



## Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating

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# 1. Introduction

Legionella are gram-negative bacteria that are common in both natural and man-made aquatic ecosystems, such as cooling towers, hot springs, domestic hot water systems, and also cold (potable) water systems<sup>1-4</sup>. Some species are reported as the etiological agents of Legionnaires' disease. Normally, Legionnaires' disease is acquired by inhaling the aerosol of the contaminated water. Since 1976, outbreaks of Legionnaires' disease have been diagnosed globally<sup>5</sup>. In 2013, 6012 cases were reported by 29 European countries with a fatality rate of about 10%<sup>6</sup>. In domestic hot water systems, which are strongly related to people's daily life, the contamination rate ranged from 6% to 32%, according to previous research<sup>7-15</sup>. The problem is considered to be even greater when the hot water is supplied by district heating (DH)<sup>8, 11</sup>, because this is generally combined with a centralised water heating system with a central heat exchanger, which requires longer distribution pipelines to the consumers. This creates favourable conditions for Legionella's multiplication<sup>14, 16-18</sup>, which include: 1) water temperatures ranging from 25 °C to 45 °C, 2) long-term stagnancy, and 3) low levels of disinfectant residual and the presence of biofilm and sediments.

Temperature control is still the most widely-used method for preventing Legionella in hot water systems. In Denmark, for example, the standard regulates that the circulation pipe should be kept at 55 °C all the time, and it should be possible to heat the storage tank up to 60 °C on a regular basis<sup>19</sup>. Some Scandinavian countries are currently planning to operate DH networks at lower temperatures (around 30-70 °C)<sup>20</sup> to reduce fossil fuel consumption and improve energy efficiency. However, low-temperature district heating (LTDH) will make it more difficult meet the temperature requirements for conventional systems with a circulation pipe and storage tank due to the low-temperature supply and the temperature drop in the heat transmission process. Moreover, large systems are more likely to suffer from stagnancy. It is, therefore, crucial to ensure that both comfort and health requirements will be met before LTDH is implemented.

This paper investigates various options, which can be divided into two kinds: alternative designs for water supply systems and various sterilization treatments.

Many other studies have discussed the effects of hydraulic components on preventing Legionella in hot water systems. For instance, field work studies on pipes and thermostatic shower mixer taps by van der Kooij et al.<sup>16</sup> and van Hoof et al.<sup>21</sup> have shown the effect of various materials on biofilm formation, which plays an important role in Legionella's growth. Copper pipes have been shown to perform better than PEX pipes, and systems with instantaneous heaters have been found to be less contaminated than those with storage tanks<sup>8</sup>. Vertical tanks have been shown to be more vulnerable to Legionella than horizontal ones<sup>22</sup>. The application of systematic design aimed at inhibiting bacteria in domestic hot water has seldom been mentioned, but it can play a vital role in solving potential problems with the introduction of low temperature district heating by replacing conventional hot water systems. Sterilization methods can be applied combined with alternative design for enhanced control, or as post treatment if trigger-concentrations of Legionella occur due to an unexpected fault in the system. Although many other papers have illustrated various sterilization methods for dealing with Legionella, not many have considered their use in combination with low-temperature district heating. The main objective of this study is to provide feasible solutions that can both inhibit Legionella in domestic hot water (DHW) systems and fit into the LTDH scenario of the future.

## **2. Alternative designs for water supply systems**

Since the insufficiently high temperatures and long-term stagnancy are the main risk factors for Legionella proliferation in hot water systems with district heating, alternative designs are needed that can eliminate those factors. The basic concepts behind such designs are temperature boosting and volume limitation. Temperature boosting can be achieved using local supplementary heating devices. The volume limitation concept, in accordance with the German Standard W551<sup>23</sup>, is that, if controlled properly, a system with a total volume (from hot water production to end use) of less than 3 litres can eliminate the risk of Legionella. The advantages of alternative design are numerous. For instance, it does not affect water quality, involves no long-term monitoring or regular equipment replacement, and it can improve the system's comfort and energy efficiency at the same time.

## 2.1 Decentralised substation

This solution is to equip each home with an instantaneous heat exchanger for domestic hot water (DHW) and space heating (SH) production, instead of having just one heat exchanger in the substation for all the consumers<sup>24</sup>. This design uses the limited volume approach. The schematic is shown in Figure 1.

