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MODEL FAST DEPOSITION OF FINE IRON OXIDE PARTICLES ON PVC PIPE MAINS DURING THE PASSAGE OF A SUSPENDED PARTICLE PLUME IN A FULL-SCALE LABORATORY SYSTEM

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Abstract

This paper aims to investigate the interplay of suspended sediment concentration (SSC) and the fluid velocity that are both responsible for the rapid formation of sediments deposits in a full-scale laboratory system with PVC pipes. The specific objectives of the paper were to: (1) estimate the average rate of iron oxide particle deposition on PVC pipes immediately after the rapid release, and during the passage of, a highly-concentrated plume of iron oxide particles that typifies discolouration events in real systems; (2) determine whether previously deposited particles on the pipe wall from the passage of previous iron oxide particle plumes affect the average rate of iron oxide deposition and attachment to the pipe wall. Experiments were realized in a test facility that mimics the operation of drinking water systems using a special design method to accurately inoculate and detect the passage of iron oxide particles through the pipes under steady flow conditions commonly found in water networks. The experiments consisted of the passage of 3 sequential waves of particles, tested for three different SSC and three different flow velocities.

The results showed that increasing the inlet water quality conditions and the concentration of the particulate plume tended to increase the total deposited load while fluid velocity had a negligeable impact on the total deposited load. The results also showed that both an increase of concentration and fluid velocity produced an increase in the average deposition rate, and that this was mainly caused by the shorter conditioning period of the experiments at higher velocities. Further, the experimental results did not show any change in average particle deposition rate and attachment across the three plumes. This suggests that the presence of particle deposits from previous plumes had a negligible impact on particle deposition and attachment.

Keywords
Drinking water discolouration, particle deposition, wall shear stress.

1 INTRODUCTION

It is well established that important changes in the water quality conditions often occurs between the discharge works of a water treatment facility and the consumer's tap. Indeed, as treated water is conveyed through the distribution system it is subject to several processes (e.g., internal corrosion, resuspension of fine and coarse particles from the pipe wall) that can cause its quality to change dramatically before it reaches the consumer's tap [1]. For this reason, it is not surprising that red water problems and customer complaints are still a major concern for water managers responsible for the operation and maintenance of distribution systems in North American cities.

Heavy metals such as iron and manganese are of particular concern for utilities since they are often responsible for the creation of discolouration events and for the deterioration of water aesthetic that can often lead to customer complaints [2]. Iron and manganese particles can be imported from upstream metallic pipes that have undergone some level of corrosion, as these metal products are resuspended into the bulk flow and transported to downstream pipes. Despite this, it is still unclear to researchers and practitioners alike what are the key processes that cause particles to migrate to the pipe wall from the bulk flow and to adhere to pipe wall under normal flow conditions. Moreover, water utilities often lack the tools and methods to adequately assess the build-up of material deposits in operational networks.

In this context, this paper aims to examine the extent of acute particulate attachment on pipe walls following the rapid release and travel of a concentrated plume of iron oxide particles immediately following a simulated discolouration event in controlled experiments completed in a full-scale PVC pipe loop laboratory. The specific objectives of the experiments were to: 1) estimate the load of iron oxide particle deposition on PVC pipes immediately after the rapid release, and during the passage of, a highly-concentrated plume of iron oxide particles that typifies discolouration events in real systems; 2) determine whether previously deposited particles on the pipe wall from the passage of previous iron oxide particle plumes affect the average rate of iron oxide deposition and attachment to the pipe wall.

2 METHODS

The experiments were performed in the Drinking Water Distribution Laboratory (DWDL) at Queen's University (Figure 1), using a full-scale pipe loop rig that simulates the operation of drinking water mains. The pipe laboratory system is comprised of a water tank with a volume of 3.6 m^3, two variable speed centrifugal pumps and 11 loops of IPEX Blue Brute PVC pipe Class 235 (DR18) with an internal diameter of 108 mm, and a total length of 193 m. During the experiments, the pipe loop system was operated in a non-recirculatory manner, where drinking water from the City of Kington was continuously added to the tank, pumped through the pipe system, and discarded at the end. The water from the City of Kingston has a pH of 8.1, a hardness of 123 mg L 1-CaCO3 and an alkalinity of 92 mg L 1 CaCO3, and has approximately 1.7 mg L 1 of dissolved carbon and 1.0 mg L 1 of total nitrogen [3]. During the experiments the water temperature ranged between 12°C and 14°C.

In the experiments, drinking water was amended with iron oxide particles of known particle size distribution at the inlet to the pipe loop to induce the formation of material deposits on the pipe walls. A chemical grade of red iron oxide powder from Alpha Chemicals, with a composition of 82% of Iron (III) oxide – Fe_2O_3, was chosen as the source of particles for the experiments due their representativeness of iron oxide particles found in DWDSs and their stable particulate form and insolubility in water. The powder was sent to a commercial laboratory to split it into sub-samples of 50 g with identical particle size distributions (PSD) using a mini rotary splitter from Retsch company model PT100. The PSD of two sub-samples picked at random was analyzed with a Malvern Mastersizer 3000 particle size analyzer (laser diffraction). The insolubility of the particles and negligible amounts of dissolved iron in the local drinking water guaranteed that particles remained stable during the experiments.

