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A Novel Reverse Unidirectional Flushing (R-UDF) Method to Mobilize Iron Oxide Particles from PVC Pipes of a Full-Scale Laboratory System †

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Abstract: The aim of the present work is to test a novel Reverse Unidirectional Flushing (R-UDF) approach to achieve an enhanced removal rate of iron oxide particles from drinking water pipes. The project utilized a full-scale PVC pipe loop laboratory system to successfully isolate direction as a particle mobilization factor. Even after successive flushing operations in one direction, a subsequent flush in the opposite direction mobilized new particles from the pipe wall surface. This shows that there are some areas in the pipe loop system that may protect deposited particles from flushing shear stresses in a determined flow direction.

Keywords: unidirectional flushing; iron oxide particles; pipe roughness; drinking water discoloration

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1. Introduction

It has been suggested that the spatial arrangement of iron particles on the wall of PVC pipes devoid of any biofilm depends in part on the conditioning flow field in the pipe, and the size of the particles moving through the pipe relative to the roughness elements of the pipe to which they eventually become adhered [1]. In this context, whether a particle will be mobilized by higher flows and shear stresses when a pipe is flushed depends in part on how well a roughness "valley" can protect the particle that is seated in it against the wall shear stress (WSS) induced by the flow in the pipe. Working with PVC pipes, Braga and Filion [2] found that the self-weight of the particles seated in these roughness "valleys" played an important role in determining whether they could resist the WSS and remain attached to the pipe wall.

The aim of the present work is to test a novel Reverse Unidirectional Flushing (R-UDF) approach to achieve an enhanced removal rate of iron oxide particles from drinking water pipes [3–5]. The working hypothesis is that inducing a flushing flow in the opposite direction to the operational flow of the network will reduce the capacity of the roughness "valley" to protect the seated particle, and thus facilitate the particle's mobilization from the pipe wall.

2. Materials and Methods

The experimental program was performed in the Drinking Water Distribution Laboratory (DWDL) at Queen's University (Canada)—a full-scale pipe loop system with 200 m of 108 mm diameter PVC pipes capable of partially replicating the hydraulics of operational networks. An open-end configuration was used in the experiments: (i) drinking water was supplied to a 3800 L tank, (ii) centrifugal pumps drew water from the tank and introduced flow at the pipe loop entrance, and (iii) after passing through the pipes, the water was discarded to a drain.

A set of two experiments (A and B) were performed, each divided into two phases: conditioning and flushing, where only the flushing phase differed between experiments. During the conditioning phase, a constant flow rate of 0.9 L s^{-1} was established in the pipes and synthetic iron oxide particles (Fe_2O_3) were injected into the middle of the pipe loop. Precise control over particle injection was achieved using a diaphragm pump that drew water from a mixing tank with a known particle concentration. This setup allowed the production of finite 'particle plugs' with a length of 240 m to travel through the pipe loop. The conditioning phase of each experiment consisted of the passage of a total of two particle plugs to allow a higher quantity of particles to be deposited at the pipe wall.

Following the conditioning phase, the pipe loop was flushed using a sequence of flushing stages at different directions and flow rates to test the new R-UDF technique. Forward and reverse flushing directions were tested, and two flow rate magnitudes (1 and 2) with flow rates of 6.5 L s^{-1} and 11.0 L s^{-1}, corresponding to velocities of 0.70 m s^{-1} and 1.2 m s^{-1}, and WSS values of 1.2 Pa and 3.0 Pa, respectively. In Experiment A, the flushing phase consisted of a forward flushing stage 1 (FFS1), reverse flushing stage 1 (RFS1), forward flushing stage 2 (FFS2), and reverse flushing stage 2 (RFS2) (Figure 1). While in Experiment B, the reverse stages were performed before the forward stages in the following sequence: RFS1, FFS1, RFS2, and FFS2. In addition, three flushing repetitions were executed for each stage to guarantee that all mobilized particles exited the system. For each flushing repetition, the pipe loop was flushed for a total of three pipe loop volumes. Figure 1 indicates the different phases and the order they were executed during Experiments A and B.

