

# Can a Valve Closure Transient Cause Mobilisation of Adhered Particles?

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## ABSTRACT

*Dynamic forces induced by hydraulic transients are traditionally associated with structural consequences, however attention should also be given to water quality implications. Conceptually the dynamic forces due to hydraulic transients could mobilise adhered particles and release hazardous material into the bulk water, potentially causing public health and economic problems. This paper presents a set of controlled and systematic experiments that conclusively prove, for the first time, the ability of valve closure transients to mobilise an adhered particle where steady state conditions cannot. This is a significant finding as there is a net decrease in flow, hence pseudo steady state shear stresses, yet the dynamic forces are greater than the initial conditions. Future work will aim to deepen this new understanding of the impact of transients on water quality in Drinking Water Distribution Systems.*

**Keywords:** Transients; Water Quality; Mobilisation.

## 1 INTRODUCTION

In 2015 one in three significant incidents in UK Drinking Water Distribution Systems (DWDS) involved discoloured water, an aesthetic indicator of water quality [1]. These failures affected 6.7 million people and led to heavy fines for associated water companies despite significant ongoing investment. The commonly-accepted theory explaining discolouration incidents is that cohesive material is mobilised from the pipe wall into the bulk flow by increasing the hydraulic shear stress beyond the material's conditioned strength [2,3]. These hydraulic changes are commonly considered to occur gradually as DWDS are historically considered as steady state systems, yet recent studies have challenged this interpretation by showing DWDS are truly dynamic due to the occurrence of hydraulic transients [4,5]. Transients are traditionally associated with structural consequences, however attention should also be given to the water quality implications.

## 2 BACKGROUND

Hydraulic transients, or water hammer, are generated by any and every rapid change in velocity and manifest as proportional changes in pressure. Transients in DWDS include, but are not limited to, sudden flow control valves opening/closing, pump changes and burst events. These may be initiated by the system operator, be imposed by an external event, be caused by a faulty component or develop insidiously because of poor maintenance. Transients can be identified by key characteristics of an oscillating nature, short duration, and a propagating dynamic wave speed ranging from 100 to 1400 m/s as a function of the pipeline material. Critically dynamic shear stresses are induced by transients, originating from the formation of complex velocity profiles, impulse wave propagation and other

dynamic effects [6]. Valve closure transients have been shown to generate unsteady shear stresses up to an order of magnitude, or more, greater than steady state conditions [7].

Previous literature examining transient mobilisation ability is limited and not conclusive, either through modelling [8, 9] or physical testing [10]. Transient mobilisation is indicated; however, for data collected in operational DWDS, high temporal resolution pressure data was not presented, it is unknown if transients were systematically generated. In a laboratory setting, Lehtola et al. [11] specifically explored the mobilisation effect of pressure shocks introduced by air valves halting water flow rapidly before rapidly being opened in experimental copper and plastic pipelines. The authors observed that immediately after the pressure shocks concentrations of materials (iron, copper, heterotrophic plate counts) increased by up to 19 times, as well as levels of turbidity and electrical conductivity. However, it is not known if this increase is directly attributable to the rapid valve closure as the valve opening could have increased the flow rate past the conditioning value.

### 3 AIM

The aim of this paper is to determine if a valve closure transient can mobilise adhered material, where steady state flow cannot, for a range of flow rates. The purpose of exploring a valve closure transient is that there is a net decrease in flow, thus any potential mobilisation will be solely due to dynamic effects.

### 4 METHODOLOGY

A key requirement of the experiments performed here was to create repeatable and representative adhered material. Naturally accumulated/grown material associated with discoloration is inherently non-engineered, i.e. not standardised in terms of structure, strength or control [12]. However, it has been established that the material strength is a variable function of the hydraulic conditions [13]. Hence, this research used a pseudo system to repeatedly test hydraulic forces necessary for mobilisation. The bespoke system created used magnetic particles placed individually in the pipe held by an electro-holding magnet placed flush against the pipe, see Figure 1. An electromagnet was selected as the variable current through the magnet could simulate a range of controlled adhesion forces on the particles.

