Energy savings in hot water supply by legionella modelling


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Abstract

Legionella contamination in domestic hot water (DHW) systems can cause severe health problems and the actual concentration is often unknown. Prevention measures such as thermal disinfection are highly energy-demanding and hardly improved during the last decade. Within this study, we investigated the interplay between the risk of legionella on the one side and energy saving potential in a DHW supply system on the other side. A proper prediction of legionella concentration could enable both: targeted legionella risk management and reducing energy demand for legionella risk management. Therefore, a mathematical description for the legionella development was formulated. We established a MATLAB/Simulink model considering all components of a typical single-family house. The results support that legionella risk is mainly dependent on the hydraulic conditions (e.g. hot water storage volume, tapped water volume). Single households with hot water consumption of 50 ℓ/d (at 42°C) and 150 ℓ storage tank size remained below 100 CFU/100 mℓ. Thus, no prevention or counter measures were required and the energy demand for thermal disinfection could be saved completely. Simulations indicate that energy demand for DHW systems could be decreased by 62% by operating with disinfection-on-demand and replacing electric heating with a heat pump (tank size 300 ℓ and profile S). The integration of a UV light-emitting diode (UV-LED) technology reduced additional 6% of energy demand in our setup and could replace thermal disinfection completely in some cases. These results pave the way for alternative hot water supply components with a lower temperature level (e.g. heat pumps).

Introduction

Bacterial contamination of domestic water supply is one major reason for water related health risks (WHO, 2011). In particular, legionella pneumophila (legionella) is of key interest as causative agent for Legionellosis and Legionnaires' disease (WHO, 2007). Being present in natural water bodies, legionella can find favourable multiplication conditions in DHW systems such as beneficial temperature levels and water stagnation. A common threshold value for legionella in drinking water is 100 CFU/100 mℓ (DVGW, 2004; Lee et al., 2017; Van Kenhove et al., 2019). The detection of legionella is mainly based on grab samples, leaving a gap of unknown concentration between sampling due to the high dynamics of domestic hot water consumption. This leads to a potential risk of contamination within domestic infrastructure.

Hot water production and mainly legionella prevention in DHW are responsible for around 17% of total energy demand of German households (Eurostat, 2019). While energy consumption for room heating was reduced by 21% between 2010 and 2018, energy consumption for hot water production remained more or less the same in the last decade (Eurostat, 2019). Common disinfection strategies recommend a storage temperature of 55°C and a disinfection at 60°C (DVGW, 2004; Lee et al., 2017; Van Kenhove et al., 2019). Reducing disinfection demand and lower water temperatures would enable more energy-efficient operation with a heat pump (Hepbasli & Kalinci, 2009), but it is proposed that the potential risk of legionella becomes higher.

This study aims to challenge the trade-off between energy demand and sanitation. Furthermore, we investigate the potential risk of legionella for a typical DHW supply under different hydraulic conditions based on a simulation approach.

Building model

The simulations are performed using MATLAB/Simulink (Matlab R2017b, MathWorks, Natick, MA, USA). We used MATLAB to implement a typical DHW system including tapping locations at three different points: kitchen sink, washbasin and shower (**Figure 1**). The most important infrastructure data and assumptions are:

- pipe volume below 3 ℓ
- pipe inner diameter = 15 mm
- flow velocity 0.07 ℓ/s / 0.15 ℓ/s
- pipe material = polyethylene/aluminium/polyethylene
- conductivity of pipe insulation = 0.035 W/m K
- set room temperature of 20°C (kitchen) or 26°C (bath room)

