# Coupled thermodynamic and biologic modeling of *Legionella Pneumophila* proliferation in domestic hot water systems

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## 1 SUMMARY

The production of Domestic Hot Water (DHW) dominates the total energy demand. One of the main reasons for the high energy demand is that DHW is stored and distributed at temperatures above 55°C to mitigate the risk of infecting the DHW system with *Legionella Pneumophila*. At these temperatures, *Legionella* bacteria are effectively killed. For most of the applications of DHW, temperatures of only 30-40°C are required. This disparity (between 55 and 30-40°C) doubles the temperature difference between the DHW system and the environment and has a detrimental effect on the efficiency of DHW production units.
A simulation model will be developed that allows to investigate the infection risk for *Legionella* in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. In addition to the modeling work, a test rig will be built and the relevant temperature and use profiles will be measured in DHW systems of several buildings. With the thermodynamically validated model, the *Legionella* infection risk of 5 to 10 DHW system configurations will be assessed and new design guidelines will be proposed based on an optimization study that looks for the trade-off between infection risk and energy efficiency.

## 2 INTRODUCTION

### 2.1 State of the Art

Domestic Hot Water (DHW) is 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 170m² and 3.5 occupants (Defruyt et al., 2013), this amounts to 15kWh/m² 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 stored and distributed at temperatures above 55°C to mitigate the risk of infecting the

DHW system with *Legionella Pneum.*, an aerobic gram-negative bacterium that, upon exposure, causes acute respiratory disease (Pontiac Fever) or severe pneumonia (Legionnaires disease). At these temperatures, *Legionella* bacteria growth is stopped and remaining bacteria are effectively killed.

For most of the applications of DHW, such as showering or doing the dishes, temperatures of only 30-40°C are required. This disparity (between 55 and 30-40°C) doubles the temperature difference between the DHW system and the environment along with the associated heat loss and has a detrimental effect on the efficiency of DHW production units such as heat pumps. The 55°C temperature limit has been established by investigating the growth dynamics of *Legionella* bacteria in lab conditions and studying infected cases (Brundrett, 1992). Recent studies focus on the survival of *Legionella* 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*, 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* 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 assessment 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* mitigation. Although a lot is known about the growth dynamics of *Legionella*, these need to be combined with the advances made in hydronic modeling that now allow an accurate prediction of the dynamic flow conditions (temperatures, velocities, pressures) in DHW systems (Vandenbulcke, 2013) in order to be able to assess the *Legionella* infection risk on a system level.

### 2.2 Objectives

This project aims to develop a simulation model that allows to investigate the infection risk for *Legionella* 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 allows to assess the infection risk in dynamic conditions, HVAC designers will be able firstly to thoroughly assess the *Legionella* 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.

### 2.3 Challenges

There are 2 types of challenges with the proposed integration task: bringing together the different system models and filling in the gaps between the known elements. Dynamic biological growth models and DHW hydronics models usually operate on a very different scale. To come to a manageable model in term of computational resources while designing a DHW system, a multi-scale model will have to be developed. The relevant timescales for both the biological and hydronic models are similar, around 1 minute.
As mentioned above, the available data on growth dynamics contain a number of gaps. Some decontamination techniques or the response of the bacterial growth to a certain parameter have only been tested under a number of very specific conditions. The growth dynamics are clearly a multivariate problem, necessitating extrapolation beyond the known results to come to a full model.

## 3 METHODOLOGIES

### 3.1 Simulation model

A simulation model will be developed that allows to investigate the infection risk for *Legionella* in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. To come to an adequately validated model, three parallel tracks will be followed: compiling the simulation model on the one hand, building a test facility on the other and measuring the relevant temperature and use profiles in DHW systems of several buildings in addition to the modeling work.

To compile the simulation model, the 'Modelica' (URL: http://www.modelica.org) environment will be used. This equation based programming language is non-proprietary and object oriented, making it extremely appropriate for the development of multi-scale models such as required here. Extensive libraries for the simulation of buildings and their services have recently been developed in IEA EBC annex 60.
The work within this project will add to the capabilities of the Modelica simulation environment by providing a biological growth library that is not available today. Modelica’s open source and modular structure will allow users to use this library to model similar biological growth problems in all kinds of applications. This approach is preferred over creating a multi-simulation environment from available part-models. The goal is to have a tool that is flexible and that can be used in multiple contexts, from design to decontamination. Having a large number of different tools work together in such conditions is much less stable. Additionally, it requires that the users get acquainted with all different simulation packages and is less flexible towards extensions of the model to other situations.