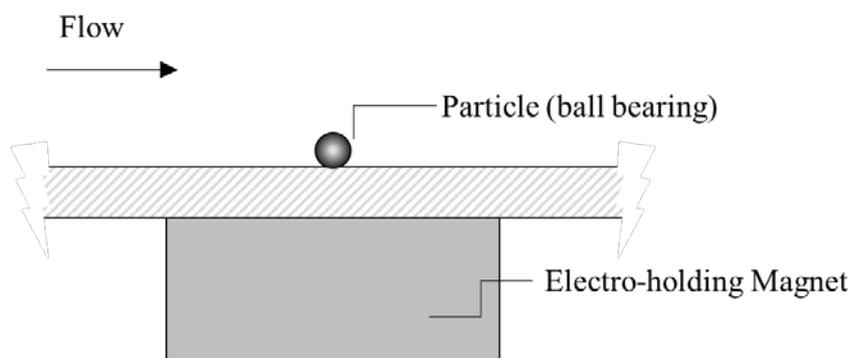


Figure 1: Schematic of particle and electro-holding magnet system

To determine if a valve closure transient could mobilise the particle where steady state could not, steady state hydraulic conditions were tested followed by valve closure tests for direct comparison. The approach involved establishing the hydraulic condition and gradually decreasing the current until

the particle met the threshold for mobilisation, judged from high speed video. This established a ‘current at which mobilisation occurred’ where the resistive force was just overcome by the hydraulic forces.

## 4 METHOD

### 4.1 Facility

The facility utilised for this experiment consisted of 141 m of 50 mm nominal internal diameter medium-density polyethylene (MDPE) pipe configured as a recirculating system, where steady state flow rate and pressure were manipulated by a variable speed pump and downstream control valve (see Figure 2). The system was instrumented with a Flow Systems Model 910E Electronic Flow Meter, accuracy  $\pm 0.01$  l/s, and three GEMS 2000 series pressure sensors, accuracy  $\pm 0.16$  m, recording at 2000 Hz. At an approximate distance of 82 m from the reservoir tank, a 600 mm section of clear acrylic pipe replaced the MDPE to create a test section between pressure sensors B and C. Pressure transients could be repeatedly generated via rapid change of a quarter turn butterfly valve just downstream of this test section. It is of note that prior to all dynamic tests the facility was run continuously for three days so that the pipeline material was at maximum strain, thus generating repeatable wave speeds and propagating transients.

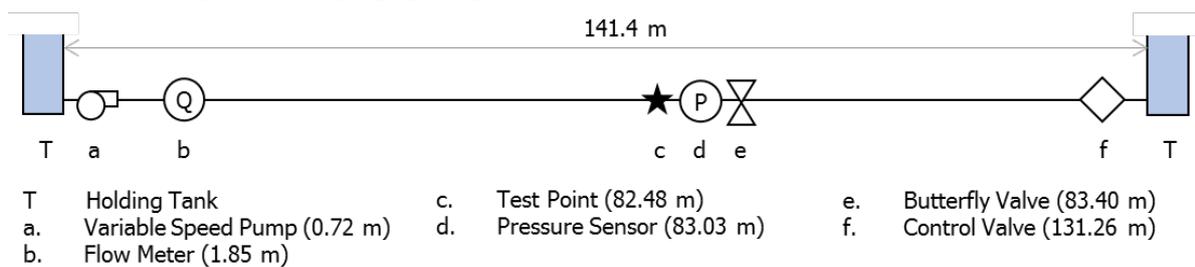


Figure 2: Laboratory facility schematic, including key features and distances from the holding tank

Availability and handling considerations led to the selection of 0.5 mm spherical magnetic particles. A small valve was fitted near the crown of the test pipe to directly pipette these particles into position in the pipe invert above the electromagnet. A SVSi Gigaview High Speed video camera was positioned directly over the electromagnet recording at 100 fps. Combined with a thin grid placed between the external pipe wall and the electromagnet as well as a local light source, the particles were illuminated and tracked to confirm if mobilisation occurred.