Figure 1. Drinking Water Distribution Laboratory (DWDL) at Queen's University.

A total of five experiments were performed with a variable concentration of suspended particles (F1C1, F2C2 and F1C3 in Table 1) and a variable conditioning flow rate (F1C1, F2C1 and F3C1 in Table 1). During all the experiments, the pipe flow rate and turbidity were continuously monitored at a sampling frequency of 1 Hz using two Sierra InnovaSonic® 205i Ultrasonic Flow Meters (±0.5%) and two online Hach TU5300sc turbidimeters (±0.01 NTU). The turbidimeters were configured to monitor turbidity at the inlet (7% of the pipe length) and outlet (98% of the pipe length). Turbidity was measured from water continuously sampled from the centre of the pipe at a constant sampling flow rate. Only steady flow conditions were tested, but due to the short duration of the experiments, these flows can be interpreted as the highest daily peak flows of operational systems commonly used to determine the conditioning WSS in systems with variable demands [4, 5].

***Table 1**. Hydraulic and water quality conditions for the experiments.*

Experiment	*SSC [a] (mg L^{-1})*	*Flow (L s^{-1})*	*Velocity (m s^{-1})*	*Reynolds Number*	*WSS [b] (Pa)*	*Pipe loop RT [c] (min)*
F1C1	*20.0*	*0.60*	*0.07*	*7 000*	*0.02*	*50.9*
F1C2	*40.0*	*0.60*	*0.07*	*7 000*	*0.02*	*50.9*
F1C3	*60.0*	*0.60*	*0.07*	*7 000*	*0.02*	*50.9*
F2C1	*20.0*	*1.80*	*0.20*	*21 000*	*0.11*	*17.0*
F3C1	*20.0*	*2.75*	*0.30*	*32 000*	*0.24*	*11.1*

a. Suspended solids concentration.
b. Wall shear stress based on the Darcy-Weisbach equation.
c. Pipe loop residence time (RT) calculated by dividing the pipe loop volume of 1.7 m^3 by the flow rate.

Each experiment was divided in three independent sub-stages (P1, P2 and P3), where plumes of suspended particles were produced at the inlet of the pipe loop and completely transported through the pipe loop outlet before the introduction of the next plume in the next sub-stage. Each plume was created by injecting a known volume of a concentrated solution of iron oxide particles

(CSIOP) at the inlet of the pipe loop with a known SSC over an injection period equal to the time required for the water to travel 60 m downstream of the injection point given the prevailing flow rate in the pipe loop. The plume length of 60 m was mainly defined by a limitation of the maximum injection volume under stable mixing conditions in the CSIOP. A new CSIOP was prepared for each plume, by adding a known mass of iron oxide particles (IOP) into a known drinking water volume in a mixing baffled tank operated at a fixed mixing intensity. After the IOP addition in the tank, a period of 5 minutes was used to allow the particle suspension to stabilize in the mixing tank. A diaphragm pump was used to pump water from the bottom of the CSIOP tank (approximately 10 cm away from the tank walls) from a position of intense mixing between two of the four vertical baffles and inject it at a constant flow at the inlet of the pipe loop, at the centreline cross-sectional position of the pipe. At the end of each injection period, the steady flow conditions were maintained in the pipe loop for an additional period required to refresh the equivalent of 1.5 pipe loop volumes to guarantee that all suspended particles from the sediment plume had exited the pipe loop. Between each of the different experimental conditions tested, the pipe system was cleaned at the highest flowrate (16 L s^{-1}) to re-establish identical initial condition for all the experiments.

Following each injection, grab samples were collected at the inlet and outlet sampling port locations to determine SSC at those locations and to assess changes in the particles in suspension after the passage of each plume. The collection of grab samples was synchronized with the fluid velocity in the pipe loop to collect 4 L of water from the centre of the passing sediment plume. The SSC of the grab samples was determined using a dry-weight method, by filtering the sample volume with pre-weighed 0.45 μm glass microfiber filters, drying the filters at 105°C for 1 hour, and weighing them again after drying with a precision scale. The full details of the experimental design can be found in Braga and Filion [6].

3 RESULTS & DISCUSSION

The impact of source concentration and velocity on the average deposition rate were examined. Figure 2 plots the fraction of the inoculated particles that was deposited in the pipe wall after the passage of each plume and the average deposition rate for different inlet concentrations and fluid velocities. Note that the deposited load is calculated by taking the difference between the total material load at the injection point and the total material load at the outlet. The results in Figure 2 shows that a stable fraction of 74% of particle was deposited in the walls for the experiments with same velocity and three different concentrations, while the same fraction reduced for 69% for the two experiments with higher velocities and similar concentration of the experiment F1C1. This result suggests that the conditioning velocity of 0.07 m s^{-1} were not sufficient to maintain a large fraction of the particles in suspension (74%), and a velocity increase above 0.2 m s^{-1} was only sufficient to keep an extra 5% of the particles in suspension, preventing their deposit in the pipes. Figure 2 also shows that both an increase of concentration and fluid velocity produced an increase in the average deposition rate (secondary y-axis in Figure 2). Such increase was mainly caused by the shorter conditioning period of the experiments at higher velocities. Is hypothesized that most of particle deposition occurred right after their injection into the pipe loop. Therefore, the instantaneous deposition rate at the beginning of the experiment must have exceeded several times the average deposition rate estimated here, which was reduced by the longer period required for the plume passage through the pipes.

