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Non-destructive biofilm thickness monitoring in drinking water pipes using thermal and flow dynamics

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Abstract—**Biofilms in drinking water distribution systems (DWDS) pose a critical challenge to water quality. If left unchecked, they can compromise the biological stability of delivered water and ultimately public health. Existing biofilm sensing techniques primarily focus on metabolic or genetic indicators of activity, often using local and destructive methods. While rich in information, such data are difficult to apply in developing practical biofilm growth models. Biofilm thickness, however, is a more representative and scalable metric for this purpose. Yet, limited research exists on non-invasive thickness sensing in DWDS. This study introduces two non-destructive methods for measuring biofilm thickness by leveraging changes in heat resistance and residence time. Heat resistance was evaluated using ambient and water temperature measurements, while residence time was assessed with a conservative tracer. Both techniques were tested in the Slimer experimental setup (50 m long, 13.2 mm diameter PVCp pipe) under realistic hydraulic conditions. Results showed a strong correlation between biofilm thickness and residence time drift, indicating flow disturbance as a reliable indicator of biofouling. In contrast, heat resistance sensing exhibited considerable natural variability, limiting its analytic value. The findings highlight residence time analysis as a promising, non-invasive approach for estimating biofilm thickness. This method offers continuous, non-destructive monitoring, enabling early detection of biofilm-related anomalies and providing valuable input for both laboratory and field applications aimed at enhancing DWDS resilience.**

I. Introduction

Biofilms are microbial communities that adhere to pipe surfaces in Drinking Water Distribution Systems (DWDS), contributing to water quality issues such as changes in taste, odour, and clarity, as well as infrastructure corrosion and microbial contamination [1]. These biofilms can harbour pathogens like Escherichia coli and Pseudomonas aeruginosa, posing health risks [2]. Despite efforts to control biofilm growth using disinfectants or mechanical cleaning, such measures are often ineffective, especially with increasing environmental stresses and climate change [3]. This necessitates the development of better monitoring methods to manage biofilm growth in DWDS.

Biofilm features like microbial composition, activity, and physical properties (e.g., thickness) are commonly studied. Among these, thickness is a critical indicator, correlating with biofilm maturity and volume, and directly influencing pipe hydraulics [4, 5]. However, methods for measuring biofilm thickness are limited, especially for large-scale, real-world applications.

Monitoring biofilm thickness is essential for maintaining water quality. Intrusive techniques, like removing biofilm samples, disturb the system, while non-intrusive methods, such as optical and electrical sensors, face issues like sensitivity and spatial coverage [6]. To address these gaps, this study explores two non-intrusive methods, heat transfer sensing and hydraulic residence time monitoring, as potential solutions for biofilm thickness measurement in DWDS, tested in a controlled lab environment [7].

II. Material and Methods

A. Experimental Facility and Conditions

Biofilm thickness in drinking water pipes was measured using a lab-scale facility at KWR Water Research Institute, named "Slimer" [8]. The setup consists of pPVC pipe, with an inner D_{in} and outer D_{out} diameter of 13.2 mm and 19.8 mm respectively, a length (L_{pipe}) of 50 m, and is arranged in a helical shape to optimize conditions uniformity. Temperature, flow rate, and electrical conductivity (EC) were monitored at various points using sensors, and the system operated in a pass-through mode with a break tank at the inlet. Biofilm growth occurred from February 18 to December 17, 2024, under controlled temperatures (16-20 °C) and flow rates (20-400 L/h).

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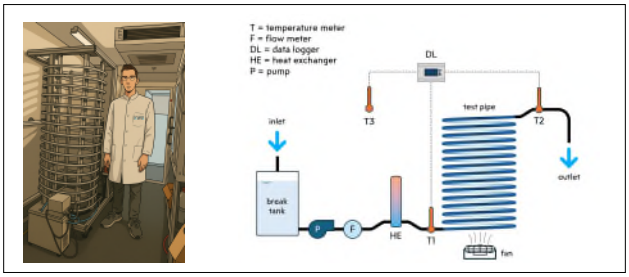

Figure 1. Left: "Slimer" setup in the KWR building. Right: Schematic representation of "Slimer" setup used for the biofilm thickness measurement experiments

B. Biofilm Presence Validation

To validate biofilm presence, both its volume and biological activity were assessed. The volume of biofilm was measured by extracting biofilm and water from the pipe using pigging and centrifuging the mixture. The biofilm was separated from the water and were centrifuged in accordance with CEN-EN16421:2014 standards. This process isolated the biofilm from the surrounding water, enabling precise measurements of its volume. The biofilm volume ($V_{biofilm}$) was then used to calculate the mean biofilm thickness ($z_{biofilm}$) in the pipe using equation (1):

$$z_{biofilm} = \frac{V_{biofilm}}{\pi \cdot D_{in} \cdot L_{pipe}} \quad (1)$$

In addition to volume, biological activity was assessed by measuring adenosine triphosphate (ATP) concentrations in the biofilm samples. The extraction, analysis, and conversion procedures followed the CEN-EN 16421 standards.

