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Optimizing production efficiencies of hot water units using building energy simulations - Trade-off between *Legionella pneumophila* contamination risk and energy efficiency

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Abstract. The energy needed for domestic hot water represents an important share in the total energy use of well-insulated and airtight buildings. One of the main reasons for this high energy demand is that hot water is produced at temperatures above 60°C to mitigate the risk of contaminating the hot water system with *Legionella pneumophila*. However, this elevated temperature is not necessary for most domestic hot water applications, and has a negative effect on the efficiency of hot water production units. A simulation model has been developed which proposes an alternative to this constant 60°C by predicting the *Legionella pneumophila* concentration dynamically throughout the hot water system. Based on this knowledge, a hot water controller is added to the simulation model that sets a lower hot water comfort temperature in combination with heat shocks. In this paper, the simulation model is used to estimate the energy saving potential in a case study building, at the level of the heat production system by reaching higher production efficiencies. Three different production units, namely an electric boiler, heat pump and solar collector have been investigated. The controller is expected to become an alternative for the current, energy intensive, high temperature tap water heating systems.

1 Introduction

1.1 Motivation

The energy needed for production, storage and distribution of Domestic Hot Water (DHW) represents an important share in the total energy use of well-insulated and airtight buildings. One of the main reasons for this high energy demand is that hot water is produced, stored and distributed at temperatures above 60°C to mitigate the risk of contaminating the hot water system with *Legionella pneumophila*, a bacteria that can cause an acute respiratory disease or severe pneumonia which can be fatal. At 60°C, *Legionella pneumophila* growth is stopped and the remaining bacteria are killed. However, this elevated temperature is not necessary for most DHW applications, taking a shower and washing our hands requires a temperature of only 30-40°C. The disparity between 60°C and 40°C doubles the temperature difference between hot water system and environment (around 20°C) which has a negative effect on the storage and distribution losses and on the efficiency of hot water production units (such as heat pumps).

1.2 Novelty

A simulation model has been developed that proposes an alternative to this constant 60°C by predicting the *Legionella pneumophila* concentration dynamically throughout the hot water system as this concentration cannot be measured in real time [1]. Based on this knowledge, a hot water controller is added to the simulation model that sets a lower hot water comfort temperature in combination with heat shocks when a predefined concentration limit has been reached in simulation. Simulation results of such a controller show savings of more than 35% on the hot water distribution energy use in an apartment building, without increasing contamination risk [2].

1.3 Problem statement

In this paper, the simulation model is used to estimate the additional energy saving potential in a theoretical case study building, at the level of the heat production system by reaching higher production efficiencies if for example a heat pump is used at a lower temperature. Additionally, the additional production energy savings by implementing the controller in three different production units, namely an electric boiler, a heat pump boiler and a heat pump boiler with solar collectors, will be investigated. This new DHW controller is expected to become an important alternative for the current, energy intensive, constant high temperature tap water heating systems.

1.4 Background

The 60°C temperature limit has been established by investigating the growth dynamics of *Legionella pneumophila* in laboratory conditions and studying infection cases [3], [4], [5]. At these temperatures the DHW system is considered to be safe.

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Similarly, the Domestic Cold Water (DCW) temperature should be kept below 20°C to be considered *Legionella* safe.

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 around 35°C-41°C. Beyond 45°C, pasteurization starts and higher temperatures will eventually kill the organisms [6]. This can be seen on *Figure 1A*.