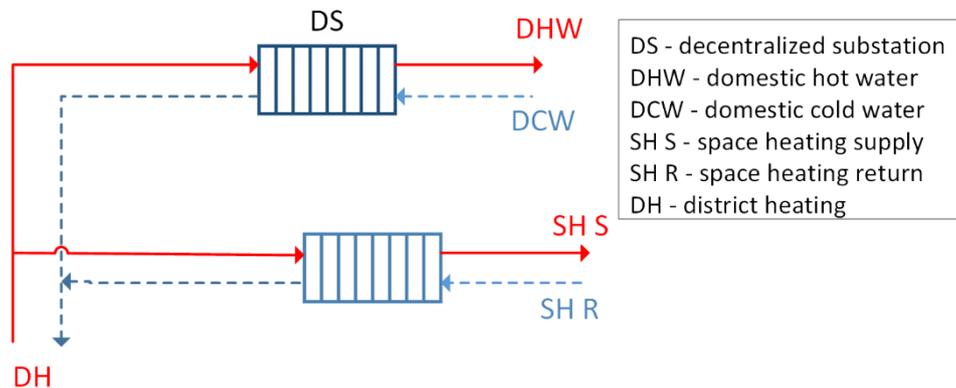


Figure 1 Schematic of decentralized substation system

By installing a decentralized substation in each home, the volume of the DHW system is much reduced. Moreover, consumers can regulate the heat demand and set-point temperature of their own substation, so both control and operation are flexible.

With a decentralized substation system, hot water can be prepared locally, so there is no need to keep the circulation circle. A small bypass flow can ensure the consumers get hot water within an acceptable time. Moreover, the system energy efficiency is much improved. For a new 50-apartment building, the heat loss from decentralized substation systems for DHW production was only 30% of that from an electrical boiler, and only 40% of that from a centralized heating system. The annual cost was thereby reduced by 10-20%<sup>24</sup>.

The operating temperature of decentralized substation system can be lower than the conventional system. However, so far, there is insufficient documentation about the lower limit for the operating temperature with regard to health safety, and more work needs to be done on this question.

## 2.2 Micro heat pump

A micro heat pump is an application for local temperature elevation. Since the LTDH cannot heat up domestic hot water to a safe temperature, the micro heat pump can be used to boost the supply temperature using low-temperature energy sources. The energy source could be either the DH supply water itself or DH return water. Figure 2 and Figure 3 show schematic diagrams of the two types respectively.

