engineering proceedings

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Proceeding Paper

Tool to Model the Potential Risk of *Legionella* Growth in Premise Plumbing Systems †

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† Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: Water quality problems due to stagnation during periods of low or no demand in buildings, such as the growth of *Legionella* bacteria, may arise in potable cold and hot water systems. Premise plumbing installations should therefore be designed and constructed to prevent bacterial growth, and then operated to provide satisfactory protection against *Legionella*. In several building types, over 50% of the total energy usage is connected to hot water production. In large part, this is because hot water systems are maintained at 60 to 70 °C to deter *Legionella* growth, which may be at odds with sustainability goals. With the latter in mind, recent studies have combined both hydraulics and temperature modelling, obtaining satisfactory prediction results when tested by making digital twins. In the present study, a tool was developed which allows users to see the detailed results of premise plumbing system modelling through a web-based interactive dashboard. The hydraulics are modelled using WNTR, water demands are generated with pySIMDEUM, and temperature is modelled using heat transfer theory for conduction and convection. Some examples are presented to illustrate the extent of the tool, as well as visualising indicators relevant to *Legionella* growth potential, such as water age and temperature range. This tool can support building managers and designers with improving serviceability, minimising environmental footprint, and providing safe water in new and existing premise plumbing systems.

Keywords: premise plumbing modelling; serviceability; sustainability; water quality; automation

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Citation: Vargas, K.; Waak, M.; Tscheikner-Gratl, F.; Rokstad, M. Tool to Model the Potential Risk of *Legionella* Growth in Premise Plumbing Systems. *Eng. Proc.* **2024**, *69*, 162. https://doi.org/10.3390/engproc2024069162

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 23 September 2024

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1. Introduction

Legionella can cause severe or fatal Legionnaires' disease among water users who inhale contaminated aerosols from showers, faucets, or toilets. These problems may arise due to stagnation [1]. Building water installations should therefore be constructed and designed to ensure good health through the prevention of bacterial growth, and then operated to provide satisfactory protection against *Legionella* [2].

A study on 805 samples taken from multiple operating hot water systems found that the highest levels of colonisation by *Legionella pneumophila* were found at water temperatures between 30 and 35 °C and decreased significantly at temperatures above 50 °C, although there were still a few samples with temperatures between 55 and 60 °C with the presence of *L. pneumophila* [3]. In several building types, over 50% of total energy usage is due to hot water production, likely in large part because hot water systems are maintained at 60 to 70 °C to deter *Legionella* growth, as seen in some Norwegian hotels and nursing homes [4].

There have been a few studies attempting to model temperature in water supply systems [5] and urban drainage systems [6], with diverse approaches and assumptions. For premise plumbing systems in particular [7], recent studies have combined both hydraulics

and temperature modelling proposing a one-dimensional radial approach which has had a satisfactory performance when tested against temperature measurements in real premise plumbing systems.

2. Materials and Methods

2.1. Model Description

For stochastic water demand generation, pySIMDEUM is used. This is an open-source Python package for stochastic water demand modelling at premise plumbing system level [8].

Hydraulic modelling is carried out using the Water Network Tool for Resilience (WNTR), which is another Python package designed to simulate and analyse water distribution networks [9]. Most importantly, this package provides several useful methods and supports their manipulation for a wide variety of custom applications. The package is capable of handling minor losses properly at the scale of premise plumbing systems, even though it was developed for larger scale networks where friction is the main source of head loss.

Temperature modelling is performed assuming heat transfer by conduction and convection in a one-dimensional (radial) direction based on the circular symmetry of the cross section for pressurised pipes. Heat flow rate ($\dot{Q}$) is assumed to be constant in this radial direction for any given timestep (Δt). Lumped system assumption is also used, which implies that the water temperature is equal along the cross section for any given Δt.

The equation used to estimate the change in temperature (ΔT) for any Δt is therefore:

$$\Delta T = T_\infty + (T_i - T_\infty)e^{-b\Delta t} - T_i, \quad (1)$$

where T_∞ is the room temperature, T_i is the current water temperature, b is:

$$b = \frac{1}{mC_pR}, \quad (2)$$

m is the mass of water, C_p is the specific heat of water, and R is a constant that can be interpreted as the "thermal resistance" of the cross section by using the one-dimensional electrical circuit analogy. This constant will depend on the thickness and thermal conductivity of the pipe's wall, the structural wall (if applicable), the insulation (if applicable), pipe inclination, and the physical properties of the surrounding air [10]. This equation is applied to every element in the network and then displaced through the network in the form of discrete "water packages" using the hydraulic results from WNTR. Temperatures for every element are the weighted average temperatures of the water packages contained within them and are stored in custom variables created within WNTR.

Finally, results are post-processed and presented through a web-based interactive dashboard. This includes a 3D visualisation and dynamic plots. Two variables that have shown a strong correlation with a high potential for *Legionella* growth are selected for display and analysis as an example. These are:

- Peak Water Age (PWA), and
- Consecutive Time in Temperature Interval 20–35 °C (CTI)

2.2. Example Network

An illustrative example (Figure 1) was created consisting of a system with one hot water heater (HWH) tank, one shower, one faucet, and one toilet. The cold water source temperature was 5 °C, hot water in the tank output was 70 °C, the objective temperature in the shower and faucet was 40 °C (regulated automatically by valves on demand), the toilet used only cold water, and the global room temperature was 18 °C. For the network, all pipes were made of copper with an internal diameter of 25.4 mm (1"), no longer than 10 m each, with 1" of insulation, and surrounded by a 20 cm thick lightweight concrete

wall. Demand patterns were generated for four adults, one weekend period (two days), and a five second timestep for 500 random demand-pattern scenarios.

