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Towards energy efficient and healthy buildings: trade-off between *Legionella pneumophila* infection risk and energy efficiency of domestic hot water systems

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Abstract

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 pneumophila 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 DHW system and environment and has a detrimental effect on the efficiency of DHW production units.

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. By developing a simulation model that allows assessing the Legionella pneumophila 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 addition to the modelling work, a test rig is built which will serve to run experiments that will allow testing, validating and improving the simulation model.

In future research this thermodynamically validated model, will be used to assess the Legionella pneumophila infection risk of 5 to 10 often used DHW configurations from REHVA design guidelines for DHW systems and new design guidelines for these configurations will be proposed based on an optimization study that looks at the trade-off between Legionella pneumophila infection risk and energy efficiency.

Keywords - domestic hot water systems; energy efficient buildings; healthy buildings; Legionella pneumophila; simulations; test rig

1. Introduction

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 (Figure 1). On average 15kWh/m² per year is needed for DHW production [1]. This demand is unchanged, while projected energy performance requirements for 2020 state to reduce the total energy demand for heating, cooling and DHW production to 1/3 of what they were in 2006.

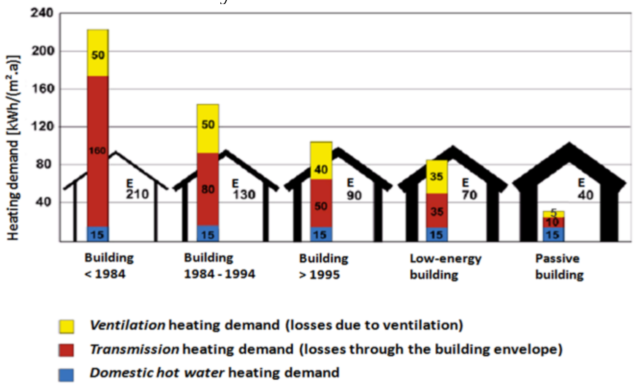


Fig. 1 Comparison of ventilation, transmission and domestic hot water heating demand for buildings built before 1984 to passive buildings

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 produced, stored and distributed at temperatures above 55°C to mitigate the risk of infecting the DHW system with *L. pneumophila*, an aerobic gram-negative bacterium that, upon aerosolized exposure, causes acute respiratory disease or severe pneumonia. At these temperatures, *L. pneumophila* 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 DHW system and environment, which causes high temperature heat losses (>15%), and has a detrimental effect on the efficiency of DHW production units. Heat pumps for example can be 20 to 25% more efficient at lower temperature.

2. Profitable Conditions for the Bacteria to Multiply

One of the aims of this research is to identify the conditions in an installation which favour the growth of *Legionella* bacteria. To have a better understanding an overview is given of the profitable conditions for the bacteria to multiply and reach dangerous concentrations.

Legionella exists as part of the natural microbial flora of many aquatic ecosystems. *L. pneumophila* bacteria appear in most water supplies like lakes, ponds and rivers, this is harmless. Very low concentrations of *Legionella* from natural habitats can be increased markedly in man-made hot water systems where the temperature is optimal for their growth and reach a dangerous concentration [2]. The growth of *L. pneumophila* is influenced for example by lukewarm water between 20 and 45°C (Figure 2), stagnation, an acid environment and the presence of nutrients through for example dirt and traces of rust.

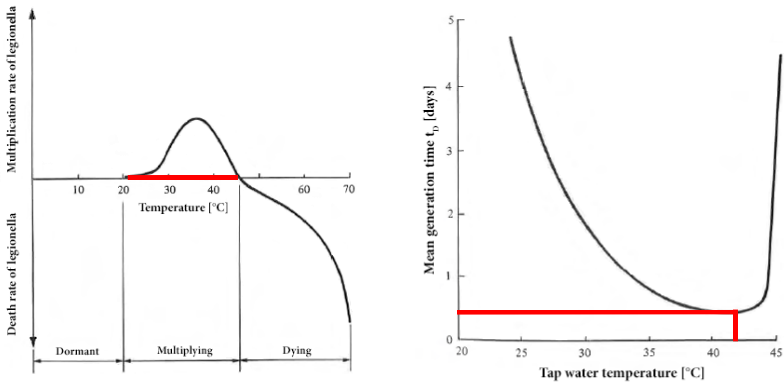


Fig. 2 *L. pneumophila* growth curve as a function of temperature [3]

L. pneumophila bacteria appear in water and in biofilm. This biofilm structure is composed of a consortium of microbial cells that are attached to the surface and associated together in an extracellular anionic polymer matrix [4]. The matrix is extremely hydrated (97% water) and consists mainly of exopolysaccharides, biological macromolecules (proteins, lipids, DNA and RNA), nutrients, metabolites, and inorganic compounds and particles, as well as cellular lysis products [5]. The bacteria attach to the biofilm because it consists of microorganisms which allow cells to adhere, it forms a protective layer for the bacteria which allows them to grow and multiply in the biofilm. Biofilms adjust to their surroundings and can resist antimicrobial agents. According to Flemming et al. [6], 95% of *Legionella* and other micro-organisms are surface-associated (biofilm).