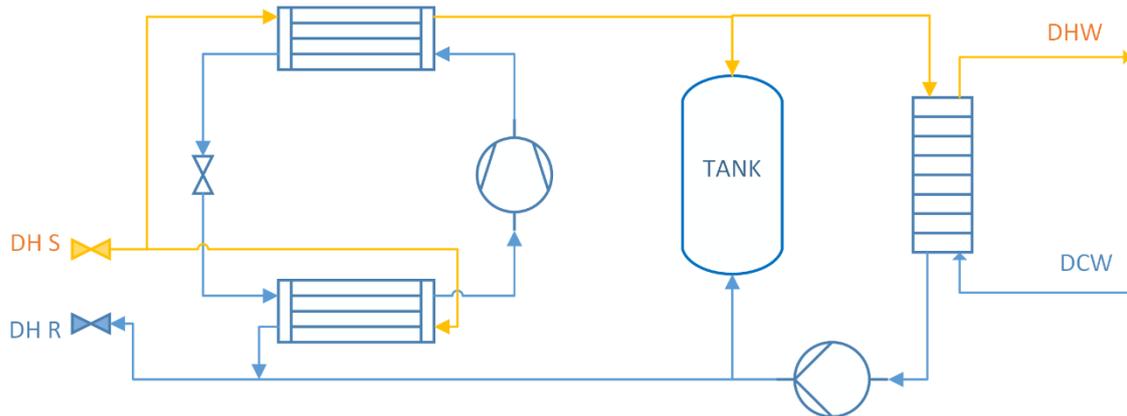


Figure 2 Heat pump application using DH supply water as heat source

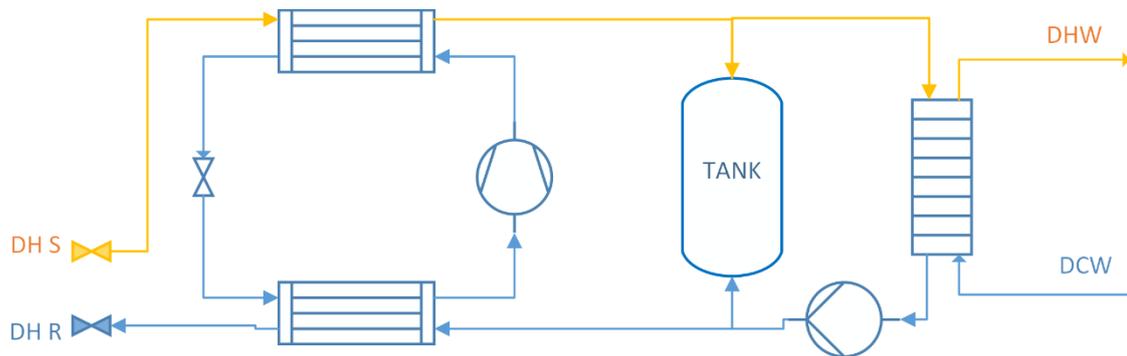


Figure 3 Heat pump application using DH return water as heat source

In Figure 2, district heating supply water is divided into two streams. One flows through the evaporator of the heat pump system, which is used to boost the temperature of the other stream. In Figure 3, the heat source is the DH return water. In this scenario, the benefit is the cool-down effect of the DH return line, but the huge temperature difference between the DH supply and return water has a negative effect on the heat pump efficiency. In practice, to boost DH supply water from 40 °C to 53 °C, a system using DH supply water as the heat source might achieve a COP of 5.3, while for a system using DH return water as the heat source could only achieve a COP of 3.5<sup>25</sup>. In both scenarios, the heat storage tanks are installed before the heat exchanger, so the contamination of the tank is not considered. The temperature

boosting gives flexible and precise control. One disadvantage is that the heat pump consumes electricity as driving power, which decreases the exergy efficiency of the system. But the energy saved in the network by implementing LTDH should be taken into account for a full picture.

### 2.3 Electric heating element

In contrast to a micro heat pump, an electric heating element uses electricity as a supplementary heat source. Its design and installation are much simpler than the heat pump solution. The electric heating element can be either integrated with storage tank or fitted separately. The principles of this system are shown in the following diagrams.