To assure that the result can be used in as broad a context as possible, the biological growth model is split into a number of part-models, each of which can be used in Modelica independently and therefore has value on its own, considerably reducing the 'all the eggs in one basket' risk associated with this project. If the development of one of the part-models fails, it can be replaced by a rough estimation model. The general framework for the infection risk assessment will still be able to function (although with an approximation for a certain component) and the failed component can easily be replaced at a later stage. The basic split will be between: **1/** water based proliferation of the bacteria (growth in the water itself and transport within the water), **2/** biofilm growth, **3/** *Legionella* growth in the biofilm and **4/** bacteria transport between the biofilm and the water.
To model the proliferation of *Legionella* bacteria in water it will be modeled as a pollutant with a variable source term in the bulk of the water. Based on an extensive literature review, the main parameters that have an impact on the growth of the bacteria are selected and added to the model as equations. This includes the equations of water temperature, flow conditions, pH...

***Pasteurization (temperature).*** Multiplication of *Legionella* is dependent on water temperature in the first place, followed by nutrient availability. At temperatures below 20°C the bacteria become dormant but remain viable for months. The bacteria grow best at temperatures between 20°C and 45°C with an optimum at 35°C. Beyond 45°C pasteurization starts and higher temperatures will eventually kill the organism. Figure 1 shows an estimation of the mean generation time (time to double the number of cells) of *Legionella Pneum.* in tap water. The death rate at any temperature is proportional to the number of living cells present (Brundrett, 1992).

$$\textit{Death rate} = dn/dt = B\,n \qquad \textit{Number of cells } n = n_0\, e^{-Bt} \qquad (1)$$

Where $n$ is the number of cells present at time $t$, $t$ is the time, $B$ is a constant which is a function of the water temperature, the species of the organism and the chemical nature of the water and $n_0$ is the number of cells at time $t$ = 0.

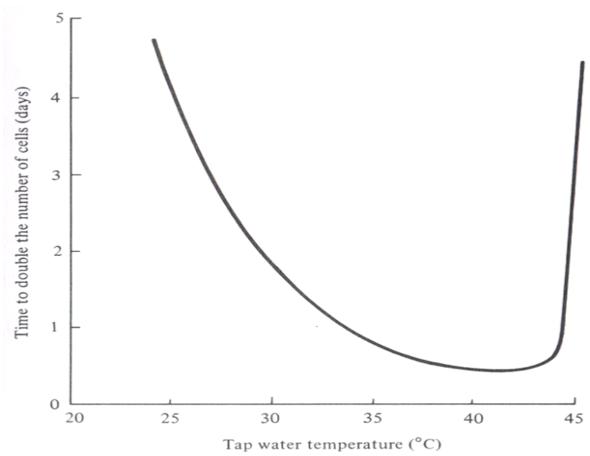


Figure 1. An estimation of the mean generation time of *Legionella Pneumophila* in tap water.

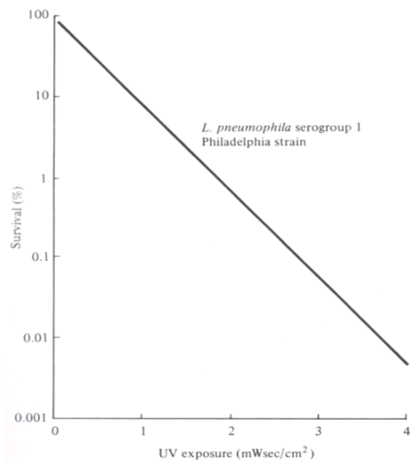


Figure 2. UV inactivation curve for *Legionella Pneumophila*.