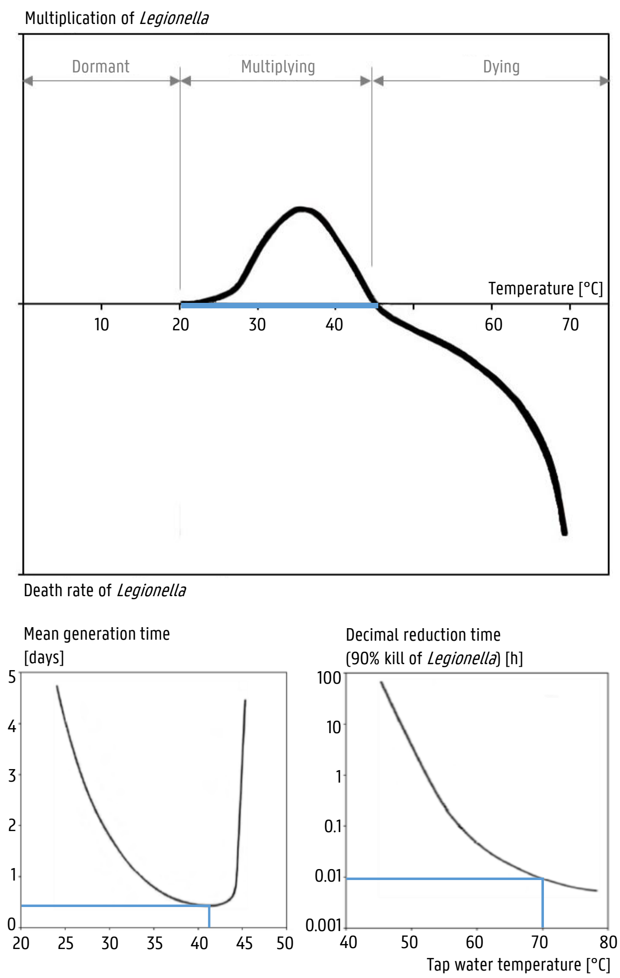

Fig. 1. A. Growth function of *Legionella pneumophila* in water (adapted from [6]). B. An estimation of mean generation time (time to double the number of cells) of *Legionella pneumophila* in tap water (data from [7], adapted from [6]). C. The change in decimal reduction time (90% reduction of *Legionella pneumophila*) with temperature (data from [3], [8], adapted from [6]).

On the x-axes, the water temperature in degrees Celsius can be seen and the units on the y-axes are quantified in *Figure 1B* and *1C* as they both have a different scale. On the y-axes in *Figure 1B*, the time to double the number of *Legionella pneumophila* (mean generation time) is given and, in *Figure 1C*, the time to reach 90% reduction in cells (decimal reduction time). *Figure 1B* is based on data from Yee and Wadowsky [7] from experiments on unsterilized tap water and Figure 1C is based on data from laboratory experiments [3], [4], [5], [8], and is consistent with field data [9]. *Figure 1B* shows that the time to double the number of *Legionella pneumophila* cells in water is less than half a day at 41°C and in *Figure 1C* it can be noted that at 70°C, 90% of *Legionella pneumophila* in water gets killed in less than a minute.

2 Methodology

Three simulation models of a theoretical case study DHW system have been developed. With these models a dynamic calculation has been performed of the different DHW heat production units, in order to compare the energy savings that correspond with fixing the DHW temperature at 60°C (DHW standard regime) and controlling the temperature in the system with a time based heat shock regime.

The Modelica language and Dymola (Dynamic Modelling Laboratory) environment is used to develop the simulation models. The Modelica language is suitable for modelling various kinds of physical systems. It can handle large, complex multi-engineering models and is open to add user defined model components, such as the biological components that are required here. To model the hydraulic system, the Modelica library 3.2.2, the Buildings 5.0.1 library [10] and IDEAS library 2.0.0 [11] has been used. To calculate the *Legionella pneumophila* concentration, a biologic library developed by the authors has been used that makes it possible to predict the *Legionella pneumophila* growth. More details regarding the numerical model used can be found in [2].

3 Case study DHW system

The principle of the simulation model of the DHW system is shown in *Figure 2*. The model consists of a component for the production unit, components for the distribution pipes, two distal pipes connected to two tap profiles corresponding with typical DHW kitchen and shower profiles of a single family household and the control of the DHW system. For all three production units, a different simulation model is made. In the next paragraphs, the different case study DHW system components are being discussed.