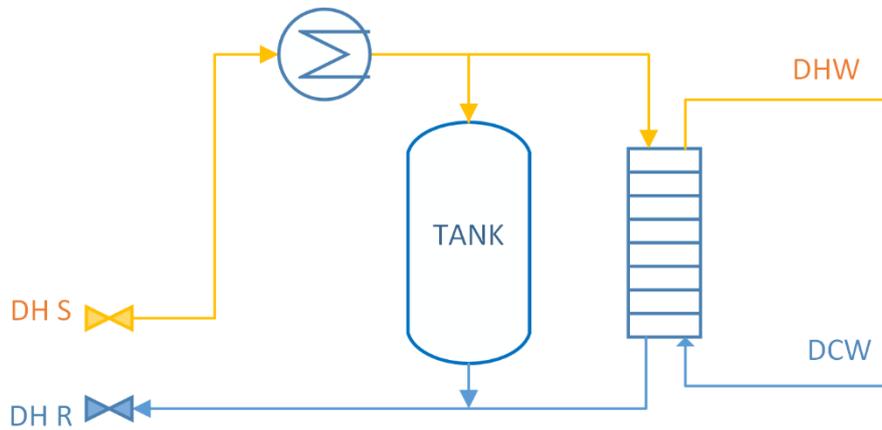


Figure 4 Separate electric heating element

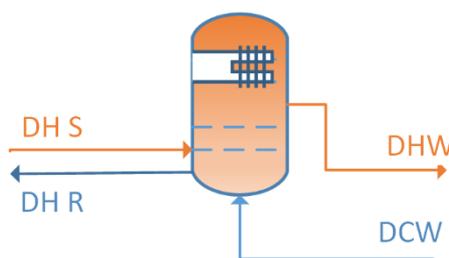


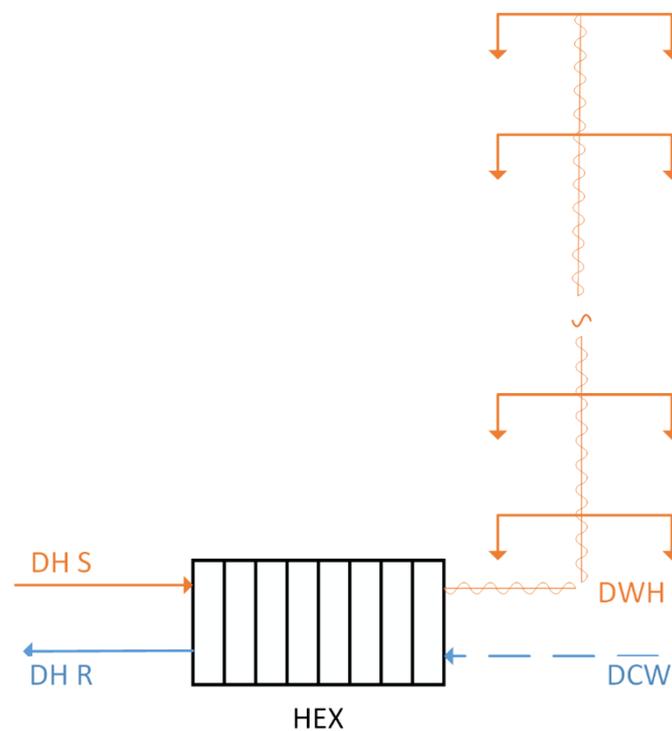
Figure 5 Integrated electric heating element

The heating element can be used to boost the DH supply temperature (Figure 4) or heat up the domestic hot water directly (Figure 5). Under the same conditions, both types have much lower COP and exergy efficiency than the heat pump scenario, because the total supplementary heating energy is supplied by electricity. However,

the separate heating element scenario has slightly higher exergy efficiency than the integrated version<sup>25</sup>. Moreover, in the integrated scenario, domestic hot water has to be stored in the storage tank, which increases the risk of Legionella multiplication.

## 2.4 Electric heat tracing

The electric heat tracing solution is another application of the temperature elevation approach. The electric tracing cable is wound around the DHW supply pipe. As a supplementary heating device for LTDH system, electric heat tracing uses electricity to heat up the water when necessary.



**Figure 6 Schematic of electric heat tracing solution**

As shown in Figure 6, since the DHW supply line is kept warm by the electric heat tracing system, there is no need for a circulation pipe or a heat storage tank, which reduces the risk of stagnancy in the system. Moreover, in multi-storey buildings with large hot water pipe works, the removal of the circulation pipe can reduce the overall heat loss by as much as 50% by removing the circulation pipe. Electric heat tracing is also very flexible. It can heat up either the whole supply line or part of it. To suppress the multiplication of Legionella, tracing cable can be used to maintain a safe temperature continuously, or for periodic thermal treatment.

The characteristics of each design are listed in Table 1.6. For the evaluation of the difficulty of the installation and operation, the complexity of installing the devices and setting up the control system are the main factors considered. The investment costs were compared by using the general prices of the devices in the market.

**Table 1 Characteristics of each alternative design**

<b>Approach</b>	<b>Solution</b>	<b>Building type applicable in</b>	<b>Circulation required</b>	<b>Energy source for hot water</b>	<b>Installation &amp; operation difficulty</b>	<b>Investment cost</b>
Volume restriction	Decentralized substation	New	No	DH	Complicated	High
	Micro heat pump	Existing/new	Yes	DH +electricity	Medium	High
Local Temperature elevation	Heating element	Existing/new	Yes	DH +electricity	Simple	Medium
	Electric heat tracing	Existing	No	DH +electricity	Simple	Low

### **3. Sterilization methods**

Sterilization methods for Legionella inactivation can be divided into three kinds: thermal treatment, chemical treatment, and physical treatment. All sterilization treatments aim at inhibiting the growth of Legionella or keeping the bacteria separate from the users. Every method has its pros and cons. This study investigates only methods that are applicable for domestic hot water treatment. And more focus is put on methods that can be combined with alternative design as supplementary security for domestic hot water with LTDH. In this way, even in the event of an unexpected temperature drop or stagnancy, the sterilization treatment can still protect the system.