Besides pasteurization (killing *Legionella* bacteria at high temperature) there are 2 other commonly used disinfection techniques; ultraviolet (UV) irradiation and the addition of biocides. When exposed to UV light the cells progressively die in a mathematically similar way to the effect of heat:

| | |
|---|---|
| *Number of cells living* $n = n_0\, e^{-kIt}$ | (2) |

Where $n_0$ is an initial number of cells at time = 0, $k$ is a constant, $t$ is the exposure time and $I$ is the intensity of irradiance.

***UV irradiation.*** The influence of UV on the percentage living bacteria is plotted in Figure 2 (Antopol and Ellner, 1979). At a UV exposure of 1mWsec/cm², 2mWsec/cm² and 3mWsec/cm² there is respectively 90%, 99% and 99.9% reduction in cells.

To take the UV irradiation into account, 1 component is added to the model according to the above equations, without affecting the rest of the model.

***Biocides.*** A third possibility to kill *Legionella* effectively is by adding biocides. Biocide addition is a chemical method of cell inactivation. Bacterial death rates are proportional to the cell population, as in the pasteurization process described earlier:

| | | |
|---|---|---|
| $dn/dt = K\, n$ | *Number of cells* $n = n_0\, e^{-Kt}$ | (3) |

Where $n$ is the number of cells at time $t$, $t$ is the time, $K$ is a constant which is function of the species of the organism, the temperature, the water chemistry and the type and concentration of biocide and $n_0$ is the number of cells at time $t$ = 0.

The potency of biocide depends on its dilution, the temperature, the pH and the cleanliness of the water. There are 3 oxidizing biocides: chlorine, ozone and hydrogen peroxide. Ozone is the most powerful biocide, followed by chlorine. Hydrogen peroxide requires a much higher dosage to produce a similar death rate (Figure 3).

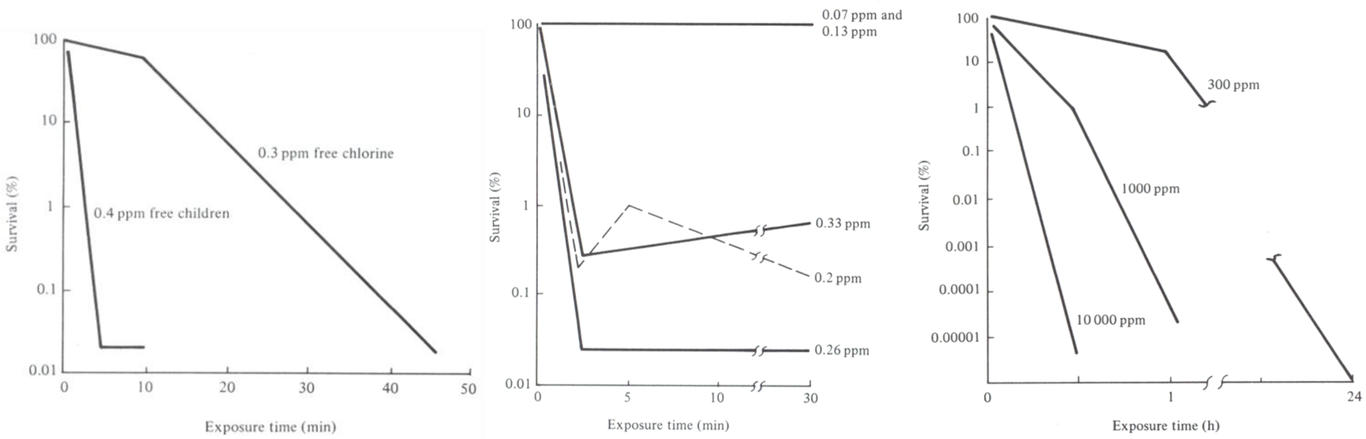


Figure 3. Effect of chlorine (25°C, PH 7.2), ozone (25°C, pH 9) en hydrogen peroxide (25°C, pH 7.2) on the inactivation of *L. Pneum.* serogroup 1 (Brundrett, 1992).

The presence of nutrients or disinfecting agents such as Chlorine or Ozone are added to the model as pollutants based on their concentrations. By choosing intensive properties to model the growth rate, the dynamics can more easily be taken into account.

