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Examining the Effect of Small-Amplitude Transients on Biofilm Development in Water Distribution Pipes †

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Abstract: This research explores the influence of chronic, small-amplitude hydraulic transients on biofilm development within water distribution systems (WDSs). Utilizing a unique experimental setup, it contrasts the biofilm dynamics under steady and transient hydraulic conditions. Findings reveal biofilms developed by transient conditions notably enhance adhesion and resistance to flushing, challenging the conventional focus on steady-state hydraulic scenarios. The research underscores the importance of integrating transient hydraulic effects into water distribution system management and design, to improve water quality and system integrity.

Keywords: drinking water biofilms; small-amplitude transients; drinking water discolouration

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1. Introduction

The dynamic interplay between hydraulic conditions and biofilm formation within water distribution systems (WDSs) presents a complex challenge to the management of drinking water quality. Biofilms are communities of microorganisms that adhere to surfaces in an extracellular polymeric substance (EPS), and they are a central concern for water utilities due to their potential for harboring pathogens, contributing to biocorrosion, and affecting water quality through the release of metabolites and particulates [1].

Research [2,3] highlights how variations in hydraulic patterns can influence biofilm characteristics, such as cell quantity and bacterial diversity, and underscores the critical role of hydraulic conditions in shaping bacterial community structure. Furthermore, Zhang and Lu (2006) provided evidence that disinfectant residuals with assimilable organic carbon levels influence biofilm accumulation in DWDSs, suggesting a nuanced approach to disinfection strategies is essential for effective biofilm management [4].

Recent research has examined how large hydraulic transients created by catastrophic events (pipe burst, accidental valve closure) can mobilize sediment and biofilm from pipes [5]. Despite this, no research to date has examined how short-lived accelerations caused by small-amplitude transients can affect the development of biofilms and their properties. The aim of the paper is to examine the effect of unsteady conditions created by such chronic, small-amplitude hydraulic transients on biofilm development.

2. Material and Methods

A 28-day experiment was performed in the Drinking Water Distribution System Laboratory (DWDL), a unique research facility in North America, using two identical pipe loops (A and B) 200 m in length of full-scale PVC pipes with 108 mm of inner diameter.

The experiments were divided into two phases: conditioning and flushing. During the conditioning phase, both pipe loops were operated with steady flow rates of 0.6 L/s and pressure of 280 kPa. The system was operated as a closed loop (water was not refreshed) without disinfection. Pipe loop B was subjected to regular 20 kPa transients every hour, caused by a sudden closure/open operation of a solenoid valve; while pipe loop A was used as a control and kept at steady state. The experiment was started with the addition of an equal microbial population in both pipe loops that was harvested from local water supply using a granular activated carbon (GAC) filter. The water was continuously amended with a small quantity of Nutrient Broth No.3 to allow biofilm growth. At the end of the conditioning phase, each pipe loop was flushed with 3 incremental flushing steps using flow rates of 6.5 L/s, 11 L/s, and 14 L/s (wall shear stresses of 1.2 Pa, 3.1 Pa, and 5.0 Pa), to promote detachment of accumulated biofilms and investigation of their adhesion shear strength. During the flushing phase of the experiment, the water flowing through the pipe loops was discarded to the drain to avoid reintroducing mobilized materials into the pipe loops, while fresh drinking water was continuously added to the inlet tanks.

Several parameters were used to track the microbial activity in the systems, comprising (a) volatile suspended solids concentration (VSS); (b) adenosine triphosphate (ATP); (c) bacterial cells concentration in the bulk water (BCC); and (d) bacteria cell density in the inner pipe wall of the pipe loop (BCD). Cell count metrics (BCC and BCD) were measured by flow cytometry, whereas biofilm from BCD was harvested from pipe wall samples by swabbing and resuspending the sample in an aqueous solution. A specialized pipe wall sampling system developed by Braga and Filion [6] was used to retrieve representative pipe wall samples for the assessment of BCD. Pipe wall samples were collected from five strategic sites along longitudinal and circumferential positions of the pipe loop. A longitudinal triplicate was collected from the (i) pipe loop inlet (INLT), (ii) pipe loop midpoint (MIDPT), and (iii) pipe loop outlet (OUTLT) all situated at the invert position of the pipe circumference; while a circumferential triplicate was collected with the addition of two extra sampling locations to MIDPT, comprising of (iv) the springline position (MID-SPRGLN) and (v) the obvert position (MID-OBV) of the pipe loop midpoint.

