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Proceeding Paper

Water Quality Modelling in Water Distribution Systems: Pilot-Scale Measurements and Simulation †

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Abstract: We present the results of water quality measurements in a pilot-scale, continuously circulated test rig consisting of HDPE pipe segments, where pH, conductivity, turbidity, salinity, temperature, and dissolved oxygen were measured daily. Microbiological measurements (CFU) on the pipe wall and in the bulk water were measured at least once every week. The measurement campaign lasted for 18 weeks. In the first part of the paper, we provide an overview of the results and our experiences. In particular, the time histories of the measured quantities are presented and assessed. Additionally, the flow velocity was increased in six steps from 0.4 to 1.1 m/s to study biofilm detachment once every week. In the second part of the paper, we attempt to use these measurement results for the parameter identification of standard biofilm models. In particular, we search for indirect connections between our measurement results and model parameters (e.g., yield and growth-limiting parameters) via optimising, where the objective is to recover the measured CFU concentration results as closely as possible. Finally, we present preliminary results on the critical wall shear stress resulting in biofilm detachment.

Keywords: biofilm growth; water quality; modelling; biofilm detachment

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1. Introduction

The importance of biofilm modelling in water distribution systems lies in its role in understanding the behaviour of microbial communities and predicting biofilm formation and its impact on water quality. Measurement-validated mathematical models are crucial as they provide a means to accurately represent the complex dynamics of biofilm growth and dispersion, thereby enhancing the reliability of predictive assessments. Incorporating empirical data into these models allows for refining the understanding of biofilm dynamics and improving the efficiency of water treatment and distribution processes. Integrating measurement-validated mathematical models in biofilm research ultimately contributes to public health safeguarding by enabling proactive water infrastructure management.

This study reports the first series of measurements at the water quality test rig built at the Dept. of Hydrodynamic Systems, Budapest University of Technology and Economics. The 18-week measurement period allowed for the monitoring of biomass formation and decay. Based on the measurements, the parameters of mathematical models could be adjusted, and the critical wall shear stress resulting in biofilm detachment was estimated.

2. Measurements

A new, unique piece of equipment was built to measure the behaviour and growth of biofilm in pipe systems. To mimic modern water distribution systems, approximately

140 m of HDPE pipe was used with an inner diameter of 28 mm. A peristaltic pump was used to maintain continuous flow in the system, which was chosen to avoid the damage of the bacteria circulating in the system. A pressure relief valve and a bypass valve were also mounted to avoid unwanted high-pressure peaks (due to the positive displacement nature of the pump). Several detachable and replaceable segments had to be built into the system to analyse the biofilm on the pipe walls, separated by valves (see numbered sections in Figure 1). A refill tank, a sampling tap for water quality analysis, a pressure sensor, a flow meter, and other operational parts were also added. A temperature stabiliser was also used to minimise the effect of temperature variation during the 18 weeks of measurement.

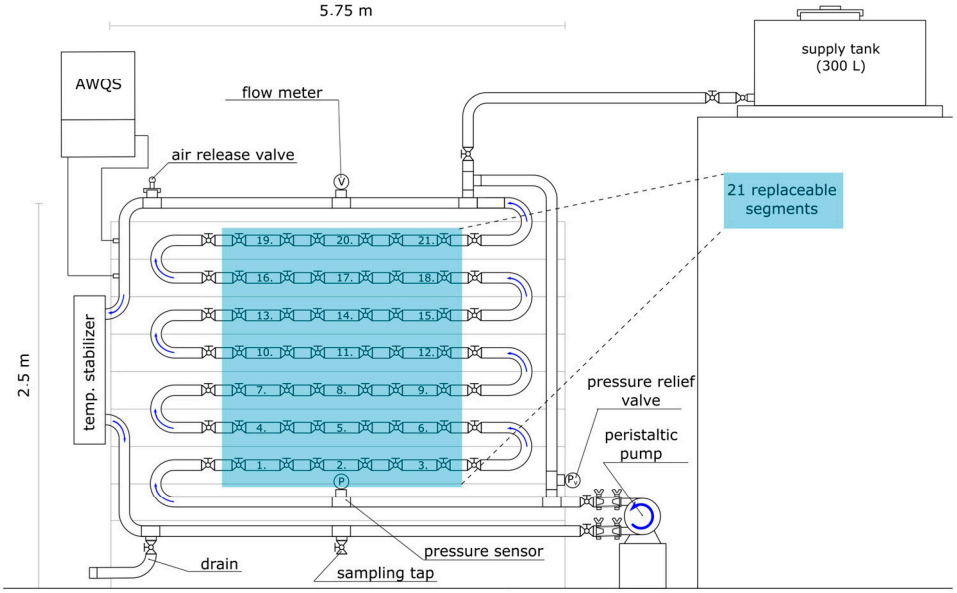

Figure 1. Schematic figure of the test rig.

The temperature slowly decreased during the 18-week-long campaign but remained between 21 °C and 31 °C. The resistivity moderately increased from 2.13 kΩcm to 2.19 kΩcm. The conductivity remained between 470 µs/cm and 460 µs/cm, such as the TDS, as its value fluctuated from 471 mg/L to 460 mg/L. The salinity stayed constant at 0.1 mg/L during the campaign. The measured pH values were between 7.3 and 6.8 but showed no particular pattern. The turbidity fluctuated between 1.10 FNU/NTU and 3.78 FNU/NTU. The amount of DO slowly decreased during the campaign. However, it must be noted that the uncertainty of the measured values is high due to the instrument's sensitivity. The decreasing amount of DO indicates biological activity in the system. The number of bacteria found in both the water sample inside the segment and the biofilm formed on the surface of the segment was determined under sterile conditions during the microbiological examination. The number of colony-forming units per millilitre of the sample was determined by pour plating after making decimal dilution series from the liquid phase.