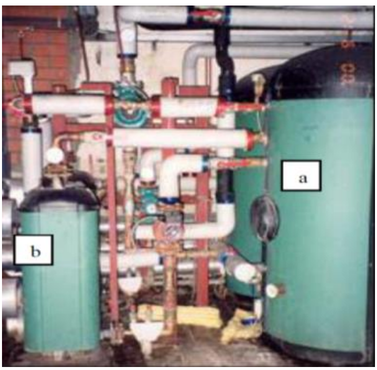
In the first place you should consider avoiding *L. pneumophila* by regarding some plumbing practices, such as avoiding stagnant sections of piping that would allow the growth of biofilm, like dead pipe ends, pipes towards little used taps,...

The presence of microbiota is essential for the survival of *L. pneumophila* in water systems, but their presence alone does not determine the occurrence of the pathogen [7]. The presence of microbiota and protozoa increased the risk of *L. pneumophila* colonization. Protozoa are protecting the bacteria from harsh conditions. Probably these microorganisms were structured in biofilms from where the bacteria were detached contaminating running water [8].

The presence of metals such as Fe or Zn derived from pipelines and fittings are important parameters for bacterial growth and virulence. Fe favored bacterial growth. Bacteria cannot grow in culture media without Fe. The logistic analysis showed that the presence of Fe above 0.095 ppm is associated with *L. pneumophila*. Water can be enhanced with Fe as a result of corrosion of ferrous installation components like for example galvanized steel pipes. Authors, such as Rogers et al. (1994) and Borella et al. (2004), stated that Cu inhibits its growth. The risk of *L. pneumophila* colonization in the circuit significantly decreased with respect to Cu concentration [8].

3. *Legionella* Points of Risk in DHW Installations

In the following section an overview of the 2 most common *Legionella* points of risk in DHW installations is given which will be further researched in the simulation model and test rig [9].

Point of risk	Description
Hot water production and distribution at < 55°C   	**Production** A typical way to produce hot water is to make use of a storage vessel (“boiler”) which is heated by a heat exchanger connected to the heating system. In the example on the picture the heat exchanger is located outside the vessel: (a) storage vessel, (b) heat exchanger. In hospitals and hotels it often happens that water for kitchens is produced at 60°C while water for the rooms only at 40 to 45°C. When the production temperature is 45°C, water temperature in the distribution system will be even lower.

Risk assessment	Solution
Hot water production at 40 to 45°C creates quasi ideal conditions for the growth of *Legionella* in the storage vessel. This situation is very risky, the probability that *Legionella* is present in this installation is very high.	The domestic hot water production temperature should be at least 60°C and the distribution temperature at least 55°C. If this requirement cannot be fulfilled in an existing installation, then additional measurements should be performed, like: • monitoring of water quality through water analysis, • heating the boiler regularly (daily in high-risk and weekly in moderate risk installations) up to minimum 60°C, • systematically providing chemical decontamination or • applying a continuous anti-*Legionella* treatment which has been recognized by the government.

Point of risk	Description
Dead pipe-ends: little used showers 	In schools, swimming pools, sports complexes, there are often a large number of showers, as shown on the left.
Risk assessment	**Solution**
In such cases, there is almost no certainty about the frequency of usage of these showers. Often cabins located furthest away from the entrance will be used the least. As a result, it is possible that stagnation occurs in the pipes upstream of the little-used showers. The risk of *Legionella* development is high because the bathroom remains at a fairly high temperature due to its usage.	The risk can be minimized by a control measure such as regular flushing of all showers. This can be done manually or automatically. Instead of flushing all showers, it is possible to install an automatic rinsing device on the downstream end of the water supply pipes that can be programmed.

4. Simulation Model

A simulation model is developed that allows to investigate the infection risk for *L. pneumophila* (Figure 3) in the design phase of a DHW system and to test the effectiveness of disinfection techniques on an infected system. By developing a simulation model that allows assessing the *L. pneumophila* 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. With the thermodynamic model, the *L. pneumophila* infection risk of the DHW recirculation loop in a multi-family residential case study building (Figure 4) is assessed and important components for an optimization study on the trade-off between infection risk and energy efficiency are identified.