Bulk water and pipe wall samples were collected weekly during the conditioning phase and at each one of the flushing stages. All samples were collected in triplicate.

3. Results

Figure 1 indicates the results for VSS, ATP, and BCC measured in the bulk water sample during the conditioning phase and the three subsequent flushing events. At day 0, the bulk water exhibited negligible levels of VSS and ATP, alongside minimal BCC. Also, at the beginning of the conditioning phase (days 0 and 1), ATP levels and BCC were similar between the systems, indicating uniform initial conditions. However, by day 28, substantial differences were observed.

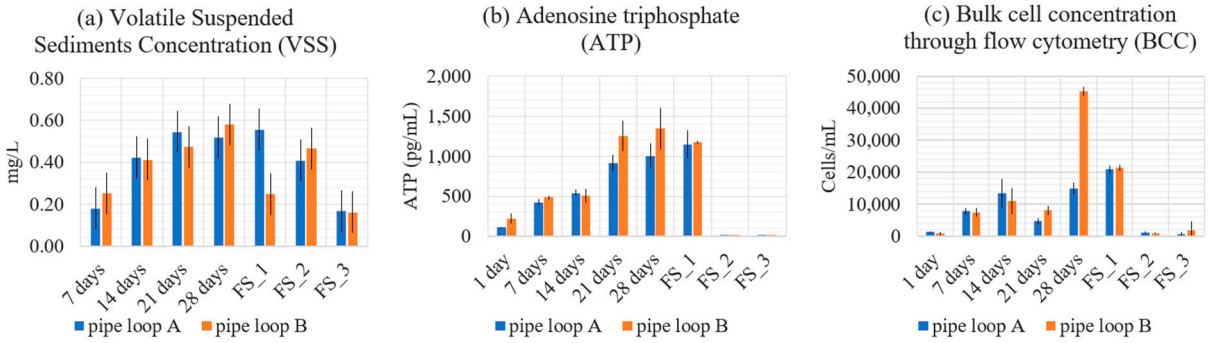

Figure 1. During the conditioning and flushing phases of the experiment in pipe loops A and B.

In pipe loop B, which was subjected to small-amplitude transients, BCC levels in the bulk water were twice as high compared to pipe loop A (control—no transients), which

experienced steady-state conditions. Additionally, the VSS and ATP levels in pipe loop B were 11% and 34% higher, corresponding, compared to those in pipe loop A. This difference suggests a higher occurrence of microbial activity in the bulk water of pipe loop B, which may indicate that small-amplitude transients were regularly mobilizing those cells that managed to attach to the wall into the bulk water.

In the case of the flushing stage of the experiment, Figure 1 data show that after the first and second flushing stages, measurements for ATP, BCC, and VSS were higher in pipe loop A (control). Interestingly, during the third flushing phase, while the VSS levels were similar between both pipe loops, the ATP and BCC levels were higher in pipe loop B. This pattern may indicate that a similar level of bacteria existed in both pipe loops but the small-amplitude transient conditions in pipe loop B prevented the growth of EPS to the same extent as in pipe loop A.

Figure 2 presents bacterial cell density (BCD) at the pipe walls obtained from the retrieval of pipe wall samples from the pipe loops during the experiment. Results are divided into a BCD distribution along the longitudinal direction of the pipes (Figure 2a), and a BCD distribution along the circumferential direction of the pipes (Figure 2b).