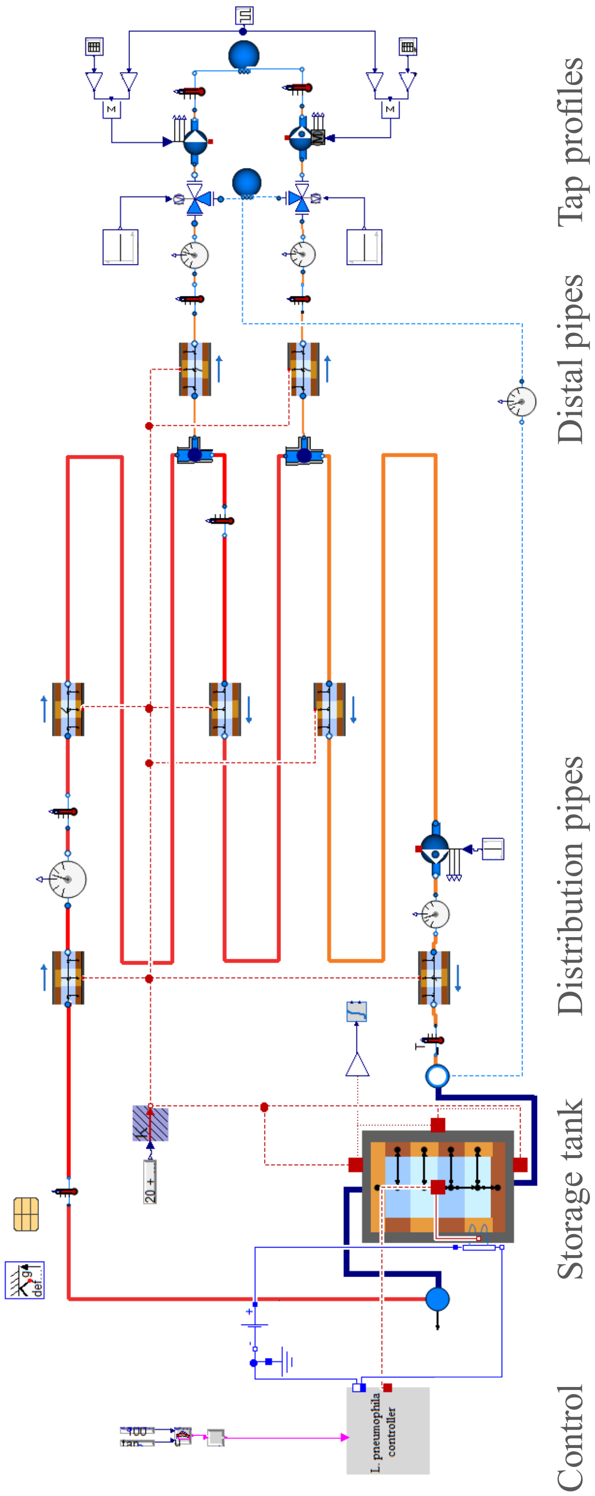

Fig. 2. Simulation model of the DHW system.

3.1 Production units

Each production unit consists of a storage tank with a volume of 200L. The internal height of the tank is 1.5m and the internal width is 0.4m. The tank is insulated with 10cm of mineral wool with a thermal conductivity value of 0.04W/(m·K). The water outlet is situated at the top. The water inlet (of return and cold water) is situated at the bottom of the tank.

The thermostat to control the water temperature is located at the bottom layer of the storage tank. To model the temperature in the storage tank, a one dimensional storage tank model is used that divides the height of the tank into several volumes (multi node approach), allowing to calculate the occurring temperature stratification. This is necessary because the growth of *Legionella pneumophila* bacteria is temperature dependent. By neglecting the stratification in the boiler, the death rate of the bacteria would be too high, leading to an underestimation of the corresponding health risks.

As mentioned before, three different DHW production units are compared. The base component used to model the storage tank will be the same. However, depending on the type of production unit, an additional heat exchanger and/or resistor has been added to the storage tank model.

The component model used to simulate the storage tank is extended from the StratifiedEnhanced tank model, available in the Buildings 5.0.1 library. This component, as it is used in this paper, is updated by the authors in three ways [1].

- Addition of the possibility to vary the height of each volume segment.
- Addition of the possibility to choose different insulation thicknesses for the top, side and bottom of the tank.
- Addition of *Legionella pneumophila* growth equations to the thermohydraulic model.

The storage tank component used in the case study DHW system simulation model consists of eight layers. The six middle layers have a height of 0.1725m. The top (layer 1) and bottom layer (layer 8) have a height of 0.086m.

3.1.1 Electric boiler

The first production unit is an electric boiler (*Figure 2*). This holds that heat is added to the tank using an electric immersion heater. The electric immersion heater is placed in horizontal position at the bottom of the tank (layer 7). Generic specifications of the electric boiler are given in *Table 1*. The efficiency of the boiler is provided in the technical sheet and is determined according to Regulation (EU) No 814/2013 [12].

Table 1. Electric boiler specifications.