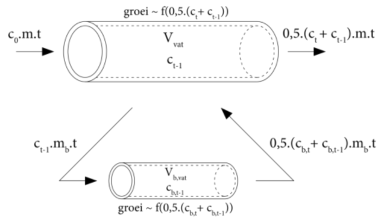


Fig. 3 Scheme of the implemented *L. pneumophila* growth model where *c* denotes the concentration of *L. pneumophila* bacteria, '*groei*' relative growth rate depending on the growth parameters, *V* volume, *t* time and *m* mass

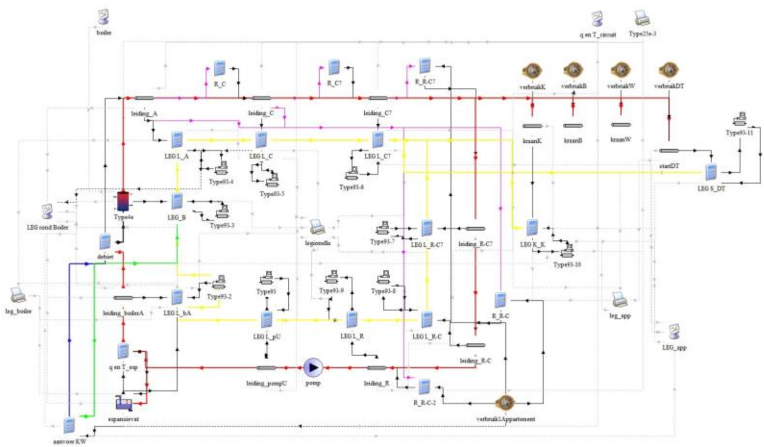
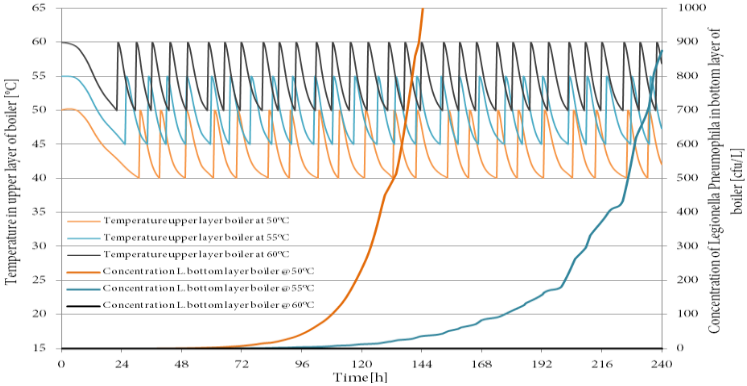


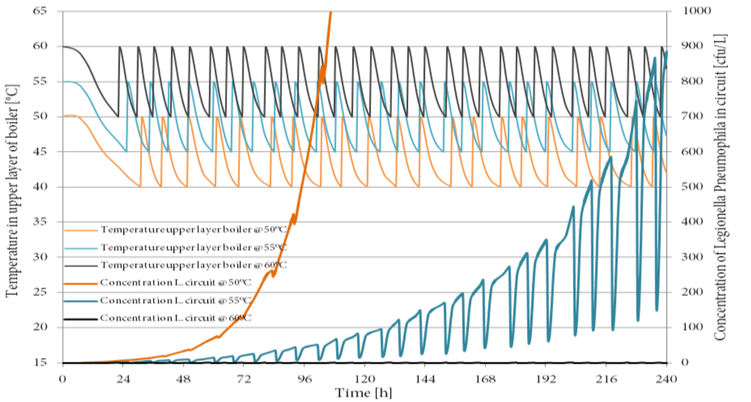
Fig. 4 Scheme of the overall DHW model (red) with implemented *L. pneumophila* growth model (yellow)

The *L. pneumophila* concentration at the bottom layer of the boiler is investigated. The simulation proves that the bottom layer of the boiler is a critical location for the growth of the bacteria (Figure 5). Figure 6 shows the influence of the production temperature (like the example assessed in section 3) on the concentration of *L. pneumophila* in the circuit.



