DYNAMIC THERMAL MODELING OF LEGIONELLA PNEUMOPHILA PROLIFERATION IN DOMESTIC HOT WATER SYSTEMS

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ABSTRACT

A simulation model is developed that allows to investigate the infection risk for Legionella Pneumophila in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. With the thermodynamic model, the Legionella P. infection risk of the DHW recirculation loop in a case study building is assessed and important components for an optimization study on the trade-off between infection risk and energy efficiency are identified.

INTRODUCTION

Domestic Hot Water (DHW) systems are an important part of building services in residential building typologies such as dwellings, apartments, hotels, retirement homes, as well as in sports facilities, hospitals, spa's etc. (Stout and Muder, 2004).

With ever improving insulation levels and air tightness of building envelopes due to the tightening of energy performance requirements for buildings, the production of DHW, which has seen comparatively little innovation, now easily dominates the total energy demand. On average, about 800kWh per occupant per year is needed for DHW production. For the average dwelling with a floor area of 170m\(^2\) and 3.5 occupants (Defruyt et al., 2013), this amounts to 15kWh/m\(^2\) per year. This demand is unchanged, while projected energy performance requirements for 2020 reduce the total energy demand for heating, cooling and DHW production to 1/3 of what they were in 2006.

One of the main reasons for this high energy demand is that DHW is produced, stored and distributed at temperatures above 55°C to mitigate the risk of DHW production units such as heat pumps.

The 55°C temperature limit has been established by investigating the growth dynamics of Legionella P. bacteria in lab conditions and studying infected cases (Brundrett, 1992). At these temperatures, 90% of the Legionella P. bacteria are effectively killed in half an hour and the DHW system is considered safe. Recent studies focus on the survival of Legionella P. bacteria and amoeba in biofilms (Konishi et al., 2006) (Buse et al., 2014). Other research projects look at the exposure mechanics once a system is infected (Schoen et al., 2011) (Hines et al., 2014) or focus on the influence of tubing material (Van Der Kooij et al., 2005) etc.

The literature about decontamination strategies for infected systems is similarly scattered as that on the proliferation of Legionella P., usually focusing on a single disinfection technique and tested in limited lab configurations or in case studies (Lehtola et al., 2005). The limitations of these studies are summarized in Decontamination of Biological Agents from Drinking Water Infrastructure (Szabo and Minamyer, 2014). Other papers focus on the effect of these techniques on biofilms (Mathieu et al., 2014).

Reports from infection cases demonstrate that popular decontamination strategies such as applying thermal shock or chlorination often only have a temporary effect. After returning to normal use, Legionella P. growth resurfaces, probably due to flow stagnation or biofilm residue.

So far, accurate information on how to incorporate dynamic temperature profiles, piping design or DHW use profiles in a risk assessments such as required by ASHRAE standard 188P and other Legionella P. risk management standards is not available, limiting design options for DHW systems and forcing the available standards to require continuously high temperatures. This is reflected for example in the new REHVA (Federation of European Heating, Ventilation and Air Conditioning Associations) handbook on Legionella P. mitigation (REHVA 2013).

Although a lot is known about the growth dynamics of Legionella P., this knowledge needs to be combined with the advances made in hydronic
modeling that now allow accurately predicting the dynamic flow conditions (temperatures, velocities, pressures) in DHW systems (Vandenbulcke, 2013) in order to be able to assess the Legionella P. infection risk on a system level.

This project aims to develop a simulation model that allows investigating the infection risk for Legionella P. in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. With that model, DHW system configurations that now dominate the market and alternatives proposed to lower the energy demand will be assessed to come to new ‘best practice’ guidelines. As was outlined in the previous section, the current state of the art is disperse.

Many aspects of the infection risk assessment chain are well documented, but there is no general framework that allows bringing them all together and performing an actual detailed risk assessment. This impedes the optimization of DHW system design, both on a principal and a case by case basis, resulting both in frustrated energy efficiency ambitions by strict and high design temperatures and unaccounted risk taking by blindly choosing ‘acceptable’ design options in practice. Additionally, in infection cases, decontamination is carried out more or less on a trial and error basis, making it very time consuming, costly and above all unsafe.

By developing a simulation model that incorporates the Legionella P. proliferation in dynamic conditions, HVAC designers will be able firstly to thoroughly assess the Legionella P. infection risk associated with their design and secondly to optimize the temperature regimes, choose better hydronic controls and reduce the energy demand for DHW production.

**SIMULATION MODEL**

A simulation model is developed that allows investigating the infection risk for Legionella P. in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. The model is set up in the TRNsys environment.

The basic TRNsys model only includes a hydraulic model that allows modelling the water flow through the system. The results presented in this paper are from a model where the geometry of the hydraulic system is based on the DHW loop found in a case study building from a low energy renovation project in Flanders. It is a 10 story multifamily residential building, shown in Figure 1.

The DHW tap profiles are based on the average flow rates reported for large residential buildings by Bleys (2015).

Each of the components of the hydraulic model are coupled with a Legionella P. growth model based on the temperature growth curves described by Brundrett (1992) as shown in figure 2 and described in equation 1.