Boiler volume [l]	200
Heating power immersion heater [kW]	3.35
Efficiency electric boiler [%]	39
Location of the immersion heater	Layer 7

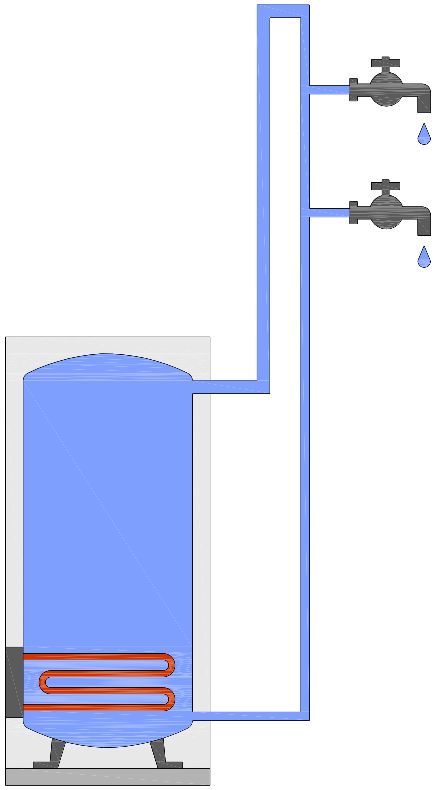

Fig. 2. Schematic view of the case study DHW system with electric boiler as heat production system.

3.1.2 Heat pump boiler

The second type of production unit is a heat pump boiler (*Figure 3*).

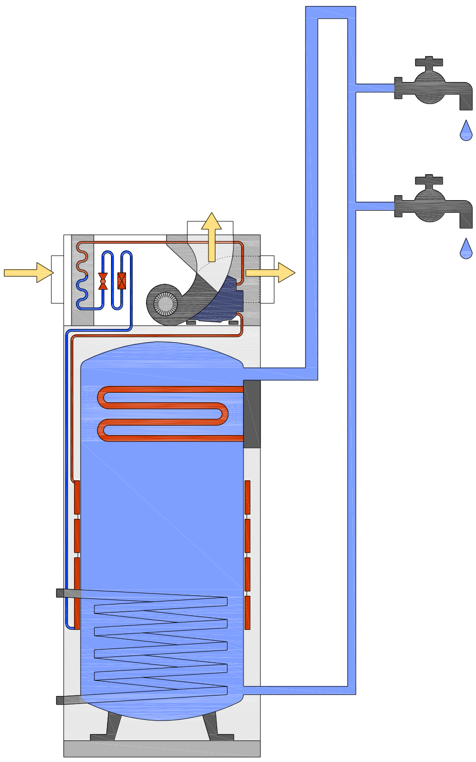

Fig. 3. Schematic view of the case study DHW system with heat pump boiler as heat production system.

This is a combination of the storage tank with a modulating air-to-water heat pump. The second heat exchanger, situated at the bottom of the tank, is not connected in this case.

The heat pump heats the water in the storage tank with a mantle heat exchanger located around the shell of the storage tank. At the top of the tank an additional immersion heater is located. This additional heater is only used in case the heat pump does not achieve the required set point temperature. Generic specifications of the heat pump boiler are given in *Table 2*. To model the heat pump, the component HeatPumps.Carnot_TCon, available in the Buildings 5.0.1 library is used. This is a model of a heat pump whose Coefficient Of Performance (COP) changes with temperature in the same way as the Carnot efficiency changes.

Table 2. Heat pump boiler specifications.

Boiler volume [l]	200
Heating power heat pump [kW]	2
Efficiency heat pump boiler [COP]	3.5
Mass flow rate water [l/h]	50
Mass flow rate air [m³/h]	450
Location of the heat exchanger	Layer 3-6
Heating power additional immersion heater [kW]	1
Efficiency electric boiler [%]	39
Location of the immersion heater	Layer 2

3.1.2 Heat pump boiler with solar collectors

The third production system is comparable with the second production system (heat pump boiler), but additional heat is provided by a solar collector loop (*Figure 4*). In this case, a second heat exchanger, an immersed coil exchanger, is used that is situated at the bottom of the tank. Generic specifications of the heat pump boiler are given in *Table 3*.