### 4.2 Particle Oscillation

During periods of flow a small amount of particle movement occurred in the radial and streamwise directions. To quantify these oscillations, the particle was tracked during three seconds of high speed video at different flow rates and the standard deviation of these movements calculated in both directions. The higher the flow rate, the greater the oscillation, see Figure 3; most likely due to turbulent structures acting upon the sphere, however this was not measured. The combination of the electromagnet, curvature of the pipe and flow structures resisted motion in the dominant streamwise direction, consequently these oscillations are smaller in general. The mobilisation thresholds, steady state and valve closure, must be further than these distances to establish a clear difference between induced mobilisation and these movements.

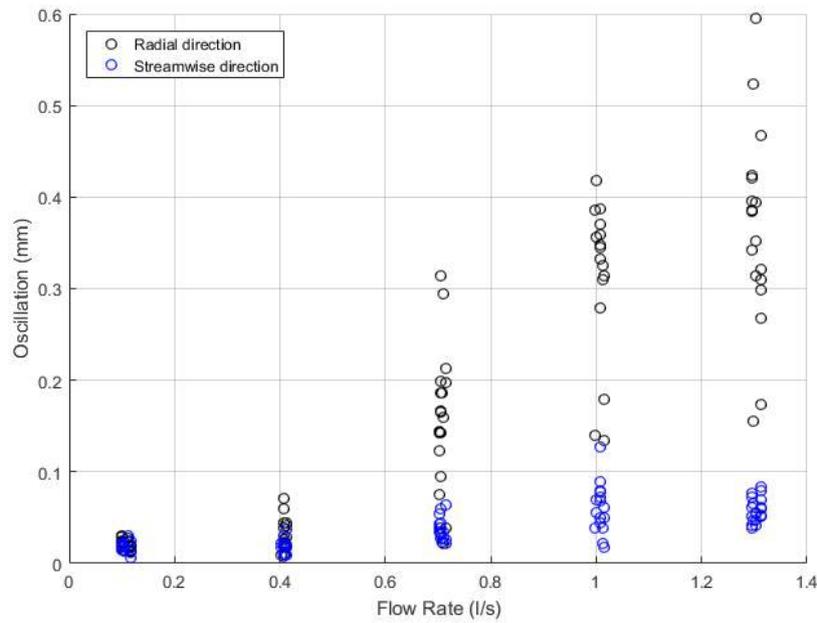


Figure 3: Quantified particle oscillation in the radial and streamwise directions for a range of flow rates.

#### 4.2 Steady State Testing

The aim of performing steady state tests was to establish a ‘base line’ so that additional dynamic forces could be compared. The particle is considered mobilised, i.e. steady state mobilisation threshold, if the particle is carried downstream by the flow further than the magnetic field. To test, the desired flow rate was established and the current decreased until the particle mobilised. Preliminary testing showed that at the electromagnet maximum current capacity, a flow rate of 1.57 l/s could mobilise a particle. Similarly, a flow rate of 0.26 l/s mobilised a particle when the particle was acting solely under its self-weight. Therefore, seven desired flow states for testing were selected between 0.3 to 1.5 l/s and five repeats conducted at each in a fully randomised order to remove any testing bias. Random tests (‘spot-checks’) of the steady state relationship were performed throughout the transient experimental work to determine system repeatability.

#### 4.3 Valve Closure Testing

The aim of these transient tests was to determine if a valve closure transient could mobilise an adhered particle. A butterfly valve (see Figure 2 label e) was rapidly moved from fully open to fully closed to generate transients. The particle is considered mobilised, i.e. valve closure mobilisation threshold, if the particle is carried in the streamwise direction by 0.5 mm, the diameter of the particle. This is five times the maximum streamwise oscillation, see Figure 3, therefore a clear threshold between induced mobilisation and the particle oscillations. Five desired initial flow rates were selected for testing between 0.1 to 1.3 l/s, again five repeats performed at each flow rate in a fully randomised order.