![Figure 1 Case study building](image1)

![Figure 2 Legionella P. growth curve as a function of temperature (Brundrett 1992)](image2)
\[ \Delta c = c_t - c_{t-1} = c_{t-1} \cdot (f(growth))^t - 1 \]  

(1)

Where \( c \) denotes the concentration of Legionella \( P. \) bacteria and growth the relative growth rate as a function of time \( t \).

For each of the components, 2 relevant volumes are defined: the main water volume that comprises 80% of the total volume of the component and a 'stagnant' region of 20% of the total volume. The main flow rate through the component is in the main volume, while only a small amount of exchange (10% of the total flow rate) exists between the main volume and the stagnant region. The overall scheme of the Legionella \( P. \) growth model is shown in figure 3.

The total model in the TRNsys studio is shown in figure 4. The red line is the DHW recirculation loop, fed by the fresh water supply in blue. In parallel, the yellow line is the connected ‘Legionella \( P. \)’ loop, consisting of the interconnected Legionella \( P. \) growth models per component, each of which is composed of the 2 sub-volumes as described above.

**RESULTS**

The Legionella \( P. \) growth in the model, in accordance with the growth model discussed above, only depends on the temperature of the water.

Figure 5. provides an overview of typical temperature distributions in the different components of the DHW loop in the model. The use profile in DHW systems is highly intermittent, as is shown in the blue line in the figure. This ‘flushes’ the loop with fresh water, bringing the Legionella \( P. \) concentration back to the concentration of the fresh water supply, preventing excessive proliferation.

The TRNsys simulation of the proliferation of Legionella \( P. \) in water in the DHW system recirculation loop of the studied case study model shows that it is necessary to take the 2 volume approach for the model to come to realistic results, because the growth of Legionella \( P. \) in water is partly neutralized by the large amount of fresh water that enters the system (Figure 6).

In real life situations, due to turbulence, sediments on the walls of the loop and gravitational forces, the ‘flush’ is limited to the main streamline volume of the water flow, while a stagnant area exists where infected water remains and quickly re-infects the main volume after the flush.

Figure 7. shows how the concentration in a stagnant bottom part of the boiler affects the Legionella \( P. \) growth in the main water volume. The fraction of stagnation needs to be determined experimentally or by detailed CFD simulations.
Figure 5 TRNSYS simulation of temperature profiles in the DHW loop in the case study building (10 days) with the power of the water heater (red) on the left y-axis (J) and the temperature in the boiler vessel at the top (pink), middle (blue) and lower part (green) as well as the temperature at the most remote point in the loop (black) and at the return of the recirculation loop/bottom of the boiler vessel (yellow) on the right y-axis.

Figure 6 TRNSYS simulation of Legionella P. growth in water in the case study building without 2 volume approach (1 week)
Figure 7 TRNSYS simulation of Legionella P. infection risk of a stagnant area at the bottom of a boiler vessel (10 days) with the Legionella P. concentration in the bulk volume of the boiler vessel (pink) and at the stagnant bottom of the boiler vessel (brown) on the left y-axis (J) and the temperature at the top of the boiler vessel (blue) as well as the temperature at return of the recirculation loop/bottom of the boiler vessel on the right y-axis.

Figure 8 TRNSYS simulation of Legionella P. infection risk of a dead pipe-end in ‘Drie Hofsteden’ (2 months), the blue line showing the waterflow in the dead pipe-end.
The *Legionella P.* infection risk of a dead pipe-end branched from a circulation network system is investigated. The simulation proves that dead pipe-ends are critical locations for the growth of the bacteria. Due to the lack of water flow, the temperature drops into the critical range over a short end of the pipe, which then infects the remainder of the dead pipe-end (Figure 8).

**CONCLUSION**

By developing a simulation model that allows assessing the *Legionella P.* infection risk in dynamic conditions, HVAC designers will be able firstly to thoroughly assess the infection risk associated with their design and secondly to optimize the temperature regimes, choose better hydronic controls and reduce the energy demand for DHW production.

In this paper, we presented a 2 volume approach to model the stagnant part of the water volume that is not flushed out by intermittent usage in DHW systems. Modeling a multi-family residential case study building pointed at considerable *Legionella P.* proliferation risks in the boiler vessels and dead pipe-ends.

We are currently developing a more detailed biofilm model to model the exchange between this stagnant region and the main water volume. With this model, the *Legionella P.* infection risk of 5 to 10 often used DHW configurations from REHVA design guidelines for DHW systems will be assessed and new design guidelines for these configurations will be proposed based on an optimization study that looks at the trade-off between *Legionella P.* infection risk and energy efficiency.

**ACKNOWLEDGEMENT**

This research is founded by the Agency for Innovation by Science and Technology-Belgium (IWT), Project 141608. The authors thank the Belgian Building Research Institute (BBRI/WTCB/CSTC) and especially Karla Dinne en Bart Bleys for their assistance and feedback. The authors thank the partners of the Proeftuin R&D building projects for contributing the information about the case study building.

**REFERENCES**