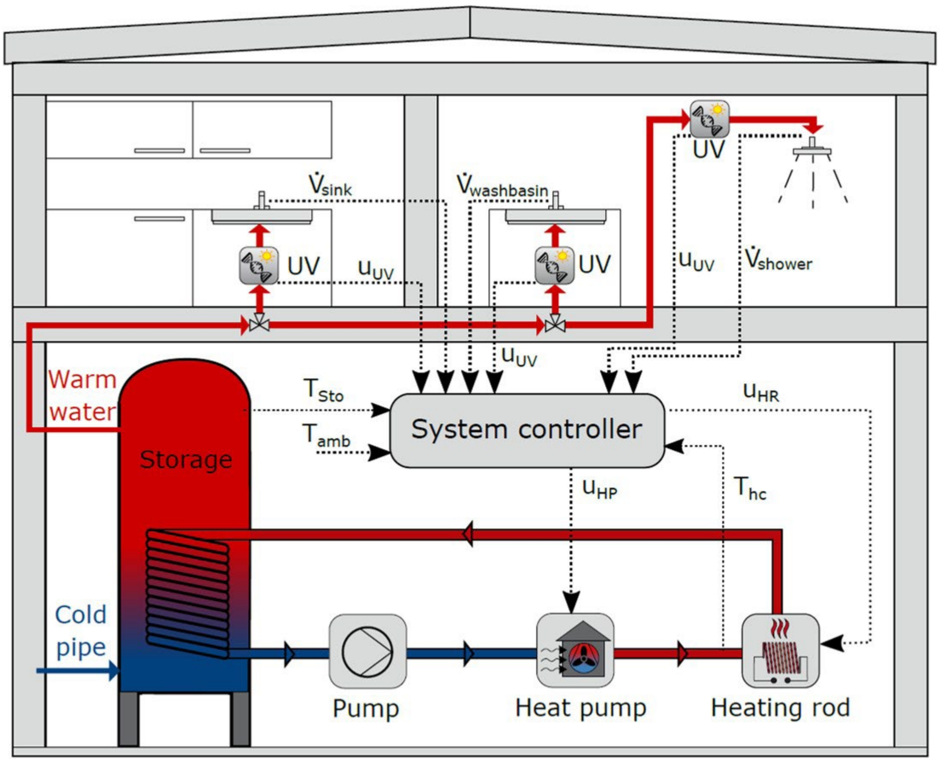

Figure 1. Modelled DHW supply system with key components including water storage, tapping locations, pipes, heat pump and UV LEDs.

We considered three tapping profiles to model the operating conditions: profile S (50ℓ/d at 42°C), profile M (150 ℓ/d at 42°C) and profile L (300 ℓ/day at 42°C) (DIN 16147).

Legionella model

The legionella concentration in the DHW system is predicted with a mathematical model integrated in the MATLAB/Simulink model. The model considers:

- temperature-related legionella growth and disinfection rate according to Brundrett (1992)
- detachment rates of biofilm from the pipe due to hydraulic conditions (Shen et al., 2015)
- UV disinfection rates according to Rattanakul et al. (2018).

During stagnation, the concentration of legionella in biofilm

X_b (or in water phase X_w) at time step t_i depends on the concentration of the previous time step t_{i-1}. Temperature-dependent growth or decay is expressed in $\mu(T)$ for a time step of size Δt.

$$X_b(t_i) = X_b(t_{i-1}) \cdot e^{\mu(T(t_i))\cdot\Delta t} \quad (1)$$

$$X_w(t_i) = X_w(t_{i-1}) \cdot e^{\mu(T(t_i))\cdot\Delta t} \quad (2)$$

In case of a tapping event, biofilm in detached from pipe walls and enters the water phase. The amount of legionella cells released into the water phase depends on the initial concentration in biofilm before tapping $X_{b,init}$ and the velocity-dependent detachment factor for this time step $\Delta k_d(t_{tap})$ adapted from Shen et al. (2015).

$$X_b(t_i) = X_b(t_{i-1}) - X_{b,init}(t_i) \cdot \Delta k_d(t_{tap}) \quad (3)$$

$$X_w(t_i) = X_w(t_{i-1}) \cdot e^{\mu(T(t_i))\cdot\Delta t} + X_{b,init}(t_i) \cdot \Delta k_d(t_{tap}) \quad (4)$$

At the beginning of a tap event, detachment rates are higher than during subsequent time steps. Minimal legionella concentration in the water phase is set at 1 CFU/100 mℓ. To investigate the energy saving potential, thermal disinfection shall only be conducted if necessary. Disinfection cycles in this work are triggered on demand at a set threshold of 100 CFU/100 mℓ.

Simulation of legionella risk

The potential legionella risk in a DHW system mainly depends on the hydraulic conditions and the equilibrium between growth and detachment of legionella. Large daily water consumption profiles with a small water storage tank result in small water retention times and therefore small legionella concentration and vice versa. The simulation results indicate that the equilibrium legionella concentration depends on the sizes of storage tanks. Below a critical storage volume of 100 ℓ and a tapping profile S (or larger), the legionella concentration remains below the threshold without additional disinfection (**Figure 2**), because retention times in the DHW system are too short for notable growth.