A similar approach is taken to model the growth of the biofilm and the growth of *Legionella* in the biofilm. The transport model between the biofilm and the bulk water will be derived from the boundary layer theory. So far, models incorporating the effect of the biofilm on the water concentration usually assume that all bacteria from the film migrate to the water flow.

## 3.2 Validation - test rig

In addition to the modeling work, a test rig will be constructed in collaboration with the Belgian Building Research Institute (BBRI/WTCB/CSTC) in their accredited laboratory. The test rig is part of the 'Instal 2020' project 'integral design of DHW and heating installations'. The aim of this project is to realise a breakthrough in the development of energy efficient installations for DHW and central heating. The project is focusing on the energetic performance of several installation concepts for the production and distribution of heating and DHW. Energy, comfort and water quality are key words in this research. This includes fighting *Legionella* in potable water. The test rig will serve to run experiments that will allow testing, validating and improving the different part-models, as well as the complete model, to see if all relevant parameters for the prediction of *Legionella* growth are accurately predicted and to test the assumptions that are made to close the gaps in the available knowledge. Therefore, the test rig will need to meet the following specifications: **1/** be composed of realistic elements of DHW systems, in a sufficient degree of system complexity, **2/** have flexibility to test different system configurations, **3/** allow to apply dynamic use patterns, **4/** monitor water velocity and temperature at the inlet and outlet of (and sometimes within) each specific section of the DHW system, **5/** have a number of *Legionella* sampling points that allow to take samples without being exposed to contaminated water, **6/** allow easy disassembly, to decontaminate the whole system between tests, **7/** have a large contaminated water storage.
Once both model and test rig are up and running, 2 or 3 system configurations will be simulated and tested. For each configuration, an 'as is' test will be followed by a set of 2 additional tests, the first with altered temperatures for low energy use (and high infection risk), the second running a decontamination procedure on the infected system. This test rig will allow model validation under different operating conditions.

## 3.2 Validation - case studies

Besides model validation on the basis of the test rig, relevant temperatures and use profiles in DHW systems of several relevant buildings will be measured. The 3 case studies used in the research on *Legionella* in DHW systems are part of the IWT 'Proeftuin' project (Belgian government agency for Innovation by Science and Technology). The purpose of the 'Proeftuin' is to stimulate scalable and reproducible renovation concepts in order to obtain affordable R&D solutions. Research is being carried out on the basis of real renovation projects (Figure 4). The 1$^{st}$ project is the 'Kielparktorens', heritage apartment buildings in Antwerp *(IWT-project nr 140131)*. The project will acquire the necessary insights in order to achieve more (cost) optimal energy efficient residential blocks. The 2$^{nd}$ project is the 'Schipjes' in Bruges *(IWT-project nr 140125)*, it aims to stimulate energy optimization in renovation of historic homesteads. The 3$^{rd}$ project is the 'Drie Hofsteden' in Courtrai *(IWT-project nr 140126)*, it aims to develop solutions for the renovation of social condominiums to Nearly Zero-Energy Building standard.

Figure 4. Case studies - Kielparktorens Antwerp, Schipjes Bruges, Drie Hofsteden Courtrai.

In the ‘Kielparktorens’, ‘Schipjes’ and ‘Drie Hofsteden’ different systems for DHW production and distribution will be implemented. Temperature profiles, flow conditions and DHW use profiles will be monitored on several locations within the installation. This will allow us to validate temperature and flow condition parameters in the proposed thermodynamic model for similar boundary and use conditions as in these projects. Furthermore it will be possible to determine the growth of the biofilm periodically on different locations inside the system since a big part of the systems will be newly installed at the beginning of the projects, which makes it possible to estimate the *Legionella* risk. It will permit to check the several part-models by punctual monitoring of *Legionella* to see if all relevant parameters for *Legionella* growth are predicted thoroughly.

## 4 RESULTS AND DISCUSSION

A TRNSYS simulation of the proliferation of *Legionella* in water in the DHW system (circulation network system) of ‘Drie Hofsteden’ shows that it is necessary to model also biofilm growth and *Legionella* growth in the biofilm, because the influence of *Legionella* in water becomes partly neutralized by the large amount of fresh water that enters the system (Figure 5). *Legionella Pneum.* can survive up to 13 weeks on these biofilm surfaces and it represents a potential health risk when this occurs in DHW systems.

