the magnetic adhesion force to resist the steady-state flow rate. Mobilisation upstream occurred only after the testing valve was rapidly closed. The high-speed camera showed that valve closing transients caused mobilisation of the ball bearing particles past the established threshold. This demonstrated that the particles were mobilised due to the additional dynamic forces generated by the transient conditions.

Figure 6 presents currents at which mobilisation occurred, as a function of initial flow rate for the valve closing transients. Limited scatter between repeats and a strong linear relationship is again evident, coefficient of determination of 0.998. Although inherent from the fact that the analogue resisted mobilisation due to the initial flow, comparison to the steady-state line confirms that, for the conditions tested, valve closings can cause mobilisation where steady-state does not. For example, a steady-state flow rate of 0.4 l/s will mobilise the particle at an average current of 44 mA, yet rapidly closing the valve at this same initial flow rate will mobilise at a higher average current of 107 mA. Therefore, a particle held at a current between these values will be mobilised by the transient and not by steady-state.

As the flow rate increases, the difference in current at which mobilisation occurs between valve closing and steady-state relationships decreases, i.e. the regression lines appear to converge. For example, the difference in average current at flow rate of 0.4 l/s is 64 mA, where at a higher flow rate of 1.0 l/s the difference is 42 mA. If the relationships were to be extrapolated, the two lines would converge at flow rate of 2.22 l/s and current of 685 mA. There is not a clear immediate reason for these specific values and they cannot be tested due to the limits of the electromagnet.

4.3 Ball Bearing Valve Opening Transients

The high-speed camera showed that mobilisation past the threshold occurred during the valve opening transients. However, mobilisation due to the dynamic transient forces was not confirmed by this as steady-state forces also increase during valve opening transients. Figure 6 presents the currents at which mobilisation occurred as a function of the final flow rates tested. Comparison of these with the steady-state flow rate vales, also presented in Figure 6 shows that the valve opening mobilisation results produce higher currents at which mobilisation occurred than for steady-state at the same flow rate. For example, a steady-state flow rate of 0.4 l/s will mobilise the particle at an average current of 44 mA, yet rapidly opening the valve to this same final flow rate will mobilise at a higher average current of 227 mA. Material held at a current (analogous to adherence force) between these values will be mobilised by the transient and not by steady-state. Figure 6 again shows the high repeatability of experiments, and a strongly linear trend with a coefficient of determination of 0.980.

As the flow rate increases, the difference in current at which mobilisation occurs between valve opening and steady-state relationships increases, i.e. the regression lines diverge. This contrasts the valve closing transient results. If the relationships were to be extrapolated, the two lines initially converge at a flow rate of 0.22 l/s and current of -20 mA, then diverge as flow rate increases. For example, the difference in average current at flow rate of 0.4 l/s is 183 mA, where at a higher flow rate of 0.5 l/s the difference is 286 mA.

4.4 Powder Steady-State

As with the ball bearing particles, steady-state experiments were performed with the powder particles to create a base line to directly compare to dynamic results. Currents at which mobilisation occurred produced a positive linear relationship with steady-state flow rate, which is presented in Figure 7. Similar to ball bearing results, experimental control and reliability was shown by a very high and a strongly linear trend with a coefficient of determination of 0.970. Subsequent repeat spot checks were consistent with this relationship.

4.5 Powder Valve Opening Transients

The high-speed camera showed that valve opening transients caused mobilisation of the powder particles past the threshold when the testing valve was rapidly opened. Fewer tests were possible with the powder material than the ball bearings due to the range of the flow rate and pressure limits set. Figure 7 presents currents at which mobilisation occurred for the range of final flow rates tested, as well as steady-state results for comparison. Limited scatter between repeats and a strong linear relationship is again evident, coefficient of determination of 0.917. Valve opening mobilisation results produce higher currents at which mobilisation occurred. Therefore, powder held at a current between these values will be mobilised by the transient and not by steady-state.

5. Discussion

5.1 Transient Mobilisation

It is clear from Figures 6 and 7 that the mobilisation current for the transient events is greater than that exhibited for the steady-state cases regardless of the type of valve operation or the type of material being mobilised. This critical results demonstrates the potential for transients to cause mobilisation in cases where the steady-state would not.

5.2 Industry Application

The ability of transients to cause mobilisation is likely to continue in pipelines with differing diameters, yet may diminish with slower valve operations. The valve operations performed in this work may be considered as extreme cases, however they are capable of occurring in operational networks. These results illustrate the importance for water network engineers to manage their networks, to understand and minimise the occurrence of transients and hence to help ensure water quality.