However, the simulation shown above is only valid for continuous tapping. Legionella concentration in water and biofilm phase is investigated separately during a stagnation period of two weeks for profile S and a tank size of 300 ℓ (**Figure 3**). Before stagnation, the legionella concentration in biofilm remains at its minimum value, as the vast amount of biofilm has been detached from the pipe walls during tapping. During stagnation, highest concentrations up to 1000 CFU/100mℓ are predicted inside the washbasin and shower pipe. This effect results from higher room temperatures in the bathroom and concluding faster grow rates. Furthermore, the grey curve shows that every shower event detaches 65% of the legionella cells from the biofilm into the water phase. Directly after a stagnation period, more frequent disinfection cycles are needed until equilibrium concentration is reached again. The concentration inside the kitchen sink pipe remains continuously low, because room temperatures around 20°C do not favour legionella growth. However, results indicate that individual water consumption behaviour and the DHW setup have a big impact on legionella concentration.

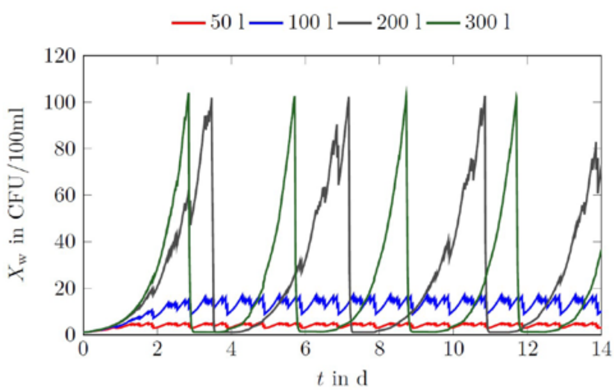

Figure 2. The effect of storage tank size on legionella concentration, considering user profile S.

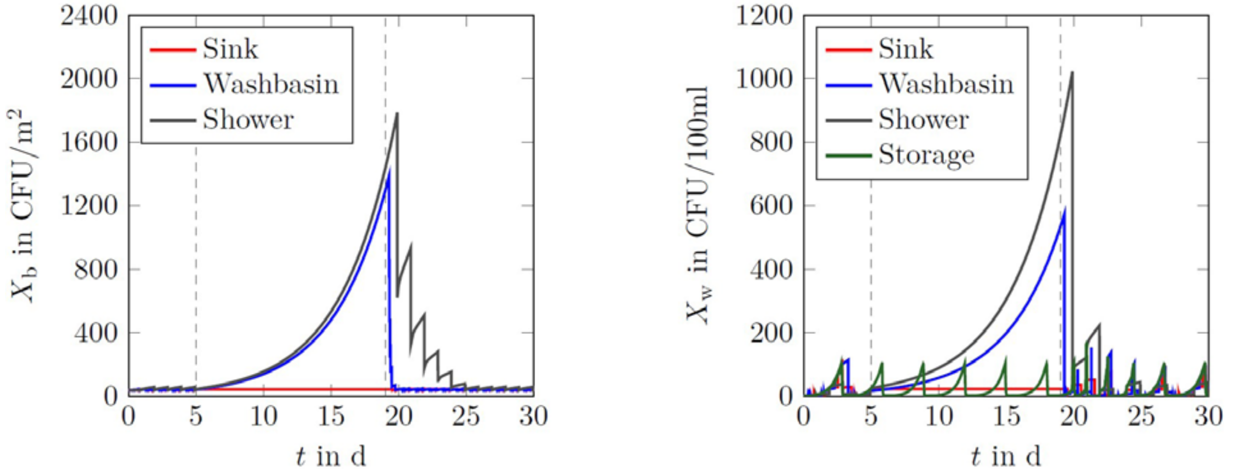

Figure 3. Legionella concentration during a stagnation of 14 days from day 5 to day 19 in biofilm (left) and water phase (right).

Energy saving potential in DHW

Thermal disinfection is currently the common strategy in DHW supplies with a recommended storage temperature of 55°C and disinfection temperature of 60°C (DVGW, 2004). The influence of hydraulic conditions (infrastructure, user´s behaviour) reveal that additional disinfection is redundant in many cases and therefore energy savings are possible. A "disinfection-on-demand" as described in the previous chapter enables energy saving while maintaining safe health conditions. Hence, water could be stored at low temperatures needed for consumption (around 42°C) and disinfection is only started if necessary.