## 5 RESULTS

Steady state hydraulic tests resulted in a relationship between the bulk flow rate and current through the electromagnet: as the flow rate increases, a higher current (adhesion force) is needed to resist motion. A linear regression line produced an extremely high coefficient of determination, 0.994, confirming the consistency and repeatability of this method. Spot-checks showed no variation from this relationship.

Figure 4a illustrates the repeatability of valve closure transients generated at a flow rate of 0.1 l/s and Figure 4b shows the distance travelled upstream of a particle due to these transients until it exceeded the mobilisation threshold at 16 mA.

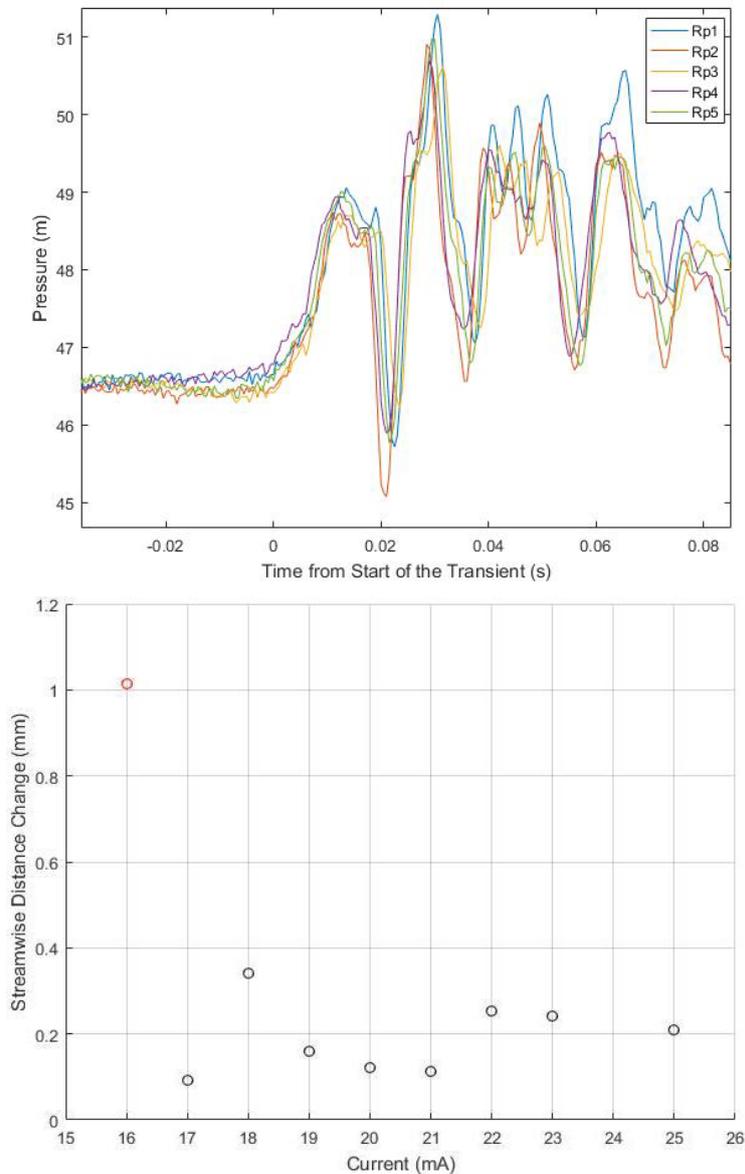


Figure 4: a) Valve closure transients at a flow rate of 0.1 l/s illustrating transient repeatability b) Streamwise distance change of a particle at 0.1 l/s. Once this particle reached 16 mA it met the mobilisation threshold (red circle).