5.3 Linear Mobilisation Relationships

Figures 6 and 7 both present linear relationships between steady-state flow rate and current at which mobilisation occurred. The Darcy-Weisbach equation says that shear stress is proportional to steady-state flow rate squared, which is equivalent to the hydraulic force generated on the particles. At the point of mobilisation, the hydraulic force is equal to the adherence (magnetic) force. If steady-state flow rate was plotted against adherence force, non-linear (squared) relationships would be seen. However, magnetic force is proportional to current squared, meaning that steady-state flow rate and current are linearly related. As a result, the linear relationships between the steady-state flow and mobilisation current are as expected.

Figures 6 and 7 also show linear relationships between transient initial/final flow rates and mobilisation current. Again this indicates that the mobilisation force induced by the transients is increasing as a square of the initial/final flow. As the Joukowski equation suggests that the magnitude of transient (in terms of the initial pressure surge) increases linearly with increasing dynamic flow rate, this suggests that the peak mobilisation force cannot simply be related to the Joukowski effect. If the mobilisation force was simply related to the Joukowski effect it would also mean that we should expect the same magnitude of mobilisation from open and closing transients.

5.4 Valve Opening and Valve Closing Operations

The results of the experiments reported here showed that, for valve opening transients, as the final flow rate increased, their dynamic mobilisation ability increased. This was indicated by the transient and steady-state relationships diverging. This finding can be conceptually explained by a larger flow rate generating a greater transient with greater dynamic force, thus a higher mobilisation ability. In contrast, valve closing transients appear to show the opposite; as initial flow rate increased, their dynamic mobilisation ability decreased. Furthermore, decelerating flow during valve closing transients appears to have lower mobilisation ability than for accelerating flow. For example, rapidly opening the valve from zero initial flow rate to 0.4 l/s induces a current at which mobilisation occurred of 240 mA, yet rapidly closing the valve from 0.4 l/s to zero final flow rate induces a significantly lower current of 110 mA. This confirms that both accelerating and decelerating transients generate dynamic forces above steady-state mobilisation forces, but suggests that these forces are not the same in magnitude or nature, when the initial / final steady-state flow rate is used as the measure to characterise the transients.

5.5 Comparing Between Individual Particles and Powder

Two types of magnetic particles were used in these experiments: 500 µm ball bearings used individually to understand idealised behaviour, and 35 – 145 µm more irregular particles used as a powder to understand cohesive layers of material. Both types were able to be mobilised due to steady-state and valve opening transients as shown in Figures 6 and 7. The same pattern of results exists for the two materials; the valve opening relationships between flow rate and current at which mobilisation occurred sit above and diverge away from the steady-state relationships. This suggests that the hydraulic processes involved in mobilisation act the same irrespective of the nature of the adhered material. It should be noted that the values of flow rate and current at which mobilisation occurred differed between the two types of particles. The currents at which mobilisation occurred were significantly lower for the powder particles than for the ball bearings, by up to a factor of three. This implies that the powder was more resistant to mobilisation, potentially due to presenting a more streamlined structure to the flow than the rigid ball bearings, by providing a greater surface area of contact with the pipe wall or the cohesive structure itself is more difficult to move. This result is very suggestive that cohesive layers would be more difficult to mobilise that large single particles in real pipeline systems.

5.6 Equivalent Boundary Shear Stress

In this study, current through the electromagnet was used to quantify the adhesion force acting upon the magnetic particles. To gain an appreciation of the equivalent forces induced, equivalent boundary shear stresses have been calculated at an example current of 100 mA. Steady state flow rates required to mobilise ball bearing and powder particles held at this current were 0.56 l/s and 1.17 l/s, respectively. Using a Darcy Weisbach roughness of 0.1 mm, the equivalent boundary shear stresses were calculated as 0.32 Pa and 1.19 Pa. Therefore, the boundary shear stress required to mobilise the powder under steady state is considerably greater than that for the ball bearings, by factor of 3.7. This simple calculation reinforces the statements made in section 5.5.

Applying the same process to the valve opening transients tested using ball bearings shows that, for a current at which mobilisation occurred of 100 mA, the final boundary shear stress was 0.11 Pa. This is considerably smaller than the boundary shear stress under steady state conditions, again by approximately a factor of three. Two-dimension modelling of transients would give a more accurate determination of boundary shear stress induced, however this is out of scope of the present study.