With only few disinfection cycles necessary and operating at low temperatures, heat pumps are more efficient and energy can be saved. Operating at disinfection-on-demand and replacing electric heating with a heat pump, energy demand decreased 62% (tank size 300 ℓ and profile S).

Another possible technology for low energy hot water production is the implementation of UV-LEDs in DHW supply systems. Operating UV-LED modules with UV dose of 10 mJ/cm² at 280 nm, the UV-LED technology is able to reduce the actual legionella concentration around a factor of $2.5 \cdot 10^{-5}$, according to disinfection kinetics proposed by Rattanakul et al. (2018). Depending on the ratio of draw-off volume and storage tank volume, the legionella concentration reaches an equilibrium (**Figure 4**). In general, the risk of legionella increases with longer residence time of the water in the reservoir. In **Figure 4**, this corresponds to a larger tank volume and lower water consumption. Up to a tank volume of 150 ℓ and continuous tapping at profile S, M or L, no disinfection is needed according to our simulation. Operating at profile M or L, disinfection is redundant even to a storage size of 400 ℓ. Considering 160 ℓ as a typical water storage tank size for a single-family house, we assume that energy for disinfection purpose can be saved completely for single family homes (daily tapping assumed). Therefore, heat pumps can operate at low temperatures. Considering that 67% of the German building stock are single family houses (Statistisches Bundesamt, 2019), this would result in a significant decrease of total energy demand.

Simulation results support that legionella risk is relatively low for single-family houses compared to other building types such as multi-family homes, hospitals or hotels (Leoni, 2005; Borella 2004).

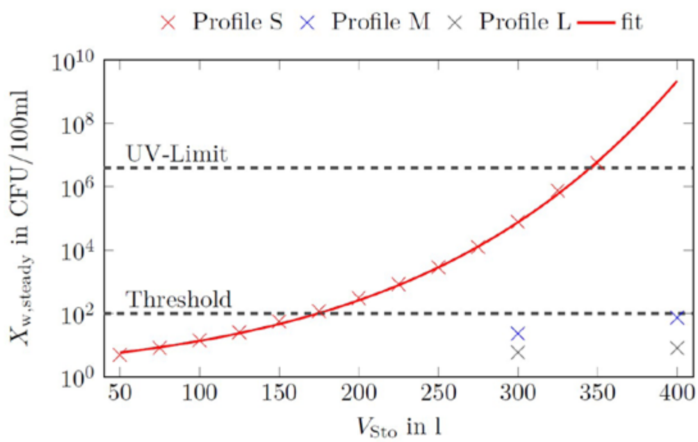

Figure 4. Legionella concentration equilibrium for different tapping profiles and storage tank sizes.

The following empiric equation approximates the red curve for tapping profile S described above. The equilibrium legionella concentration $X_{w,steady}$ is estimated depending on the storage volume V_{Sto}:

$$X_{w,steady}(V_{Sto}) = e^{800 \cdot e^{-\left(\frac{V_{Sto}-1560}{610}\right)^2}} \quad (5)$$

In some cases, thermal disinfection can be replaced by UV LED disinfection. Up to a tank size of 350 ℓ and a tapping profile of S or larger, hot water can be disinfected with UV LEDs without additional thermal disinfection (UV-Limit, **Figure** 4). Considering a heat pump and disinfection-on-demand, an energy saving of 6% is possible through the additional use of UV LEDs.

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Conclusions

In this study, we identified legionella-related health risk and energy saving potential for different DHW infrastructures and water consumption profiles. Hydraulic simulations imply that there is low legionella risk for family households and daily tapping of profile M or larger. We recommend storage volumes below 150 ℓ for single-person households (profile S) to minimize the stagnation in the storage. Operation of heat pump and disinfection-on-demand reduced energy demand around 62%.

In case of daily tapping the legionella concentration remains on an equilibrium state. This equilibrium concentration increases with higher storage volumes and decreases with larger consumption profiles. This relation is described with an equation to estimate the legionella risk. In the future, UV LED disinfection can replace thermal disinfection up to a storage volume of 325 ℓ for a single-person household (profile S), resulting in additional energy savings of 6%. ■

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