#### **3.1 Thermal treatment**

Previous studies<sup>26, 27</sup> have showed that *L. pneumophila* in vitro is killed rapidly by water temperatures >60 °C. Higher temperatures require less time to achieve the same log reduction (70 °C for 10 minutes, and 60 °C for 25 minutes)<sup>27</sup>. So, when DHW is supplied by LTDH, thermal treatment requires supplementary heating devices to achieve sufficient temperature elevation. When applying thermal disinfection, all the distal sites in the hot water system should be flushed with 60 °C or higher temperature hot water for a certain period of time<sup>28, 29</sup>. According to Krøjgaard et al.<sup>7</sup>, a protocol of keeping the boiler at 70 °C for 24 hours (after hyperchlorination) and flushing all taps for 5 minutes reduced the concentration of Legionella and limited it below 10<sup>2</sup> CFU/L over a period of 7 months.

One benefit of thermal treatment is that it puts no additives into the water. This makes it the preferred solution in countries that have strict limits on water quality. Thermal treatment has good performance in transient use. Farhat et al. observed a 5-log reduction with a 30 min treatment<sup>30</sup>. The process is also easy to carry out. Nevertheless, insufficient temperature elevation or flushing time can result in failed sterilization<sup>7</sup>. And temperature elevation and hot water flushing result in a loss of potential heating energy. Included among other disadvantages of thermal treatment are its limited

efficacy on biofilm, its potential to enhance the thermal resistance of *Legionella*<sup>30, 31</sup>, the risk of scalding, etc.

The overall expense of thermal treatment includes the fuel cost for temperature boosting, the water flow used for flushing, and the cost of labour, which constitutes the greatest part of the total cost. A 10-year study of a hospital building in Modena, Italy reveals that it cost DKK 280 (EUR 37.5) per water point for two protocols (2 days >60 °C at every distal) a year<sup>32</sup>.

### **3.2 Chemical treatment**

This section presents chemical treatments that are allowed for continuous use in a domestic hot water system. However, the use of biocide methods requires meticulous control to maintain effective concentrations without violating any local water quality requirements.

#### **3.2.1 Ionization**

Ionization works by using two different ionized metals in the water to disrupt the cell wall permeability of bacteria and cause the denaturing of proteins and subsequent cellular lysis<sup>28, 33</sup>. The most widely used electrodes are copper and silver, which are extensively applied in recirculating hot water systems<sup>34</sup>. The effective dosages vary from 0.2-0.4 mg/L for copper and 0.02-0.04 mg/L for silver<sup>35</sup> mainly depending on the water quality. Liu et al. observed that 0.4 ppm Cu and 0.04 ppm Ag successfully reduced the *Legionella* positive rate from 65% to 0.8%<sup>36</sup>. However, the concentration of Cu<sup>2+</sup> and Ag<sup>+</sup> must comply with local requirements for water quality. The European standard limits the concentration of Cu<sup>2+</sup> to 2mg/L, while the limit for Ag<sup>+</sup> is not defined. But EU member states can make stricter regulations locally. In Denmark, for instance, the limits for Cu<sup>2+</sup> and Ag<sup>+</sup> are lower than the effective concentrations, which are 0.1 mg/L and 0.01mg/L respectively<sup>37</sup>. So, this method cannot be used in Denmark.

To ensure a good reaction to the ionization process, the water should be clean. Campos et al.<sup>28</sup> suggest ionization should be applied under pH 7.6, since it is a pH sensitive method. Furthermore, higher temperatures accelerate the chemical process and are recommended when using ionization<sup>35</sup>.

One of the benefits of copper/silver ionization is its long-term efficacy<sup>38, 39</sup>. Stout et al.<sup>38</sup> report the successful control of *Legionella* using ionization in a 5-year investigation in 16 hospitals. Another 70-month investigation by Biurrun et al.<sup>40</sup> showed that the positive rates of *Legionella* were reduced to 0%-10.3% with ionization treatment. Moreover, ionization can also perform well with intermittent use<sup>41</sup>. This allows several systems to share the same generating equipment, which reduces investment costs. However, ionization is an on-site approach, and it has little effect on biofilm. Furthermore, concentrations of copper and silver that are too high will cause scaling accumulation and water discoloration<sup>42</sup>.