C. Biofilm Thickness through Heat Resistance Measurements

Heat resistance was used to estimate biofilm thickness. The setup enabled precise heat measurements by calculating the thermal energy absorbed by water, which increased in temperature as it passed through the pipe. The total heat resistance, influenced by biofilm, was decomposed into components: internal resistance, pipe resistance, and external resistance. Biofilm thickness was derived from the biofilm-induced heat resistance, which resulted from comparing the clean and biofouled conditions of the pipe. If $R_{biofilm}$ is the heat resistance added by biofilm and biofilm is assumed to have the same thermal conductivity as water (k_{water}), then the thickness is derived from equation (2):

$$z_{biofilm} = \pi \cdot D_{in} \cdot L_{pipe} \cdot k_{water} \cdot R_{biofilm} \quad (2)$$

D. Biofilm Thickness through Residence Time Measurements

Hydraulic residence time (t_{res}) was measured using tracer experiments with sodium chloride (NaCl). The pulse of increased conductivity was tracked through the pipe, and residence times were calculated based on the EC data. Biofilm thickness was derived from the reduction in residence time caused by biofilm constricting the flow. For a constant flow rate, this constriction caused a reduction of residence time from clean ($t_{res,clean}$) to biofouled conditions ($t_{res,biofilm}$). The final biofilm thickness was calculated using equation (3):

$$z_{biofilm} = \frac{D_{in}}{2}\left(1 - \sqrt{\frac{t_{res,biofilm}}{t_{res,clean}}}\right) \quad (3)$$

Various definitions of the time instance when the NaCl pulse passes through the EC sensors are used to capture the stochastic nature of the pulse shape. Each definition yields a different residence time, highlighting the method's inherent variability.

III. Results

Biofilm removed from the Slimer setup yielded a solid biofilm volume corresponding to 15.5 µm of thickness. This compares to the thickness values yielded by the two methods in Tables I and II. The results of the heat resistance method are provided in Table I.

TABLE I. HEAT RESISTANCE METHOD RESULTS

Flow Rate	***Re***	$R_{biofilm}$	$z_{biofilm}$
l/s	–	***°C/W***	***µm***
200	5,360	$-12.7 \cdot 10^{-5}$	–
150	4,020	$0.7 \cdot 10^{-5}$	8 ± 247
100	2,680	$24.1 \cdot 10^{-5}$	290 ± 394
50	1,340	$48.9 \cdot 10^{-5}$	588 ± 962

The heat resistance method revealed that biofilm thickness ($z_{biofilm}$) varied with flow rates, with invalid measurements at 200 l/h (Re=5,360), where the total resistance decreased unexpectedly, hence the negative heat resistance 'added' by biofilm presence. This suggested that biofilm might reduce flow to the point of a transition from turbulent to laminar flow, altering resistance. At 150 l/h, $z_{biofilm}$ was 8 µm, and at 50 l/h, it reached 588 µm, although with substantial uncertainty (962 µm). These changes are attributed to the effects of longer residence times and the transition to laminar flow at lower rates, which results in increased boundary layers and reduced shear stress, allowing biofilm to become "fluffier." However, the high uncertainty limits confidence to the $z_{biofilm}$ values.

The results of the residence time method are provided in Tables II.

TABLE II. RESIDENCE TIME METHOD RESULTS

Flow Rate	*Re*	$t_{res,clean}$	$t_{res,biofilm}$	$z_{biofilm}$
l/h	–	*s*	*s*	*µm*
200	5,360	137.0	135.6	33 ± 6
150	4,020	182.0	181.6	8 ± 3
100	2,680	272.8	270.3	31 ± 4
50	1,340	543.4	531.1	75 ± 4

The residence time method provided values around ten times smaller than the heat resistance method. For instance, at 200 l/h, $z_{biofilm}$ was 33 ± 6 µm. The heat resistance method showed greater uncertainty, suggesting a need for calibration between the two methods. Despite differing principles, both methods showed a similar trend of increasing biofilm thickness with decreasing flow rate, though the residence time method demonstrated orders of magnitude narrower confidence intervals, indicating higher reliability, particularly for thin biofilms.

The thickness of the solid component of biofilm pigged is the same order of magnitude as the results of the residence time method at 200, 100, and 50 l/h, though it was lower than the value at 50 l/h, i.e., 75 ± 4 µm. The discrepancy at lower flow rates suggests biofilm may become thicker when applying the biofilm thickness methods, but thinner when doing biofilm presence tests with assumed specific weight. ATP analysis showed a high level of bioactivity at 7,200 ± 620 pg ATP/cm^2, indicating that the biofilm was mature and biologically active.