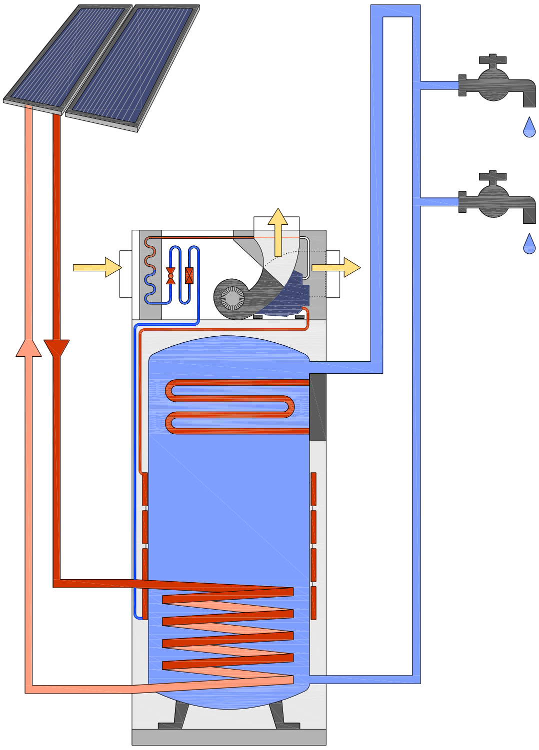

Fig. 4. Schematic view of the case study DHW system with heat pump boiler with solar collectors as heat production system.

The solar collector has a surface area of 3m², this is the average area needed for one household (4 people) in a multi-dwelling building [13]. To model the solar collector, the component for a flat plate solar thermal collector 'ASHRAE 93', available in the Buildings 5.0.1 library is used. The Meteonorm climate file of Uccle, Belgium is used to obtain the solar irradiation. The assumption is made that tater, that is incompressible and has a high internal capacity, is used in the solar collector loop.

Table 3. Heat pump boiler with solar collectors specifications.

Boiler volume [l]	200
Heating power heat pump [kW]	2
Efficiency heat pump boiler [COP]	3.5
Mass flow rate water [l/h]	50
Mass flow rate air [m³/h]	450
Location of the heat exchanger	Layer 3-6
Heating power additional immersion heater [kW]	1
Location of the immersion heater	Layer 2-3
Solar collector surface tilt	45°C
Type of solar collector	FP - Therma-Lite, HS-20

3.2 Distribution pipes

The recirculation loop, connected to the test tank, is 24m long and consists of insulated multilayer pipes (Alpex). *Table 4* shows the characteristics of the recirculation loop and the distal pipes. The characteristics of the pipes are retrieved from the technical ATG data sheet from the manufacturer [14].The mass flow rate of the recirculation loop is calculated in such a way that a maximum temperature difference of 5°C between the supply and return temperature is achieved. This depends on the heat losses of the distribution system. With the 65-60°C temperature regime and a constant environmental temperature of 15°C (in shafts), this results in a mass flow rate of 0.14kg/s. Accordingly with a regime of 50-45°C, this is 0.08kg/s.

Table 4. Length and diameters of the distribution pipes.

Supply recirculation pipe	
Length [m]	14
Outer diameter [m]	0.026
Thickness pipe [m]	0.003
Insulation [m]	0.015
Heat loss coefficient [W/m·K]	0.23
Return recirculation pipe	
Length [m]	10
Outer diameter [m]	0.016
Thickness pipe [m]	0.002
Insulation [m]	0.015
Heat loss coefficient [W/m·K]	0.17
Correction factor for thermal bridges [%]	20
Distal pipes	
Length of one distal pipe [m]	5.5
Insulation [m]	0

To model the distribution system the Pipe component from the Buildings 5.0.1 library is adapted with biological growth equations. The pipe model used is based on the finite volume method. Every pipe component is subdivided in one node every metre pipe length. Perfect mixing of water is assumed in every node. Flow reversal (back flow) is taken into account in the pipe model, based on pressure differences. Advection is included in two directions.

3.3 Taps

The required comfort temperature at the tap is 45°C. This temperature can be reached with a mixing valve (three-way-valve) in case the production unit produces water at or above 60°C or by direct withdrawal if water with a temperature around 45°C is produced.

Table 5 shows the daily tap profile schedule used in the simulation model. The total tapped daily water volume is 211.40l. The volume flow rate at the taps (at 60°C) is calculated based on DIN 1988-300 [15].

Table 5. Daily tap profile schedule.