The overall cost of ionization includes the initial investment and the maintenance cost. The initial investment varies a lot depending on the size of the water system, ranging between DKK 68,000 (EUR 9,115) and DKK 240,000 (EUR 32,171) , with an annual maintenance cost ranging between DKK 10,000 (EUR 1,340) and DKK 27,000 (EUR 3,619) for replacing electrodes<sup>42, 43</sup>.

### **3.2.2 Chlorine**

Chlorine is one of the most widely used oxidizing agents in many kinds of water systems, including potable water systems in some countries. Normally, a residual level of 2-6 mg/l chlorine is required for continuous control of *Legionella*<sup>43</sup>. Experimental work by Muraca et al.<sup>26</sup> showed that chlorine with an average concentration of 4-6 mg/L can achieve 4-log reduction in 25 °C water after 3 hours. However, when *Legionella* bacteria are associated with host protozoa, a higher concentration of chlorine is required, for example, >4 mg/l for *H. vermiformis*<sup>44</sup> and >50 mg/L for *Acanthamoeba polyphage*<sup>45</sup>. Hyperchlorination (at least 2 hours with 20 mg/L or 1 hour with 50 mg/L)

can be applied for cleaning purposes. However, the water system cannot be used until the chlorine concentration falls below the standard requirement.

Chlorine is a systematic disinfection method with good transient effect, and it can provide a residual concentration throughout the whole system. But chlorine has little effect on the persistence of Legionella in amoeba, and it is a highly corrosive chemical which will lead to pipe corrosion. To avoid this, protective coatings are required, which will increase costs. Moreover, chlorine residual has the potential to cause carcinogen disease to human beings<sup>45</sup>.

The cost of chlorine includes the investment for necessary equipment and the expense for pipe work maintenance, protective coating and labour costs. Compared to the thermal treatment at the Italian hospital mentioned earlier<sup>32</sup>, the average annual expense is slightly lower at DKK 228 (EUR 31) per water point.

### **3.2.3 Chlorine dioxide**

Chlorine dioxide is another oxidizing agent widely used to treat potable water and other water systems in some countries. It kills the bacteria by disrupting their cellular processes<sup>46</sup>. As shock treatment, Walker et al.<sup>47</sup> observed that maintaining a chlorine dioxide concentration of 50-80 mg/l for 8 hours in the system tank and 1 hour at all outlets showed a good inhibiting efficacy for both planktonic and sessile Legionella. For continuous residual control, a level of 0.5 mg/L is effective in hot water systems<sup>48</sup>.

Chlorine dioxide is more effective than free chlorine in most cases and bad odour can be avoided in potable water treatment. But one limitation with chlorine dioxide is its easy decomposition. Moreover, it is difficult to maintain a continuously effective residual concentration in water.

Chlorine dioxide is considered a cost-effective eradication method. The total cost includes investment and maintenance cost for precise injection and monitoring.

### 3.2.4 UV light

Ultraviolet light adds no chemical agents into the water system. It kills bacteria by disrupting their DNA replication process with short-wavelength light (254 nm)<sup>49</sup>. Continuous UV disinfection at 30000  $\mu\text{W}\cdot\text{s}/\text{cm}^2$  can achieve a 5-log reduction within 20 minutes<sup>26</sup>.

UV light has the advantages of good instant efficacy (5-log reduction within 1 hour according to Muraca et al.<sup>26</sup>), no chemical by-products, no damage to water quality or pipe work, and simple installation. But UV light provides no residual throughout the system, which limits its efficacy in large water systems and system colonized by biofilm. A study by Franzin et al.<sup>50</sup> showed that UV had better efficacy in central parts of a water system than in distal parts. So, to maintain long-term efficacy, other treatments should be used in combination with UV.

The investment in UV lamps accounts for the largest part of the total expense. For a 500-bed hospital in the United States, where four large (260 gal/min) and two small (30 gal/min) units were installed, the cost was DKK 339,000 (EUR 45,442)<sup>42</sup>.

### 3.2.4 Photocatalysis

Photocatalysis is a new water treatment technique for hot water systems. The method used is to activate a solid catalyst such as titanium dioxide ( $\text{TiO}_2$ ) using sunlight and produce oxidants to kill bacteria. The main oxidant generated by this reaction is the hydroxyl radical ( $\bullet\text{OH}$ ), which is accompanied with superoxide anions ( $\bullet\text{O}_2^-$ ) and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ).