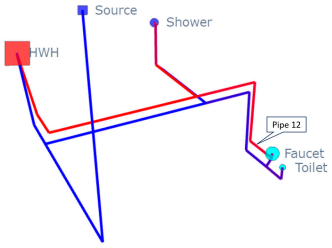

Figure 1. Three-dimensional representation of the example network.

3. Results

Out of the 500 random demand-pattern scenarios, the two that had both the highest and lowest PWA through both days were picked for comparison. The pipe with the highest PWA was pipe 12 (Figure 1) and the results are shown below (Figure 2).

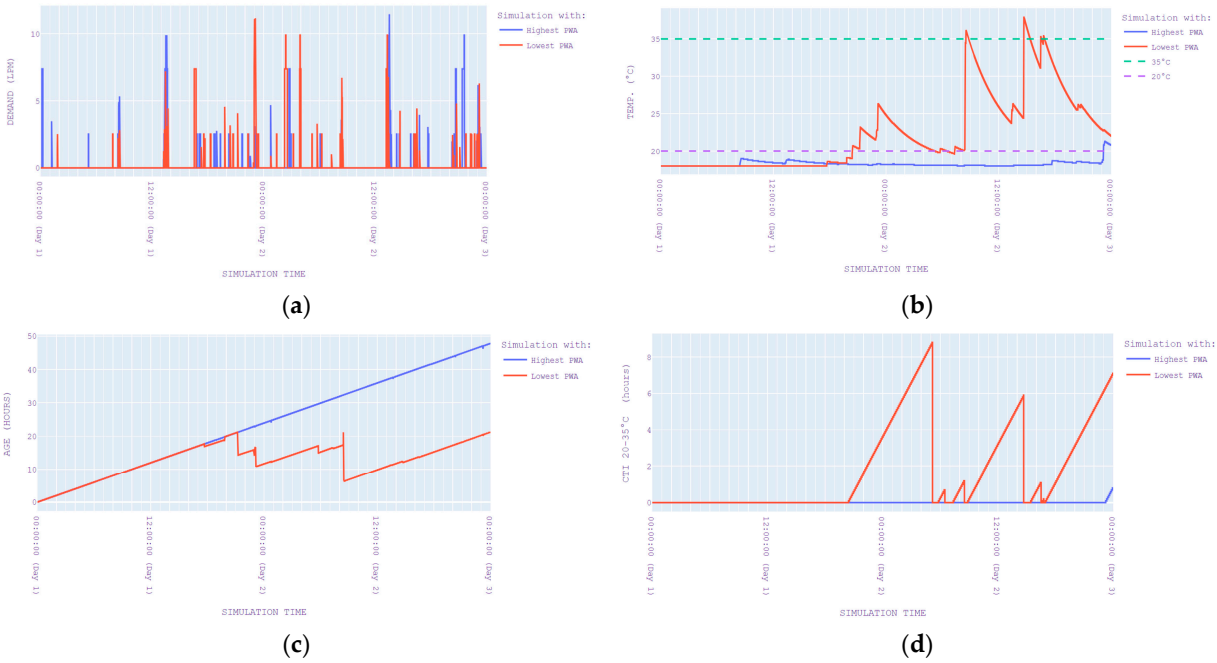

Figure 2. Results for selected scenarios (Highest PWA and Lowest PWA) for: (**a**) total water demand in the system; (**b**) water temperature for pipe 12; (**c**) water age for pipe 12; (**d**) consecutive time at temperatures between 20 and 35 °C for pipe 12.

4. Discussion

Water demand between the two scenarios is similar in overall quantity but different in time and spatial distribution (Figure 2a). The fact that both had such different results regarding water age and temperature confirms that the water-use behaviours on different seasons or periods of time should always be considered as well.

Accuracy in the definition of critical temperature interval for *Legionella* growth and room temperature is crucial. For example, if Figure 2b demonstrated a different interval or room temperature, it would change the output of the results in Figure 2d.

As shown in this example, it is possible to diagnose the potential for *Legionella* growth using system properties, given user-defined guidelines. Results and interpretation can likewise be tailored to assess compliance with sanitary regulations for *Legionella* mitigation.

Another noteworthy aspect is that demand patterns can be manually established in the input layout file (.INP) without the need of pySIMDEUM. This could be useful to simulate

specific actions such as flushing, periods of no use, or any other scenario of interest. For example, this tool is currently being tested and calibrated to replicate measurements in lab pilots with specific demand scenarios and will be validated by creating digital twins for real systems in Norwegian buildings.

5. Conclusions

Water age and temperature in premise plumbing systems should be considered in the context of water-use behaviours, which may change seasonally or temporally with occupancy. Understanding the specific temperature range conducive to *Legionella* growth and ensuring accurate monitoring of room temperature for every element in the network are essential components for defining and assessing the potential for *Legionella* growth.

Digital modelling tools and automated processes could offer building managers and designers evidence-based guidance toward sustainable operation and design practises, optimising building energy use for *Legionella* mitigation.

Author Contributions: Conceptualization, M.R. and F.T.-G.; methodology, K.V.; software, K.V.; validation, F.T.-G., M.R. and M.W.; formal analysis, K.V.; investigation, K.V.; resources, M.W.; data curation, M.W.; writing—original draft preparation, K.V.; writing—review and editing, K.V.; visualisation, K.V.; supervision, M.R. and F.T.-G.; project administration, M.W.; funding acquisition, M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by SINTEF, through the project: Serviceable, Environmentally reSponsible & Safe—Integrating automated Legionella mitigation into potable building water system design (SESSILE), project number: 328697.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: On request by the e-mail provided.

Acknowledgments: Karolina Stråby (SINTEF) and their laboratory staff for the technical support.

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

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