5.7 Experimental Setup

Transients were measured via high temporal resolution pressure data as evidenced in Figure 3. Combined with the high-speed videos recorded, this data provided simultaneous evidence of transients and material mobilisation. This is an improvement on the literature as previous studies have not presented data to clearly evidence the occurrence of transients. Furthermore, the pseudo instantaneous transients in this work generated truly dynamic forces and the tests were repeated and repeatable.

The experiments used in this work required replicating key properties of adhered material. An innovative analogue was designed and developed using an electromagnet with ferric particles inserted into the pipeline. The experiments were consistently performed so that adherence (magnetic) strength was the parameter being investigated rather than the weight of the magnetic particles. Current through the electromagnet was utilised as a reliable, repeatable and controllable measure of adherence force. Whilst current is not a metric of material layer strength within drinking water pipelines, unlike say elastic modulus, it was useful and effective as a means to facilitate comparison between the effects of different hydraulic forces. Additionally, the use of a pseudo material meant that multiple testing conditions could be tested. Findings from previous studies have been limited in this manner, commonly examining only one dynamic event.

5.8 Separating Hydraulic Forces

A critical novel aspect of this research was to separate transient forces from steady-state forces to differentiate and assess their dynamic mobilisation ability. This was achieved by comparing transient induced mobilisation to steady-state induced mobilisation. Studies reporting mobilisation due to dynamic effects do not include direct comparison with steady-state or gradually changed hydraulic conditions in order to isolate the mobilisation forces. However, as with the experiments reported here, valve closure comparison to steady-state is not strictly necessary as the closure only reduces the pseudo steady-state conditions. A rare example of this from operational drinking water distribution systems is Karney and Brunone[10]. The experiments performed in the current work are unique in that they clearly distinguish transient mobilisation forces from steady-state forces, and provide repetition across a range of different transients. The current work also independently tested both valve closing and valve opening transients in order to understand if separate decelerating and accelerating dynamic forces could cause mobilisation. This approach extended other studies where the two effects were coupled together, such as Mustonen et al.[11] and Aisopou et al.[12].

6. Conclusions

The results of the physical experiments presented in this paper make a contribution to the fields of transients and water quality by investigating transient mobilisation of pipe-wall adhered material, under conditions fully representative of drinking water distribution pipelines. These experimental findings conclusively prove transient mobilisation, which was only suggested from indirect observations in other works, and advances them by consistently and rigorously evidencing transient mobilisation in a range of conditions. The experimental programme uniquely enabled transient forces to be distinguished from steady-state forces and their mobilisation ability quantified for individual particles and a powder that replicates a cohesive layer of material.

A key finding was the confirmation that valve closing and valve opening transients, accelerating and decelerating dynamic effects respectively, can cause mobilisation of adhered material where steady-state conditions cannot. However the differences observed in the mobilisation behaviour between the accelerating and decelerating cases suggest that these processes generate significantly different magnitudes of forces on the adhered materials. Conversely the mobilisation behaviour was consistent across the two materials used, suggesting that the dynamic processes that generate the mobilisation forces are far more critical than the nature of the material. Although it should be noted that the powder material offered overall greater resistance to mobilisation (both steady-state and dynamic) than individual particles, as was expected.

Overall the results show the important role transients can play, potentially impacting water quality within drinking water distribution systems. A direct implication of this research is that by reducing transient events a water utility provider could reduce the risk of discolouration contacts, the major cause of water quality related customer dissatisfaction.

Conflicts of interest

There are no conflicts to declare.

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Fig. 1 Cross-section schematic of ferritic particles in the pipe invert held by the electromagnet under the pipe. A camera was placed directly above the particles to record the particles.

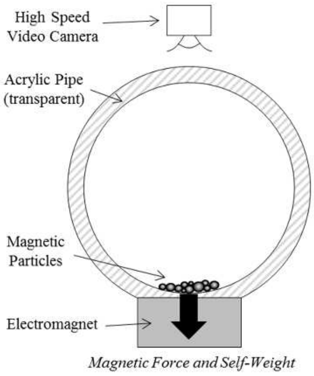

Fig. 2 Images taken by the high-speed camera of a ball bearing (a) and powder (b).

