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Energy Efficient Eradication of Legionella in Hot Water Systems

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Energy Engineering

LULEÅ UNIVERSITY OF TECHNOLOGY

Energy Efficient Eradication of Legionella in Hot Water Systems

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Licentiate thesis

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Lobna Altorkmany, December 2017

Abstract

Disease related to unsafe water, poor sanitation, and lack of hygiene is some of the most common causes of illness and death all around the world. Since the first detection of Legionella in Philadelphia 1976, Legionella is recognized to cause Legionellosis which is associated with two distinct forms: Legionnaires' disease and Pontiac fever. The fact that vaccination against Legionella disease is not efficacious enhances the effort towards developing the existence disinfection methods and inventing new technologies. Re-colonization of Legionella in hot water systems may occur within a few days or weeks after disinfection since conventional disinfection methods significantly reduce but do not eliminate pathogens.

Understanding the conditions favoring Legionella occurrence in hot and cold systems will aid in developing new treatment technologies that minimize or eliminate human exposure to legionella pathogens.

The work introduces the Anti-Bact Heat Exchanger (ABHE) system as a new innovative system inspired by nature. Compared to conventional disinfection methods, the ABHE system proposed to achieve continuous thermal disinfection of bacteria in hot water systems and in simultaneously saving energy and reducing the required costs. Thermodynamic analysis, experimental test and simulation validation of the ABHE by the Engineering Equation Solver (EES)-based model were achieved to define the thermal performance of the ABHE system at given operation conditions. The experimental test shows high potential of recovering heat and thus saving energy by the ABHE system. In addition, pumping power (PP) was relatively small compared to the recovered heat which implies that less energy was required compared to the recovered heat.

The effect of working parameters such as temperatures and flow rate on the thermal performance of the ABHE system was furthermore investigated. The study shows that supplied water temperature has similar effects as the disinfection temperature. Namely, increasing supplied water temperature enhances the regeneration ratio (RR) but it requires a large plate heat exchanger (PHE) area and PP. On the contrary, increasing the temperature in use results in a reduced PHE area and PP. Flow rate has the greatest influence on the thermal performance of the ABHE system. Increasing flow rate leads to an increase in the required area of the PHE.

The EES-based model investigated the effect of the length and the width of the plates used in the PHE on the RR and the required area of the PHE. Then, the EES-based model was used to optimize the ABHE system in which the PHE area is minimized or the RR of the ABHE system is maximized.

Appended papers

Paper A

Altorkmany, L., & Nordell, B. Overview of legionella bacteria infection: control and treatment methods. In International Conference on Thermal Energy Storage: 14/06/2009-17/06/2009.

Paper B

Altorkmany, L., Kharseh, M., Ljung, A. L., & Lundstrom, T. S. (2017). Experimental and simulation validation of ABHE for disinfection of Legionella in hot water systems. Applied Thermal Engineering, 116, 253-265.

Paper C

Altorkmany, L., Kharseh, M., Ljung, A. L., & Lundstrom, T. S. (2017). Effect of Working Parameters of the Plate Heat Exchanger on the Thermal Performance of the Anti-Bact Heat Exchanger System to Disinfect Legionella in Hot Water Systems. Submitted to Applied Thermal Engineering, 2017, ATE_2017_7142.

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1. Introduction

1.1. Background

Water is the most essential element for survival of humanity and all living species on earth. However, exposure humans to water may lead to health risk exposure due to the presence of pathogenic microorganisms. Many enteric and respiratory bacteria infect water route and cause morbidity and mortality in humans. An estimated 1.1 billion people lack access to improved water supplies; many more are forced to rely on water that is microbiologically unsafe [1]. In low and middle income countries, poor water hygiene and sanitation are responsible for around 500,000 deaths per year that 58% out of this deaths were related to diarrheal disease [2]. Collier, SA et al., (2012) found that over 40,000 hospitalizations as a result of waterborne diseases including Legionnaires' disease (LD) were estimated to occur annually in United States (US) with cost of $970 million each year [3].

Transmission of infectious diseases via contaminated water continues to be a risk to public health. During 2001-2006, Legionella was identified as the third most common etiologic agent among all US waterborne disease outbreaks [1] and the primary cause of all drinking water related outbreaks. The bacteria Legionella is considered to be the causative agent of LD, a severe and potentially lethal form of pneumonia, and Pontiac fever, an influenza-like illness, leading to increasing significantly the public health hazard worldwide [4,5]. The first described outbreak of LD was registered in Washington in 1965 with case fatality of 17. 3% [6]. In 1976, a serious pneumonia outbreak occurred in members of the American Legion attending their annual convention in Philadelphia; Legionella pneumophila (L. pneumophila) was isolated then and named. This new type of pneumonia did not respond to β-lactam antibiotics and lead to death in 29 of 182 patients (16%) [7]. Nowadays, with over 60 species of Legionella and more than 70 different serogroups registered, L. pneumophila is recognized as the main cause of LD worldwide [8] for approximately more than 70% of LD cases [9]. In particularly, L. pneumophila serogroup 1 has been recognized as the most important agent, responsible for over 84% of cases of LD worldwide [10].

L. *pneumophila* is an inhabitant of natural and artificial aquatic environments including water, wet soil, and air in addition to surviving free, in biofilms, and as an intracellular parasite of protozoa [10,11]. The disease onset is usually 2–14 days after infection with the bacteria [12]. Symptoms range from mild sickness to severe pneumonia. The symptoms of LD from most to least common are: fever at more than 38·8°C (67–100%), cough (41–92%), chills (15–77%), dyspnoea (36–56%), fever at more than 40°C (21–62%), neurological abnormalities (38–53%), myalgia or arthralgia (20–43%), diarrhoea (19–47%), chest pain (14–50%), headache (17–43%), and nausea or vomiting (9–25%) [13]. The fatality rate for hospital acquired Legionella pneumonia in patients left untreated are 40%-80%, while if cases are diagnosed and treated in appropriate time the fatality rate may be reduced to 5-30 % [14,15]. The risk factors that are associated with high mortality rates due to Legionella disease include age, especially those younger than 1 years and elderly patients, smoking, diabetes, chronic lung disease, alcoholism abusers and cancer [16].