The microbiological analyses show (see Figure 2) that after a short time of increase (biofilm build-up), the microbe concentrate in the bulk water and on the pipe wall reaches a maximum amount (10^7 CFU/mL in the bulk and 10^6 CFU/cm^2 on the wall). Once the peak is reached, the microbe starts drying out (as the system is closed, there is no substrate supply).

The effect of the flow rate (velocity) changes was monitored by the AWQS instrument, which continuously counts the number of bacteria-sized particles. This device was installed parallel to the main pipeline, and by using a separate peristaltic pump, it constantly takes samples from the main water flow. Each minute, the instrument counts the number of solid particles (within a microbe-specific size range) in the bulk floating in the flow in front of an

optical sensor. As the data in Table 1 shows, we experienced an increased count once the flow reached 30 Hz, equivalent to approx. 3500 Pa wall shear.

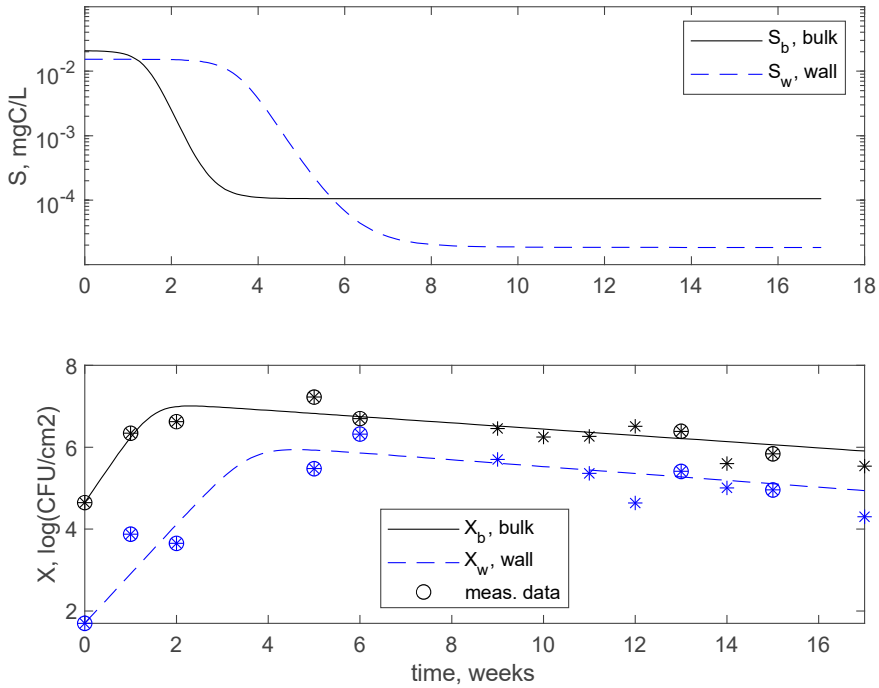

Figure 2. Optimisation result (solid and dashed lines: simulation; markers: measurement).

Table 1. Wall shear pump frequency data, the highlighting indicates the conditions where increased solid particle concentration was observed, hence biofilm detachment is conjectured.

Pump Freq. **Hz**	**Flow Rate** **m^3/h**	**Velocity** **m/s**	**Re** **-**	$\lambda = 0.316Re^{-1/4}$ **-**	$\tau_w = \lambda \frac{\varrho}{2D^2\pi} v^2$ **Pa**
10	0.6	0.27	7.6×10^3	0.034	504
15	0.9	0.41	11.3×10^3	0.031	1025
20	1.2	0.54	15.1×10^3	0.028	1695
30	1.8	0.81	22.7×10^3	0.026	3446
40	2.4	1.08	30.0×10^3	0.024	5702

3. Mathematical Modelling

The standard model for substrate/biofilm growth/decay described thoroughly in [1–5] was employed for modelling the biological activity inside the test loop.

Simulations using the initial set of parameters in Table 2 resulted in poor agreement with the measurement result. Hence, an optimisation technique was employed to find the parameters leading to a reasonable fit by adding multipliers to all parameters, augmented with the initial substrate concentration in the bulk and on the pipe wall (as these parameters were not measured). We used Matlab's fmincon function to solve the constrained nonlinear optimisation problem.

Table 2. Initial and optimised parameter set.

Name	μ_{max}	**Y**	**a**	k_{mort}	k_b	**Sb(0)**	**Sw(0)**	$k_{f,s}$	**Yw**
unit	1/day	-	-	1/day	mgC/L	mgC/L	mgC/cm^2	cm^2/day	-
initial val.	36.3	0.15	0.3	0.717	0.5	0.01	0.01	0.47	0.15
multiplier	0.62	4.	0.59	0.039	1.98	2.61	1.93	1.05	5.69

4. Summary

This study presented the first results of a biofilm reactor mimicking a circular water distribution system. We attempted to predict the substrate and biomass concentration in bulk and on the pipe wall via simplified mathematical models available in the literature. As the initial parameter set (see Table 2) with the usual literature values did not result in a satisfactory match with the measurements, parameter optimisation was performed, which improved the agreement significantly (see last row in Table 2). In particular, we used different yield constants for the bulk and the wall-attached region. All parameters were found to be in the same order of magnitude as the literature data, except the bacteria mortality rate, which was only 3.9% of the literature value. We also found that biofilm detachment (at least in our test rig) starts approximately at the critical wall shear value of 3500 Pa.

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Conflicts of Interest: The authors declare no conflicts of interest.

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