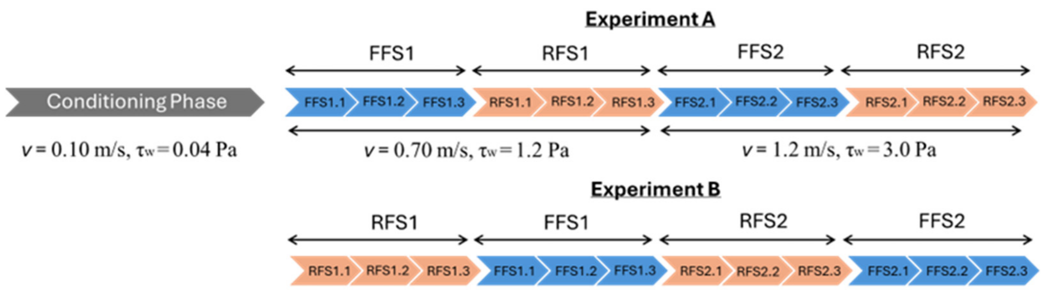

Figure 1. Description and order of stages for Experiments A and B.

Continuous high-resolution turbidity measurements (1 Hz) were collected with three Hach TU5300sc turbidimeters located at the entrance (T1), middle (T2), and exit (T3) of the pipe loop. In addition, the suspended sediment concentration (SSC) of the bulk water was measured through a traditional gravimetric method using fiberglass membranes with a pore size of 0.7 µm.

3. Results

The particle suspension injected into the pipe loop for both experiments had an SSC of approximately 500 mg L^{-1}, which resulted in a consistent particle plug concentration of 13 mg L^{-1} for both experiments. This SSC was lower than the targeted plug concentration of 20 mg L^{-1} due to the loss of part of the particles in the mixing tank. At the middle sample port located a few meters downstream of the injection point, an average SSC of 7.1 mg L^{-1} was measured for Experiment A and 7.2 mg L^{-1} for Experiment B, corresponding to turbidities of 25.5 NTU and 26.5 NTU, respectively. At the second sample port located at the end of the pipe loop, an average SSC of 5.6 mg L^{-1} was obtained for Experiment A and 5.0 mg L^{-1} for Experiment B, corresponding to turbidities of 23.5 NTU and 24.9 NTU, respectively. The decrease in the SSC along the passage of the plug demonstrates the deposition of iron oxide particles in the pipe loop. It is worth noticing that between the two monitoring sections, the SSC decreased by 26% but the turbidity only decreased by 8%, highlighting the large sensitivity difference between the two metrics.

Each plug had introduced approximately 28.3 g of iron oxide particles in the pipe loops, but only 15.7 g and 11.7 g were estimated to pass through the sample ports T2 and T3, respectively. This suggests that 12.6 g (45%) of particles were deposited between the injection point and the first sample port and an additional 4 g (14%) of particles were deposited between the first and second sample ports, while the rest of particles (41%) remained in suspension and were discarded at the end of the pipe loop.

Figure 2a shows the first repetition of *flushing stage 1*, FFS1.1 and RFS1.1 for Experiments A and B, respectively. The turbidity readings were taken from the sample ports furthest downstream from the injection point. Both curves showed dramatic spikes in turbidity followed by steep declines. The SSC measured at the first repetition of *flushing stage 1* resulted in an average value of 13.0 mg/L for both experiments. Figure 2a shows a more gradual increase and a sharper decrease in turbidity for Experiment A, while a sharper increase in turbidity and more gradual decrease was noted in Experiment B, highlighted by an increase between 0.8 and 1.0 pipe loop volume turnovers. Figure 2a also shows that the turbidity level at the end of the 1st flushing repetition was not returned to baseline levels of 0.040 NTU. This suggests that a small concentration of suspended particles remained in the bulk water even after a complete replacement of the pipe loop water.