At the outset of the study, it was hypothesized that the particle accumulation rate of the 2nd and 3rd plumes might be affected by the presence of particles deposited on the pipe wall after the first plume. The basis for this hypothesis is that the particles from the first plume might make the pipe substrate more favourable to particle attachment. The results however did not show a change in total deposited load or average deposition rate across the three plumes introduced into the pipe loop. This suggests that the presence of particle deposits from previous plumes had a negligible impact on particle deposition and attachment.

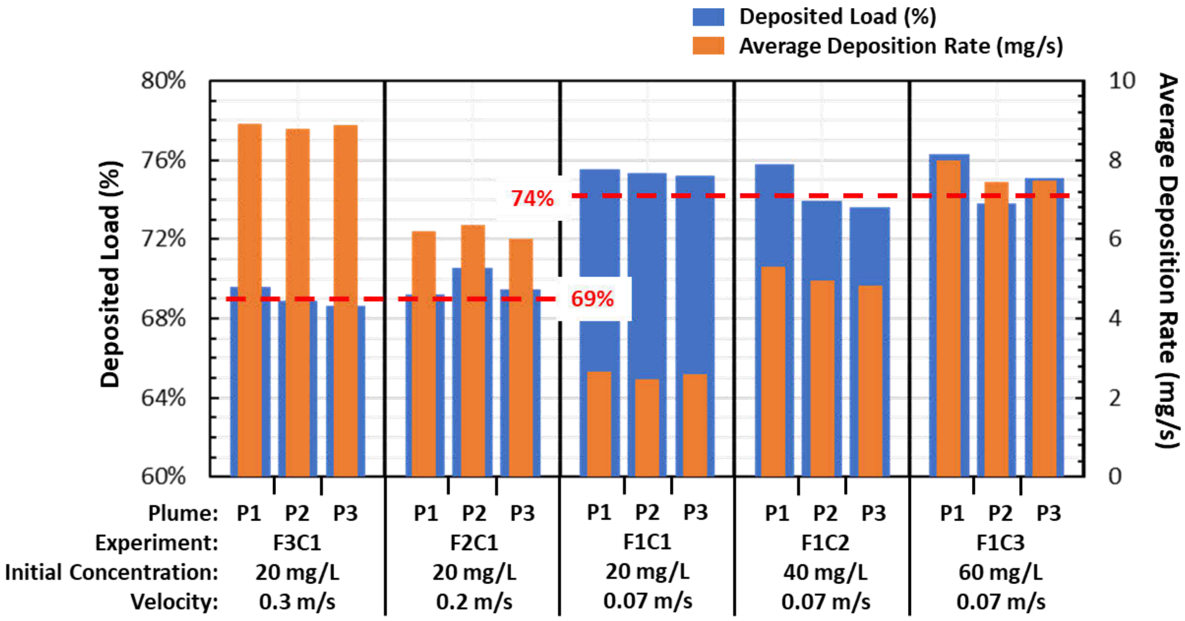

Figure 2. Deposited load and average deposition rate for each plume of each experiment performed at three different velocities and similar concentration (F3C1, F2C1 and F1C1), and at three different initial concentrations and similar velocity (F1C1, F1C2 and F1C3).

4 CONCLUSION

The aim of the paper was to examine the extent of particulate attachment following the passage of a concentrated plume of iron oxide particles that may arise in systems following a discolouration event. A set of controlled experiments were performed in a full-scale water distribution laboratory to 1) estimate the average rate of iron oxide particle deposition on PVC pipes immediately after the passage of the plumes, and 2) determine whether previously deposited particles on the pipe wall from the passage of previous iron oxide particle plumes affect the average rate of iron oxide deposition and attachment to the pipe wall.

The results showed that increasing the inlet water quality conditions and the concentration of the particulate plume tended to increase the total deposited load, but its proportion to the load of added particles remained constant for all three concentrations at the same fluid velocity. The increase of fluid velocity above 0.2 m s^{-1} produced a slight decrease of the proportional deposited load of particles of 5%. The results also showed that both an increase of concentration and fluid velocity produced an increase in the average deposition rate, and that this was mainly caused by the shorter conditioning period of the experiments at higher velocities.

At the outset of the study, it was hypothesized that the particle accumulation rate of the 2nd and 3rd plumes might be affected by the presence of particles deposited on the pipe wall after the first plume. The experimental results did not show any change in average particle deposition rate and attachment across the three plumes. This suggests that the presence of particle deposits from previous plumes had a negligible impact on particle deposition and attachment.

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