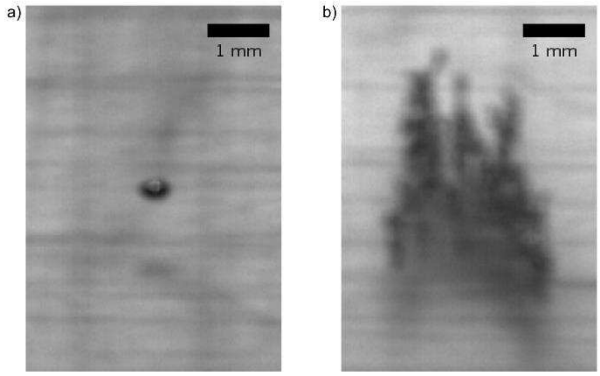

Fig. 3 Pressure traces of a) valve closing transients and b) valve opening transients tested. Traces are normalised by subtracting initial pressure and adjusted so that the first surge commences at time zero. Q_I initial flow rate, Q_F final flow rate, P_I initial pressure.

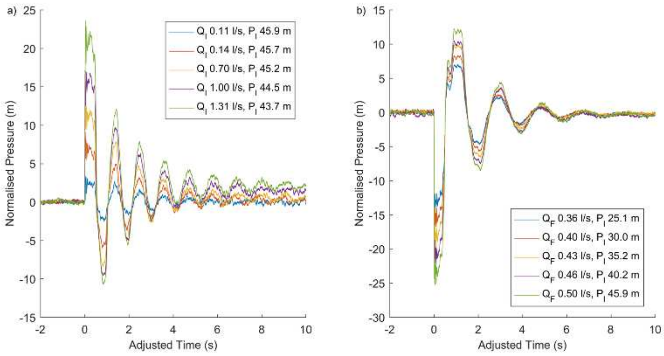

Fig. 4 Streamwise location of a ball bearing, relative to its initial position, during a valve closing transient (initial flow rate 0.70 l s^{-1}, zero final flow rate). Video frames are presented in the continuous time series data. Mobilisation occurred when the particle surpassed the upstream distance threshold.

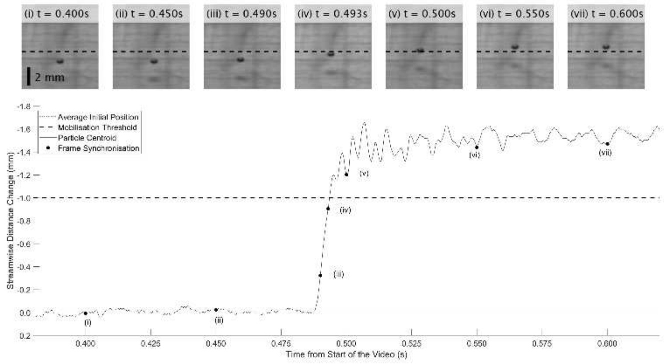

Fig. 5 Streamwise location of a ball bearing, relative to its initial position, during a valve opening transient (zero initial flow rate, final flow rate 0.49 l s^{-1}). Video frames are presented in the continuous time series data. Mobilisation occurred when the particle left the field of view downstream (image vii).

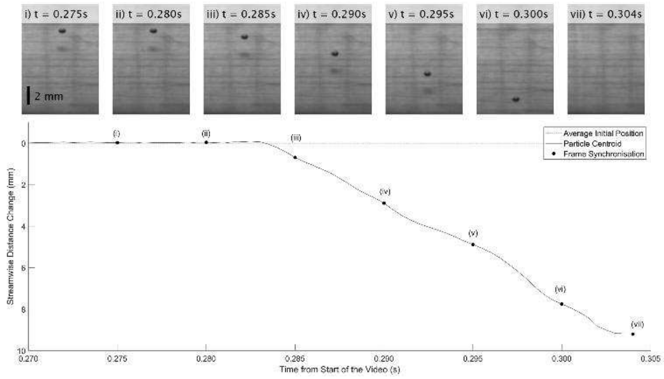

Fig. 6 Relationships between the current at which mobilisation occurred for ball bearings and steady-state flow rate, valve closing initial flow rate or valve opening final flow rate.

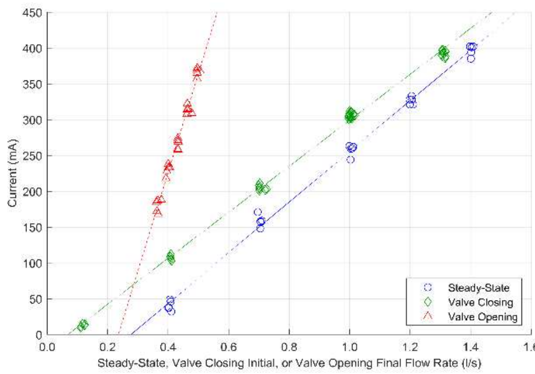

Fig. 7 Relationships between the current at which mobilisation occurred for powder particles and steady-state flow rate, or valve opening final flow rate.