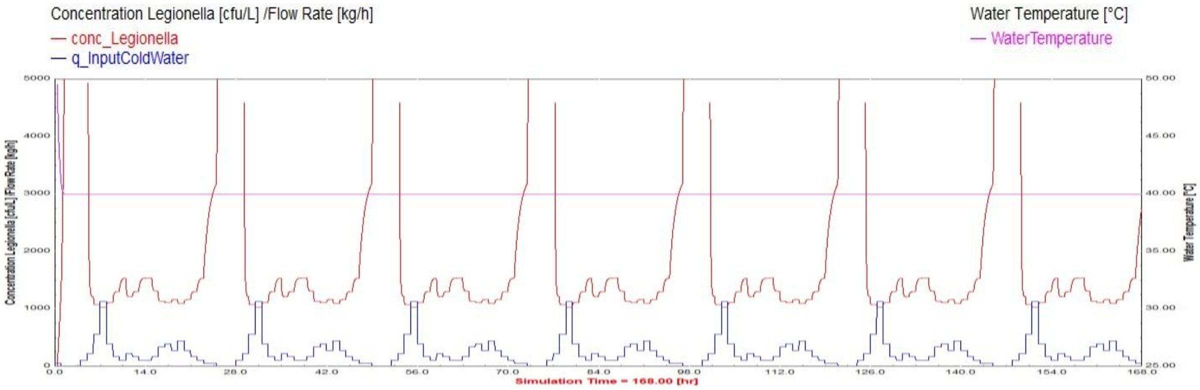


Figure 5. TRNSYS simulation of *Legionella* growth in water in ‘Drie Hofsteden’ (1 week).

The *Legionella* 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 (Figure 6).

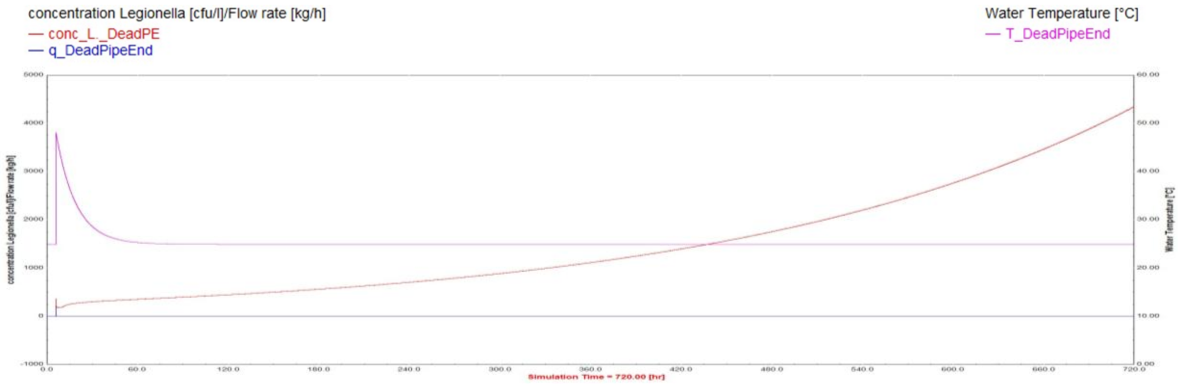


Figure 6. TRNSYS simulation of *Legionella* infection risk of a dead pipe-end in ‘Drie Hofsteden’ (2 months).

Thermodynamically validating the model on the basis of the monitoring results of the case study buildings will limit the levels of uncertainty. With the model, the *Legionella* infection risk of 5 to 10 often used DHW configurations, selected from WTCB and 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 for the trade-off between *Legionella* infection risk and energy efficiency. For these configurations 5 common decontamination strategies will be tested, compared and optimized for long-term effectiveness.

## 5 CONCLUSIONS

By developing a simulation model that allows assessing the *Legionella* 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. A final project goal is to create a reduced order model, based on the full model, which can be used in the design and control of complex DHW systems or in building management systems to actively prevent *Legionella* infection based on real-time monitoring data, as well as to remediate infected systems, thereby considerably reducing the management costs of infected systems.

## 6 ACKNOWLEDGEMENT

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