Start time [hour]	Draw-off type [-]	Flow rate [L/min]	Tap duration [s]	Tapped volume [L]
6:59	Purge of the shower/kitchen pipe	9.00	10	1.50
7:00	Shower	9.00	355	53.25
7:10	Shower	9.00	393	58.95
8:00	Shower	9.00	296	44.40
12:00	Kitchen faucet	4.20	6	0.42
12:30	Kitchen faucet	4.20	20	1.40
13:45	Kitchen faucet	4.20	30	2.10
18:15	Children's bath	9.00	311	46.65
19:00	Kitchen faucet	4.20	6	0.42
19:15	Kitchen faucet	4.20	3	0.21
20:00	Kitchen faucet	4.20	30	2.10

3.4 Control

The first modelling part was modelling the different system components, another part consists of modelling the controls.

In case the electric boiler is used, a simple on/off controller is used to control the power of the immersion heater. The dead band of the thermostat is set at 2°C.

In case the storage tank is indirectly heated through one or two heat exchangers (connected to the heat pump and solar collectors), a pump model is used to control the fluid flows between both components. The on/off signal for the pumps and the set point temperature of their controllers are received from control blocks available in the Buildings 5.0.1 library.

Two control scenarios are studied. In the first scenario the tank is operating at 62-60°C. In the second scenario, the temperature in the tank is kept at 48°C, assuring a temperature of 45°C at the taps (reverse calculation based on the distribution losses). Once a week, a heat shock takes place maintaining the temperature at 65°C during two hours. At the end of the heat shock, water usage takes place during one minute in order to also flush the distal pipes (Purge of the shower/kitchen pipe in *Table 5*).

4 Results

To compare the different simulation results based on energy use and occurring *Legionella pneumophila* concentration, the following simulation setup is chosen.

- Start time: 0s
- Stop time: 1 209 600s (14 days)
- Integration algorithm: Euler (explicit)
- Integration tolerance: 0.0001
- Time step: 1s

The outputs that are investigated are:

- Water temperatures throughout the DHW system.
- *Legionella pneumophila* concentrations at the two points of use.
- Energy use of the different production units.
- Production and distribution heat losses.

The predicted temperature and the *Legionella pneumophila* concentration at the points of use is shown in *Figure 5*. In case the temperature in the tank is constantly kept at a minimum of 60°C (according to the current standards), it can be seen that the concentration of *Legionella pneumophila* is almost zero during the whole simulation period. As expected *Legionella pneumophila* is always in starvation mode due to this elevated temperature. The steps in the concentration are caused by the tap profiles. While tapping water from the recirculation loop, in which almost no *Legionella pneumophila* is present due to the constant temperature of 60°C, enters the distal pipe. After the tap, the temperature of the water in the distal pipe decreases, bringing the temperature shortly in a zone (between 20°C and 45°C) where *Legionella pneumophila* growth is possible (*Figure 1A*).

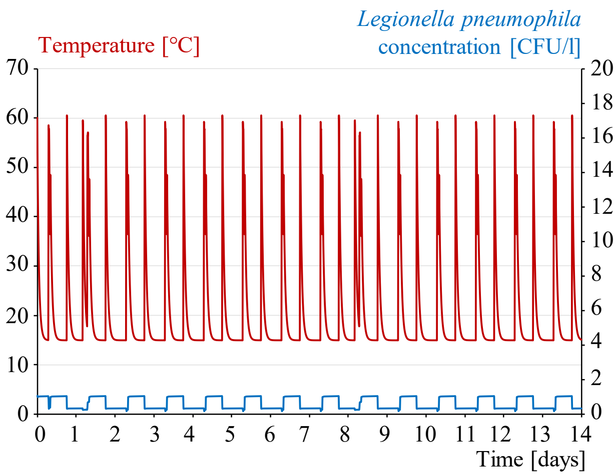

Fig. 5. Temperature and *Legionella pneumophila* concentrations at the points of use.

In case the set point temperature is kept at 48°C (45°C is reached at the tap), the simulation results show that between two heat shocks, the *Legionella pneumophila* bacteria cannot grow significantly (*Figure 6*). The dangerous contamination level of 1 000CFU/l (Colony Forming Units a litre) is never reached. There are three reasons to explain observation.

- The *Legionella pneumophila* bacteria die during the heat shock.
- The temperature coming from the storage tank is 48°C, this temperature is high enough to eliminate *Legionella pneumophila.*
- The temperature in the distal pipes cools down quickly to 15°C in between two taps, below 20°C *Legionella pneumophila* is dormant.