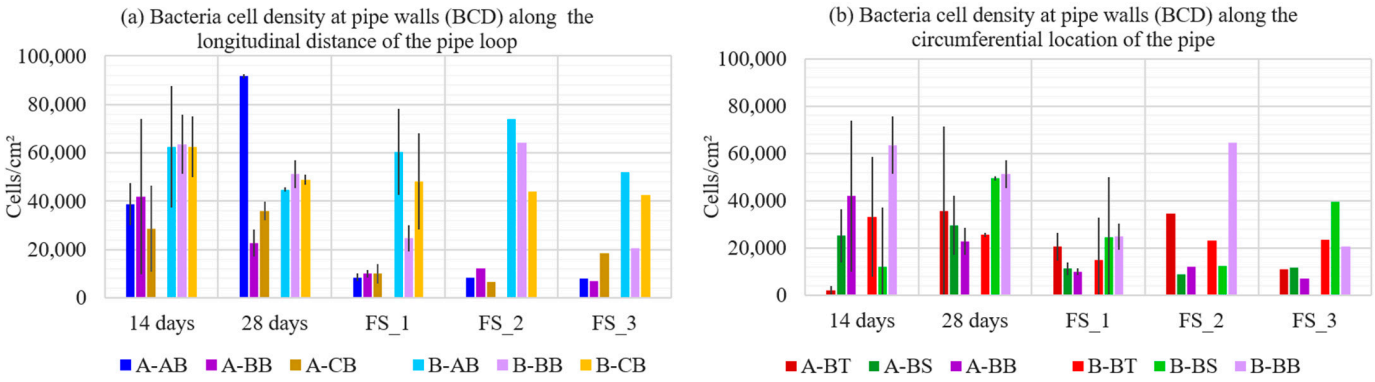

Figure 2. Bacteria cell density at pipe walls (BCD) along (**a**) the longitudinal distance of the pipe loop, and (**b**) the circumferential location of the pipe, for the 14 days and 28 days of the conditioning phase and the three flushing steps of the experiments.

Figure 2a shows that the BCD for pipe loop B (with transients) was higher and more consistent than for pipe loop A. Differences along the longitudinal direction of the pipes were considerably higher for pipe loop A (control—no transients), where higher BCD was observed in the earlier pipe sections (A-INLT). The BCD values collected after the first flushing step (FS1) highlighted that there was a lot of biofilm mobilized in FS1 in loop A (no transients) and not so much mobilized in FS1 in loop B (with transients), suggesting that the biofilm was more strongly adhered to the wall of the pipe with transients. In the case of BCD distribution along the circumferential direction of the pipes (Figure 2b), the 14-day assessment indicated a preferential accumulation of biofilm at the pipe's inverted location (MIDPT). However, between the 14th and 28th days, this was characterized by a shift towards a more homogenized biofilm distribution along the whole pipe circumference. For the flushing stages, BCD distribution along the circumference of the pipes did not show trends besides the previously mentioned higher values for pipe loop B in comparison to pipe loop A.

4. Discussion

The results showed a higher level of bacterial cells in the bulk water of pipe loop B (with transients) than in loop A subjected to steady-state conditions. This suggests that during the conditioning phase, small-amplitude transients may be more successful at mobilizing more cells from the pipe wall than when steady-state conditions prevail. The results also showed that, conversely, more cells were present on the pipe wall in the loop with transients (loop B) than in the loop without transients (loop A). This suggests

the possibility that transients may have conditioned those cells and biofilm that managed to attach to the wall to be more strongly adhered to the pipe wall compared to when steady-state flow conditions prevail.

This theory is also supported by the flushing results. Fewer cells were mobilized in the first flushing step in loop B (with transients) than in loop A (without transients), which suggests that transients may have played some role in conditioning the biofilm to adhere more strongly to the inside of the pipe. This finding not only corroborates earlier studies [1,5], which highlighted the role of hydraulic conditions in biofilm mobilization and structural integrity but also extends our understanding by demonstrating the impact of small-amplitude transients on biofilm accumulation dynamics. The resilience of biofilms to flushing in transient conditions challenges the prevailing focus on steady-state hydraulic scenarios in water distribution systems.

5. Conclusions

This study advances our understanding of biofilm accumulation dynamics within water distribution systems, revealing that chronic, small-amplitude hydraulic transients can critically influence biofilm development, mostly resulting in biofilms with higher adhesion to PVC pipe walls and resistance to flushing. These findings challenge the traditional focus on steady-state conditions, underscoring the necessity to consider transient hydraulic effects in the management and design of water distribution systems for improved water quality. Future research should delve into the mechanisms behind these observations and evaluate control strategies.

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Conflicts of Interest: Author Mariele de Souza Parra Agostinho was employed by the Parana Sanitation Company—Sanepar. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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