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Proceeding Paper

Identifying Hydraulic Conditions for Discolouration Material Accumulation †

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Abstract: Understanding the interactions between hydraulic conditions and the accumulation of discolouration material in drinking water distribution systems is crucial to help identify risk locations and inform effective maintenance. With two accumulation processes now acknowledged and the known range in size and characteristics of discolouration material, this is not a trivial challenge. A full-scale pipe loop system, adapted for precise flow control and with multiple turbidity monitors, was dosed with discolouration material collected from operational networks. By tracking changes in bulk water material loading, this study indicates that at above 1.25 L/s (0.25 m/s, Re 15,000, 0.213 N/m^2), a change in accumulation behaviour occurs.

Keywords: discolouration; accumulation; sedimentation; cohesive layers; hydraulic conditions

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1. Introduction

To understand discolouration risk in drinking water distribution systems (DWDS), it is vital to understand how the particulate material responsible accumulates [1,2]. The literature has presented two processes: firstly, sedimentation as particles settle due to gravity (particle self-weight forces) resulting in sediments at the pipe invert [3–5]. The second process involves particles coming into contact with pipe walls and accumulating there as cohesive material layers [2,6]. Only recent studies have acknowledged that both can occur simultaneously [2]. Sedimentation research has traditionally focused on defining unique hydraulic thresholds, implying the cessation of accumulation irrespective of the process, whereas cohesive layer research has reported accumulation below and mobilisation above imposed hydraulics. Given the range of particle sizes found in DWDS [6,7], the existence of specific thresholds is unlikely, and broader hydraulic conditions that influence material accumulation processes have not been identified [2,7]. It has been acknowledged that location within the DWDS will affect which process dominates; for example, sedimentation is suggested as the primary cause of localised high concentrations of material accumulation. The understanding of the hydraulic conditions that permit localised and elevated material accumulation, however, remains debated [2,5].

The aim of this study was to evidence the interactions between hydraulic conditions and discolouration material accumulation behaviour under controlled conditions by monitoring changes in bulk water turbidity. To replicate operational conditions found in areas with localised elevated material accumulation, discolouration material sourced from these locations were introduced into a full-scale pipe loop that had been modified to allow for precise hydraulic control and extensive turbidity monitoring.

2. Materials and Methods

2.1. Experimental Plan

To mimic flows found at the downstream areas of the network where increased accumulation has been reported [2], a full-scale pipe loop at the University of Sheffield was modified with precision valves to permit 0.02 L/s controlled increments up to 5 L/s (1 m/s). In summary, the pipe loop is a recirculating 200 m of 79 mm HDPE, with a 0.8 m^3 tank and pump and control valves supporting fully programmable pressure and flow management. To track changes in material concentrations in the bulk water as it undergoes exchange with the system (i.e., pipe walls or sedimentation in response to changing hydraulics) and support data validation, 3 turbidity monitors over the pipe length with 1 s logging were used. With fixed pipe loop properties (diameter, roughness, etc.), consistent conversion among hydraulic parameters such as flow, velocity, Reynolds number, and shear stress is maintained, for example, in this system flow (L/s) $\approx 5 \times$ velocity (m/s).

2.2. Discolouration Material

To focus on investigating the behaviour representative of DWDS, material samples were collected from operational networks, allowing for the comparison of different source materials, and introduced into the pipe loop. To obtain measurable responses to hydraulic changes, a starting concentration of around 1 NTU was targeted as matching the UK regulatory value for water-exiting treatment works. Particle sizing analysis showed an average particle size of 10–15 µm (volume % distribution), indicating that the material from the networks of 2 UK companies was consistent with particle sizes expected from DWDS.

2.3. Hydraulic Conditions Investigated

To test hydraulic conditions, experiments used repeated accumulation cycles at set flow rates for two hours, this time determined as sufficient to allow a major fraction of the material to transition from the bulk water to the system when conditions permitted. Following each cycle, the material was re-mobilised and mixed at the peak flow of 5 L/s. Between experimental runs, the system was cleaned prior to the fresh material being added. A baseline accumulation flow of 0 L/s (zero flow) was initially selected with the literature informing further values, including 0.3 L/s (0.06 m/s), which is considered effective for preventing sedimentation [4,5], and 1.25 L/s (0.25 m/s), which is acknowledged as the design condition for a Dutch self-cleaning network [3]. Further values included 0.6 L/s, 2.5 L/s and 5 L/s.

3. Results and Discussion

3.1. Quantifying Hydraulic Conditions and Turbidity Decrease

Figure 1 shows the bulk water decrease in turbidity and percentage decrease (where a 100% decrease would be 0 NTU in the bulk water) as box plots for different flows. The largest decrease in turbidity (and percentage decrease) was observed at a flow rate of 0.3 L/s, which was approximately 15% higher compared to the turbidity decrease at 0 L/s. In comparison to 0.3 L/s, the turbidity decrease was 7% lower at 0.6 L/s and 1.25 L/s (still higher than at 0 L/s), with both exhibiting a similar percentage decrease despite different hydraulics. At 2.5 L/s, there was only a 10% decrease, while 5 L/s showed an almost negligible decrease over the 2 h accumulation period.