In general, as the current decreased the distance travelled upstream by the particle increased. Once the mobilisation threshold of 0.5 mm was reached, however, this exact distance was not maintained with decreasing current, i.e. a clear consistent step change in streamwise distance changes did not occur. On the contrary a variety of streamwise distance changes was exhibited for current changes of 1 mA. These distance changes are not a function of current, initial flow rate or initial oscillation of the particle in the flow, see Figure 5. As the particle has moved upstream by at least 0.5 mm, mobilisation occurred in all cases and thus all currents were treated as repeats for which mobilisation occurred.

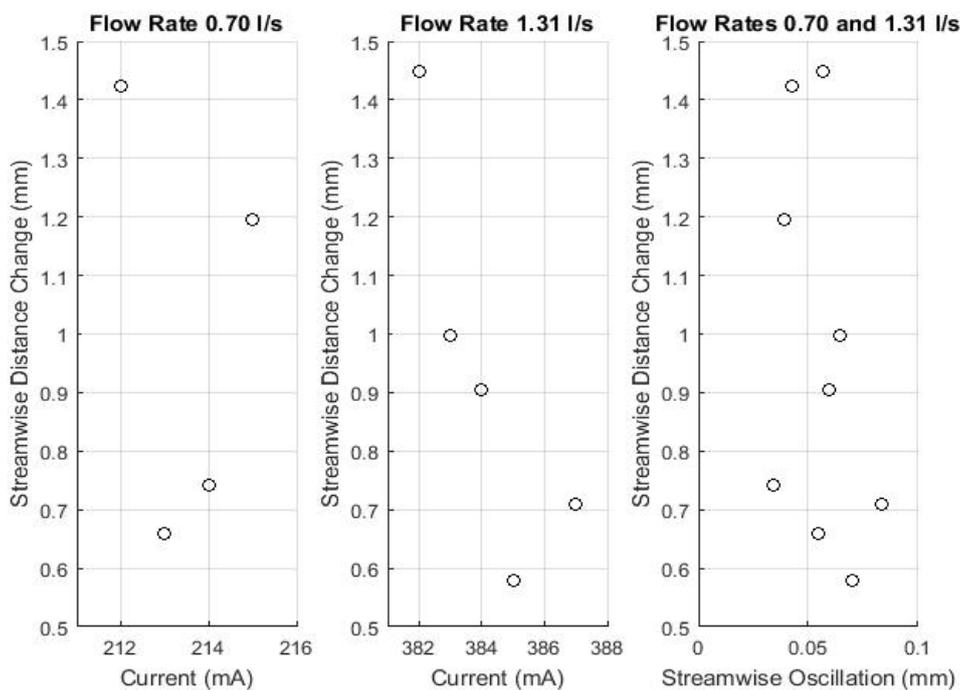


Figure 5: Two examples of particles that have passed the mobilisation threshold, but show no further relationship between streamwise distance change and current or flow.

Figure 6 presents the current at which mobilisation occurred for steady state flow rates and valve closure initial flow rates, for all repeats. The valve closure transients also result in a linearly positive relationship with an extremely high coefficient of determination of 0.998. This figure shows that a rapid valve closure transient can mobilise a particle with a higher current (adhered force) than for the equivalent initial steady state flow rate. For example, a flow rate of 1 l/s could mobilise a particle held at ~ 255 mA, but rapidly closing a valve can mobilise a stronger particle at ~ 300 mA. Over the current range tested, the average difference between steady state flow rates and valve closure initial flow rates  $0.15 \pm 0.04$  l/s. In all valve closure cases, the bulk flow rate did not exceed the initial conditions thus this variation must be solely due to the dynamic forces generated.