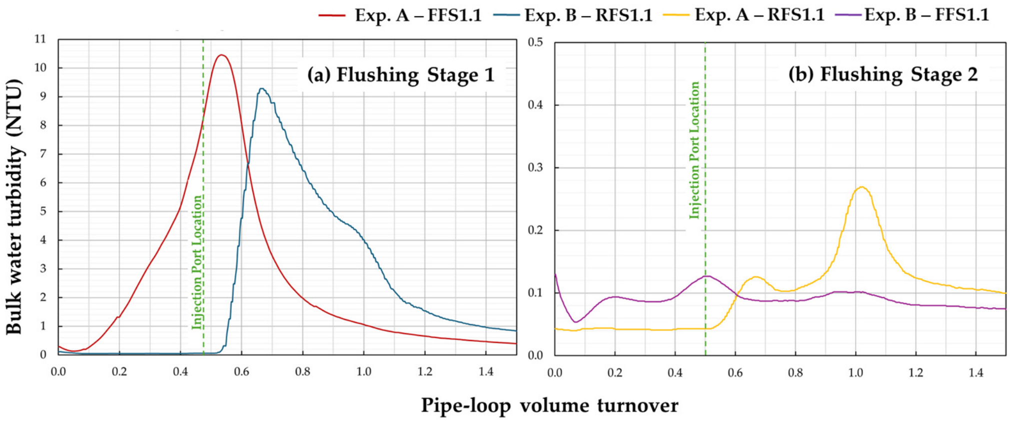

Figure 2. (**a**) Flushing stage 1 turbidity profiles for Exp. A—FFS1.1 and Exp. B—RFS1.1. (**b**) Flushing stage 2 turbidity profiles for Exp. A—RFS1.1 and Exp. B—FFS1.1.

Figure 2b shows that when the direction was switched for *flushing stage 2* there were still consistent increases in turbidity above the baseline, but in substantially smaller magnitudes than the *flushing stage 1*. Here, Experiments A and B correspond to RFS1.1 and FFS1.1, respectively. Both curves show two "humps" in turbidity; however, the increases in turbidity in Experiment A are larger and more defined than Experiment B. The increase in turbidity occurs earlier in Experiment B than in Experiment A, which shows a low turbidity until 0.5 pipe loop turnovers. These results suggest that *flushing stage 1* redistributed particles along the pipe loop which were mobilized by a change in flow direction during *flushing stage 2*. In Experiment A, particles were only detected from the second half of the pipe loop length (since it was initially flushed in the forward direction), but in Experiment B, particles were detected along the whole pipe loop length at a smaller amount.

4. Discussion

The highest loads of particles were deposited close to the injection point (immediately after their inoculation) [6]. However, smaller depositions also occurred as suggested by the shapes of the profiles in Figure 2a. This deposition pattern was further elucidated by the characteristics of the curve obtained from Experiment B (Figure 2a).

The turbidity profile of Experiment A, RFS1.1 (Figure 2b) is representative of the particle distribution in the pipe loop after a full stage of flushing in the forward direction. The curve features two "humps" with the first being approximately half the size of the second. The first increase occurs just after 0.5 turnovers, which corresponds to a location just downstream of the injection point where most particles were noted to be deposited. The second and larger hump occurs at around 1 turnover, suggesting that most particles came from a location near the exit of the pipe loop. The particles that correspond to the injection point were most likely not fully mobilized by the first stage of the forward flushes. However, the particles that correspond to the exit of the loop were most likely mobilized in the first flushing stage and then resettled along the pipe loop length and contributed to an increase in turbidity near the exit. The corresponding turbidity curve for Experiment B FFS1.1 (Figure 2b) has a higher starting turbidity due to the distribution of particles up to the exit of the pipe loop after the conditioning phase. Furthermore, the hump in the turbidity curve for Experiment B (Figure 2b) occurs earlier than the Experiment A counterpart, mirroring the relationship between forward and reverse as seen in *flushing stage 1* (Figure 2a).

5. Conclusions

The flushing protocol used in this set of experiments was successful in isolating direction as a factor in mobilizing iron oxide particles from the surface of PVC pipes using a full-scale laboratory system. The turbidity profiles of the flushing stages showed that even after successive flushing operations in one direction, a subsequent flush in the opposite direction will mobilize new particles from the pipe wall surface. This shows that there are some areas in the pipe loop system that may protect deposited particles from flushing shear stresses in a determined flow direction.

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