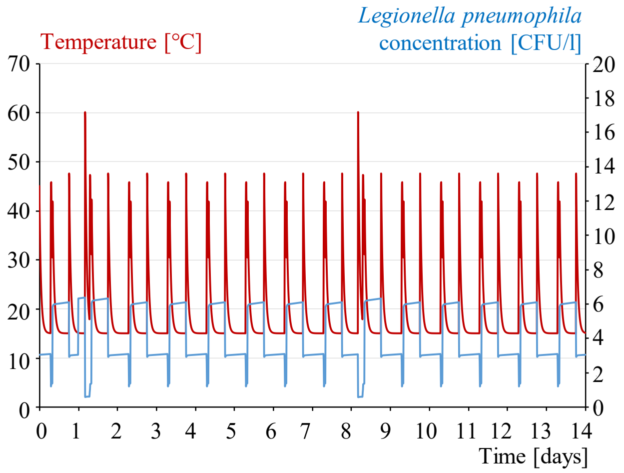

Fig. 6. Temperature and *Legionella pneumophila* concentrations at the points of use.

The energy use of the different types of production units is shown in *Table 6*. This energy use of each production unit takes into account the efficiency of the system. In case the production unit consists of a heat pump, the time dependent COP is used, which is retrieved from the simulation study. In case the temperature regime is constant 60°C, the average COP of the air-to-water heat pump is 2.32. In case of the heat shock regime, water in the storage tank is stored at 48°C (45°C is reached at the taps), the average COP is 3.45. For the electric immersion heater, the efficiency is temperature independent and thus continuously 39%. In the case of the heat pump boiler with solar collectors, 960 sun hours a year are assumed. The average amount of sun hours in Belgium for example is between 1 400 and 1700 a year [16].

Table 6. Energy use of different production unit scenarios [kWh/year].

Production unit	**Energy use at constant 60°C [kWh/year]**	**Energy use with set point temperature of 45°C and heat shock once a week (2 hours at 65°C) [kWh/year]**
Electric boiler	13 415	11 524
Heat pump boiler	3 731	2 147
Heat pump boiler with solar collectors	1 997	776

4.1 Comparison of control regimes

In case the heat shock regime is used, the total energy use of all production units decreases. For the electric boiler it decreases with 14%, for the heat pump boiler with 42% and with 62% for the heat pump boiler combined with solar collectors. As can be seen in *Figure 5* the contamination risk does not increase.

On the one hand, lower energy uses at 45°C could be related to the lower distribution losses to the environment. For all production units, the distribution losses are similar. On the other hand, lower storage heat losses occur. Although a higher volume flow rate at the taps occurs at 45°C as almost no mixing occurs with cold water and thus leading to a higher volume of cold water that has to be reheated by the production unit, this increase in volume will be compensated by the fact that it has to be heated until 45°C instead of 60°C.

For the heat pump, a third reason is related to the efficiency of the production unit which is higher at the 45°C heat shock regime than at the 60°C standard regime. As a consequence, less electricity is necessary to produce the same amount of energy.

4.2 Comparison of production units

Compared to the electric boiler, heat pump boilers have a lower energy use. This is related to the additional energy savings the use of a Carnot cycle technology offers.

When a heat pump boiler with solar collector is used, “free” energy is produced during the day (except for the additional electricity use of the circulation pump). This results in an additional energy saving compared to the heat pump boiler without a solar collector.

5 Conclusions

A simulation model has been developed which proposes an alternative to this constant 60°C by predicting the *Legionella pneumophila* concentration dynamically throughout the hot water system. A hot water controller is added to the simulation model that sets a lower hot water set point temperature in combination with heat shocks when a predefined concentration limit has been reached. Simulation results of such a controller, compared to the standard 60°C regime, show savings on DHW production energy use in a case study DHW system on household scale of respectively 14% for an electric boiler, 42% for a heat pump boiler and 62% for a heat pump boiler with solar collector, without increasing contamination risk.

6 Future research

Making the simulation models is a first step to evaluate the controller. In future research, a representation of the simulation model will be built as a test rig in laboratory.

The new domestic hot water controller is expected to become an important alternative for the current, energy intensive, constant high temperature tap water heating systems.

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