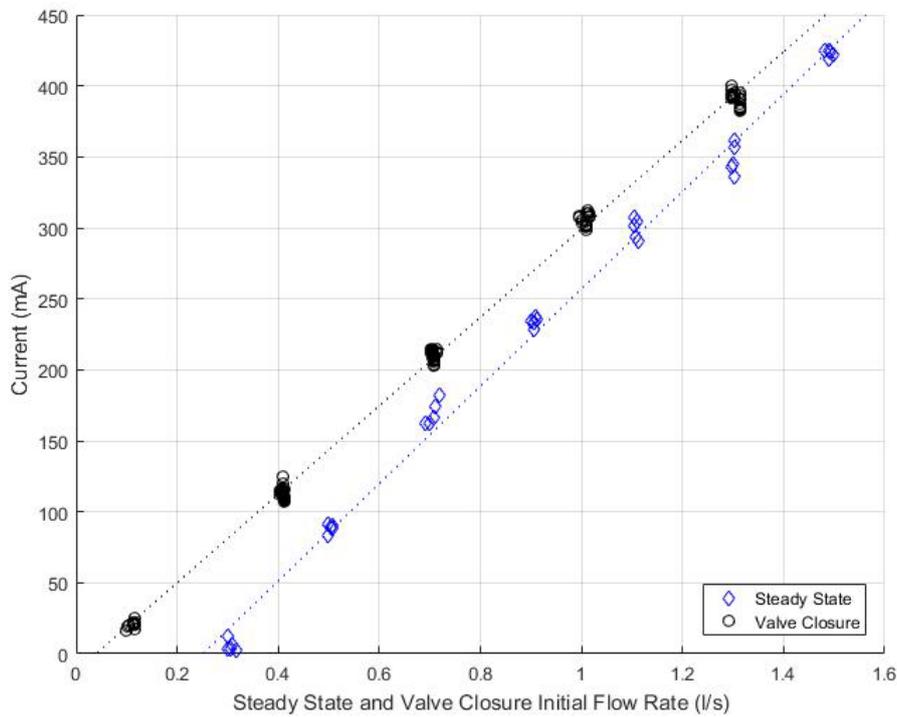


Figure 6. Relationship between the current at which mobilisation occurred and steady state and valve closure initial flow rates.

## 6 RESULTS

This experiment has shown the ability of valve closure transients to mobilise an adhered particle, where steady state cannot. The mobilisation thresholds defined are much greater than normal oscillation of the particles in the flow and produce results with a high degree of repeatability and low experimental error; the variation in the transient results is most likely attributable to experimental accuracy of results rather than a lack of repeatability in the forces imposed by rapid valve closure transients. The results show linear regression lines that are conceptually valid as a hydraulic/magnetic force balance:

$$Q^2 \propto \tau \propto F_{hydraulic} = F_{magnetic} \propto I^2$$

$$\therefore Q \propto I$$

Where  $Q$  is the bulk flow rate,  $\tau$  is the hydraulic shear stress and  $I$  is the current through the electromagnet. The results shown in Figure 6 suggest that the lines converge at a flow rate of 2.35 l/s. As there is no justification for this value, this conversion could be a by-product of the range of flow rates tested here as well as experimental scatter.

The limitations of this experimental work exist mainly in extrapolation to the material typically seen in DWDS. The particles used here are larger than typical discolouration material, thus intrude further into the bulk flow potentially causing frontal area effects. Furthermore, organic material will have elastic properties not present in the steel chrome-steel ball bearings used here, which might alter how the forces interact and cause mobilisation. Previous work has tried to test within this limitation, i.e. using organic material directly grown in DWDS as described in *Background*, but those experiments lack the rigour and repeated evidence presented in this work.

## 7 CONCLUSIONS

In this paper, a set of experiments are presented that conclusively prove, for the first time, the ability of valve closure transients to mobilise an adhered particle where steady state conditions cannot. This is a significant finding as there is a net decrease in flow, hence pseudo steady state forces, yet the dynamic forces generated are greater than the initial conditions. This experiment offers a controlled and systematic approach that shows the dynamics of a valve closure can induce significant stresses beyond the initial conditions that lead to particle mobilisation. Future work will aim to explore the mechanisms of transient mobilisation and how this relationship between hydraulic and magnetic forces develops with different particles. Ultimately this work could lead to a deeper understanding of the impact of transients on water quality in DWDS.

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