Temperature upper layer boiler @ 50°C
Temperature upper layer boiler @ 55°C
Temperature upper layer boiler @ 60°C
Concentration L. bottom layer boiler @ 50°C
Concentration L. bottom layer boiler @ 55°C
Concentration L. bottom layer boiler @ 60°C

Fig. 5 Influence of boiler temperature on the concentration of *L. pneum.* in boiler (10 days)



Temperature upper layer boiler @ 50°C
Temperature upper layer boiler @ 55°C
Temperature upper layer boiler @ 60°C
Concentration L. circuit @ 50°C
Concentration L. circuit @ 55°C
Concentration L. circuit @ 60°C

Fig. 6 Influence of boiler temperature on the concentration of *L. pneum.* in circuit (10 days)

The *L. pneumophila* infection risk of a dead pipe-end branched from a circulation network system is investigated. The simulation proves that dead pipe-ends (like the example in section 3: little used showers) are critical locations for the growth of the bacteria (Figure 7). 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.

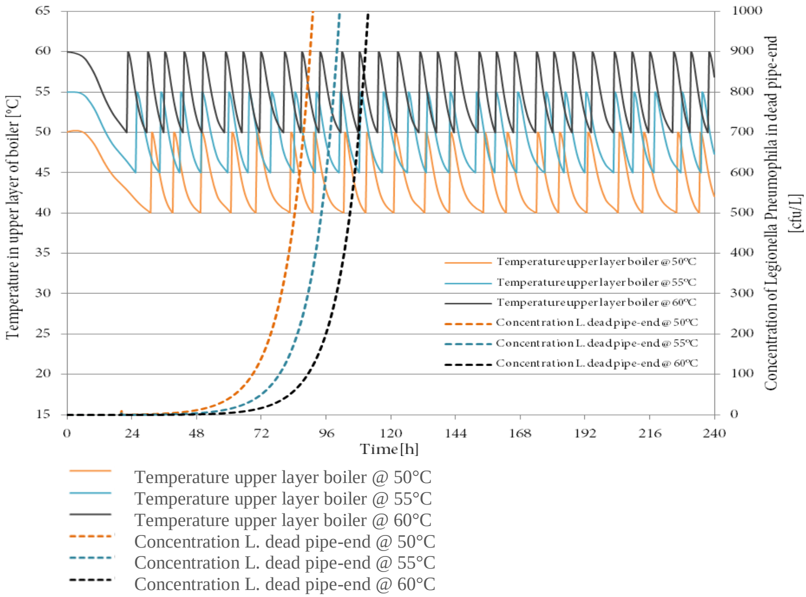


Fig. 7 Influence of boiler temperature on the concentration of *L. pneum.* in a dead pipe-end in case study building ‘Drie Hofsteden’

5. Building a Test Rig to Validate the Simulation Model

In addition to the modeling work, a test rig is 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 simulation 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 (Figure 8):

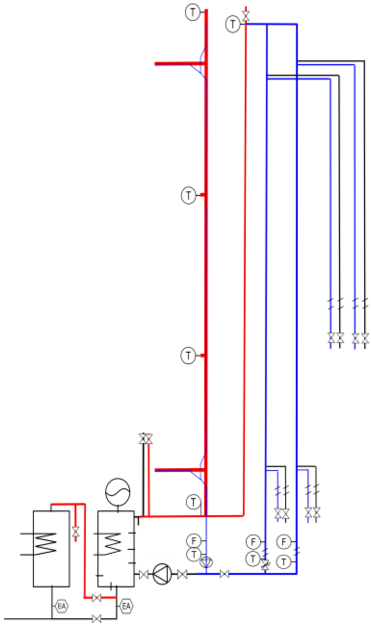


Fig. 8 Configuration of the test rig with in red supply pipes and in bleu retour pipes. There are 2 systems: a pipe-in-pipe system on the left and a recirculation system on the right

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 the test rig is 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.

A comparable pilot scale system located at the Scientific and Technical Building Centre (CSTC) in France showed that although *Legionella* diversity was reduced, pathogenic *Legionella* species (*L. pneumophila* and *L. anisa*) remained after the heat shock and chemical treatments, respectively. The biofilm was not removed, and the bacterial community structure was transitorily affected by the treatments.

Their findings, along with previously published studies, have shown that *Legionella* spp. seem to resist and proliferate in spite of the different treatment procedures applied. In fact, *Legionella* spp. can withstand temperatures of 5.0°C to 63°C and a pH range of 5.0 to 9.2 [5].

6. Results & Conclusions

By developing a simulation model that allows assessing the *L. pneumophila* 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.

Modeling a residential case study building pointed a considerable *L. pneumophila* proliferation risk in the boiler vessels and dead pipe-ends.

7. Future research

With this thermodynamically validated model, the *L. pneumophila* 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 *L. pneumophila* infection risk and energy efficiency.

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