The main reaction process works in the following way:





The wavelength of the ultraviolet light for photocatalysis should be no more than 385 nm (UV-A)<sup>51</sup>. The disinfection contact time can vary for different kinds of microorganisms, such as viruses, bacteria, spores and protozoa. Photocatalysis has superior disinfection efficacy for bacteria that have strong chemical resistance. Cheng et al.<sup>51</sup> used a 90-minute photocatalysis treatment with 1000mg/L of TiO<sub>2</sub> and 108 mW/cm<sup>2</sup> of UV light and achieved a 4.5-log reduction. Stenman et al. report<sup>52</sup> the achievement of a 5-log reduction in contaminated water with a flowrate of 10L/min using photocatalysis in a laboratory. According to Eqs. 1–5, photocatalysis is a stable treatment and produces no toxic residuals in the water system, so even countries that have strict policies on potable water quality are able to apply this method.

The main investment required for photocatalysis is the generation equipment. Compared to the investment, operation costs are small, since it only requires sunlight and a small amount of electricity.

### **3.3 Physical treatment**

Physical treatment mainly refers to filtration, which prevent the microorganisms from getting into the protected site by using membrane filters<sup>32, 53, 54</sup>. Filtration is very effective, but the short lifetime of the filter is one of its most important limitations. Operation costs of filtration are much higher than any other method, since the filter has to be replaced regularly. Another limitation is retrograde contamination. The filter can easily lose its efficacy by coming into contact with contaminated sources (such as splash water).

The cost is basically determined by the lifetime of the filter. Marchesi et al.<sup>32</sup> report that the cost of filters for a single water point was DKK 6353 (EUR 852) annually due to their short lifetime (one month).

The characteristics of each sterilization method is shown and compared in Table 2. The evaluation of the costs considered mainly the investment cost of the sterilization equipment.

**Table 2 Characteristics of different sterilization methods**

	<b>Methods</b>	<b>Efficacy</b>	<b>Operation activity</b>	<b>Additive to water system</b>	<b>Investment Cost</b>	<b>Effective range</b>	<b>Feasibility &amp; regulations</b>
Thermal treatment	Heat flushing	Short	Temperature & operation time control	No	Low	systematic	No limits
Chemical treatment	Ionization	Long term	Residual control	Yes	Medium	on-site	A+B
	Chlorine	Long term	Residual control	Yes	Low	systematic	A
	Chlorine Dioxide	Short term	Residual control	Yes	Low	on-site	A
	Photocatalysis	Long term	Residual control	No	Medium	on-site	No limits
	Ultraviolet Light	Short term	-	No	Medium	on-site	No limits
Physical treatment	Filtration	Short term	-	No	High	on-site	No limits

\* “-” represents for none specific control

\* “A” the concentration of the agents must comply with local water quality regulations

\* “B” not applicable in some countries

## **4. Conclusion**

Everyone who has the intention of promoting low-temperature district heating in the future needs to address the potential problem of Legionella proliferation in hot water systems due to insufficient temperature elevation in advance. This paper provides a broad overview of the options available in terms of both changes in design and sterilization treatments. The alternative design approach is based on two methods – temperature elevation and volume restriction. Considering the cost and difficulty of installation, decentralized substation systems are recommended for new buildings with a large hot water system and a diverse pattern of use. Micro heat pump systems can be applied in both large systems and single family houses, but might be more appropriate in future low-energy buildings. Heating element and electric heat tracing systems are preferred when renovating water systems in existing buildings because they are cheap and easy to install. Sterilization treatment can be used as supplementary protection with alternative design or for post-treatment if trigger-concentration occur. Thermal treatment is a simple and non-additive method, but with LTDH, local heating devices will be required to achieve sufficient temperature elevation. If biocides are used, the concentrations need to be meticulously controlled to achieve the right efficacy without violating water quality regulations. UV and photocatalysis are best used in newly-built water systems or uncontaminated systems, because of their on-site efficacy. Filtration is widely used in more places which the risks are higher (e.g. hospital water systems) for better protection, but the filters have to be replaced regularly.

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