The heat resistance method's reproducibility was assessed by calculating how changes in heat resistance induced by a 100 µm thick biofilm affected outlet water temperature (ΔT_{out}) for different pipe diameters and materials, but identical Reynolds number as in our experiments in "Slimer". The results are presented in Figure 2.

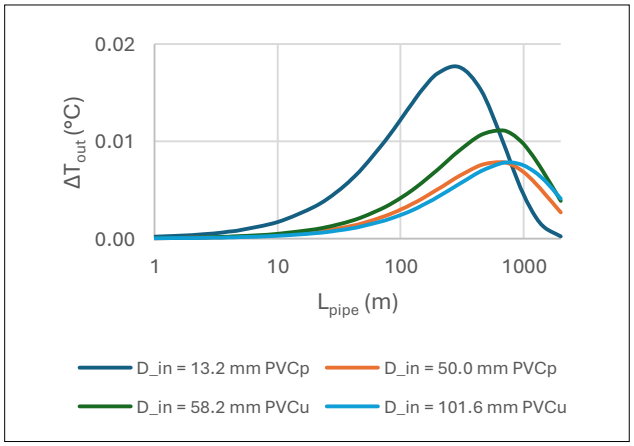

Figure 2. Theoretical variation in measured outlet temperature ΔT_{out} along the pipe length for different pipe diameters and materials, assuming identical biofilm thickness (100 µm) and Reynolds number (5360) as in the experiments conducted in "Slimer"

As is visible in Figure 2, minor variations in heat resistance resulted in very small temperature shifts, indicating that changes in biofilm thickness may not be easily detectable without refinement in the method, particularly concerning biofilm's thermal properties.

The residence time method's reproducibility was evaluated by calculating the minimum biofilm thickness $z_{biofilm,min}$ that can induce a residence time deviation of 2 s for different pipe diameters D_{in} and pipe lengths L_{pipe}, and a constant mean velocity (u_{mean}) equal to 0.18 m/s, as is shown in Figure 3.

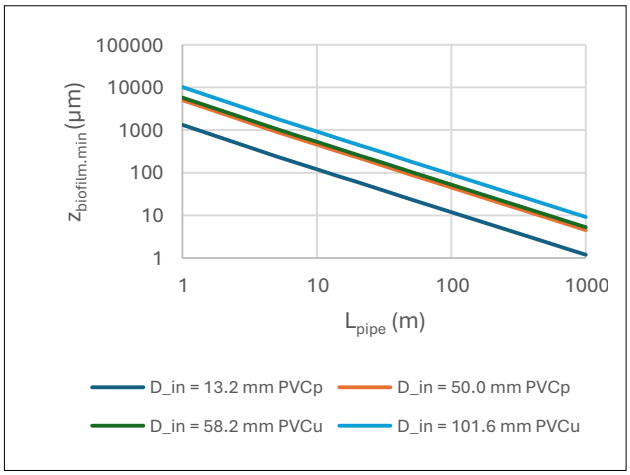

Figure 3. Minimum biofilm thickness $z_{biofilm,min}$ required to record t_{res} deviation of 2 s for different D_{in} and u_{mean} = 0.18 m/s over length L_{pipe}

In comparison to the heat resistance method, the hydraulic residence time method showed better reproducibility, with the ability to detect thin biofilms in larger pipes with higher flow rates. This method is more suitable for real-world distribution systems, where longer pipes and varied flow conditions are common.

IV. CONCLUSIONS

This study introduces two non-intrusive biofilm thickness measurement methods—heat resistance and hydraulic residence time—evaluated in a controlled lab setting. The findings highlight the strengths and limitations of each approach, contributing to the development of reliable biofilm monitoring tools for drinking water systems.

The heat resistance method showed promise but exhibited high measurement variability due to temperature dynamics, environmental factors, and biofilm heterogeneity. Its sensitivity to thermal conditions may limit its field applicability, though refinements in thermal modeling and sensor placement could improve its reliability.

In contrast, the hydraulic residence time method demonstrated robust and consistent performance, aligning well with physical biofilm volume measurements. By detecting subtle flow changes caused by biofilm accumulation, it enables broader spatial monitoring with minimal system disruption. This capability allows for early identification of biofilm hotspots, reducing the risk of flow restrictions, pressure losses, and contamination events—enhancing system resilience against operational failures.

These results emphasize the need to select monitoring techniques based on system conditions. While the hydraulic residence time method is ready for larger-scale deployment, further refinement of the heat resistance method could enhance biofilm characterization. Future research should focus on validating these approaches in pilot-scale DWDS environments and exploring their combined potential for more comprehensive biofilm assessment.

Developing reliable, non-intrusive biofilm monitoring methods will enable water utilities to adopt proactive and adaptive management strategies. By integrating these techniques into real-time monitoring systems, utilities can enhance early-warning capabilities, optimize maintenance schedules, and prevent costly interventions. This, in turn, strengthens the fault tolerance of drinking water networks, ensuring more reliable water quality and infrastructure longevity even under variable operating conditions.

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