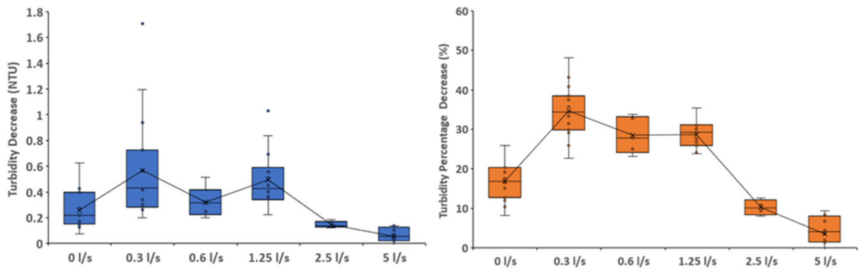

Figure 1. Bulk water and percentage decrease in turbidity over the 2 h accumulation period for set flow rates.

3.2. Identifying Change in Turbidity Decay Pattern

Turbidity percentage change (normalising the turbidity change to start from 100% and finish at 0%) was calculated across all experiments, and decay curves combined with best-fit lines are shown in Figure 2. At flows of 0, 0.3, 0.6 and 1.25 L/s, an exponential decay in turbidity was observed, characterised by an initial rapid decay at the onset followed by a more gradual decline. Due to a small change in overall turbidity (Figure 1) at 2.5 and 5 L/s, the response appears noisier. At those flows, the decay appears more linear with a distinctive rapid decay observed in experiments with lower flows absent.

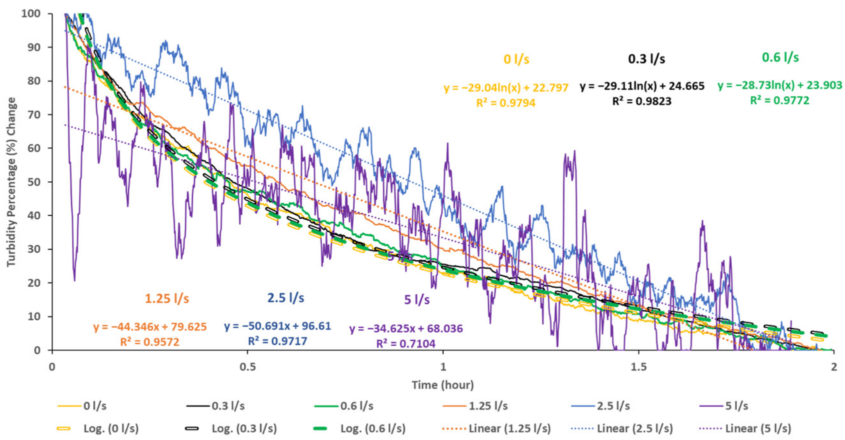

Figure 2. Turbidity percentage decay and best-fit lines over a 2 h accumulation period for set flow rates.

A summary of hydraulic conditions corresponding to the flow rates utilised and indicative of processes occurring in the pipe loop is presented in Table 1. Across all the experiments, 0.3 L/s was the flow rate at which peak accumulation occurred. While shear stress (0.015 N/m^2) and velocity (0.06 m/s) remained relatively low, the Reynolds number was on the limit of full turbulence (±3600). As individual particle sedimentation is influenced by turbulence forces, it is suggested that at this hydraulic condition, sedimentation is still able to occur and is the dominant method of material accumulation. This finding also indicated sedimentation occurring at 0.06 m/s, contradicting some previous research proposing sedimentation stops at this value [4].

The transition from exponential to more linear behaviour was observed when increasing the flow from 1.25 L/s to 2.5 L/s, which also corresponds to a doubling of velocity and Reynolds number (from 15,000 to 30,000), resulted in a 72% increase in shear stress (due to the exponential scaling with respect to flow), rising from 0.213 to 0.768 N/m^2. With the percentage reduction in turbidity decreased to 10%, it is proposed that sedimentation is less prevalent, with material accumulation now dominated by cohesive layer processes.

While velocity may be used to indicate hydraulic conditions for changes in material behaviour, both shear stress (exponential scaling) and Reynolds number (laminar-turbulent regimes) provided additional information. Shear stress or Reynolds number may also be more valid to account for diameter and roughness effects in order to characterise material accumulation processes across DWDS.

Table 1. Experimental hydraulic conditions and proposed accumulation process.

Flow (L/s)	Velocity (m/s)	Reynolds Nr ≈ (at 10 C)	Shear Stress (N/m^2)	Average Turbidity Decrease (%)	Proposed Accumulation Process
0	0	0	0	20.6	Sedimentation
0.3	0.06	3600	0.015	34.5	Sedimentation, cohesive layers
0.6	0.12	7200	0.055	28.5	Less sedimentation, more cohesive layers
1.25	0.25	15,000	0.213	28.5	Some sedimentation, more cohesive layers
2.5	0.50	30,000	0.768	10.2	Cohesive layers
5	1.00	60,000	2.770	4.0	Cohesive layers

4. Conclusions

A change in the behaviour of DWDS discolouration material transitioning between the bulk water and the system is observed above 1.25 L/s (0.25 m/s, Re 15,000, 0.213 N/m^2), with elevated material accumulation for flows below this. It is proposed that this indicates a move from sedimentation to cohesive layers as the dominant material accumulation process. Understanding this hydraulic condition can facilitate hydraulic models to identify pipes with elevated material accumulation, inform network design and support maintenance strategies to manage discolouration risk.

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