Transmission of LD is contracted through inhalation of contaminated aerosols or aspiration of infected water [17]. The principal sources of infection for LD have been identified as man-made and complex reservoirs of warm recirculated water [18]. Legionella is rarely passed from person to person. Factors that suggest person to person transmission was reported by Correia, A.M et al., (2016) including severity of the respiratory symptoms in the first patient, the very close contact with the infected person and the poor indoor air quality[19].

Legionella found worldwide in freshwater environments like stagnant lakes, rivers, springs or mud streams [20]. Also, Legionella commonly colonize complex hot water systems (HWS) [18], drinking water systems [3,21], decorative, recreational facilities such as spa pools and fountains, dental devices [22,23], air conditioning and cooling towers [18,23,24] as Figure 1.1 shows.

The ability of L. *pneumophila* to colonize drinking water systems [25]. potable hot and cold water systems such as hospitals, hotels, residential buildings and industrial facilities [10,26] becomes a universal problem for municipal water providers.

Recent studies have shown that Legionella is one of the most common agents of community acquired pneumonia in Germany [27]. In Europe, between 2000 and 2002, 10,322 cases of LD were reported [25]. Incidence of LD in US increased by 286% from 2000 to 2014 [28]. Study of Karagiannis, I et al., (2008) showed that warm, humid and showery summer weather was found to be associated with higher incidence of LD in The Netherlands [12]. Legionella Outbreak has also been reported in Italian university hospital where high levels of Legionella > 10^4 cfu/L was detected [26]. Cooling towers were identified also as a source of Legionella infection. During 2006-2015, three LD outbreaks were linked to cooling towers in New York City [23].

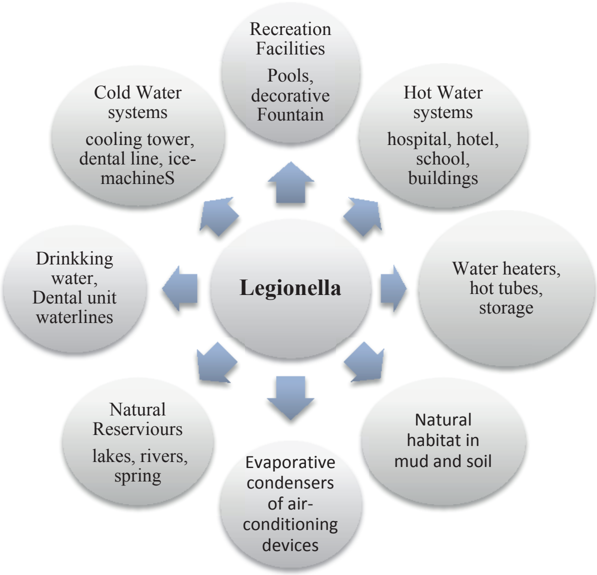


Fig 1.1. Legionella existence in natural and artificial aquatic environments

L. *pneumophila* isolated also from dental unit waterlines as Figure 1.2 shows [8]. Several studies have reported that potable water was the source of infection [30–32]. Dental personnel are exposed to contracting LD and may have significantly higher titers of Legionella antibodies in their blood compared to available populations, suggesting that aerosols generated by dental unit waterlines instruments were the leading source [29,31]. Veronesi, L et al., (2008) reported that 22.1% of dental-unit water samples were Legionella positive [32], Zanetti, F et al., (2000) found positive Legionella in 61% of samples [33]. Arvand, M et al., (2013) detected positive Legionella in 27.8% of samples [34].

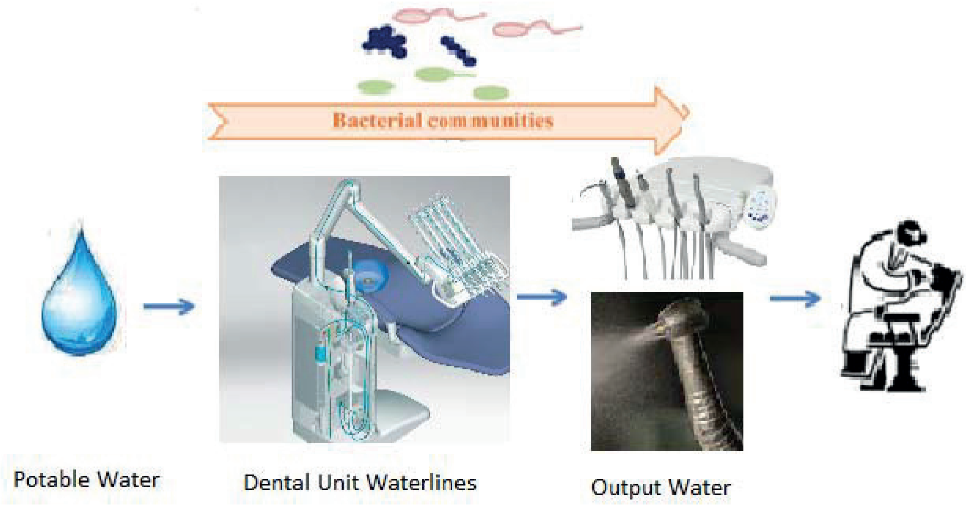


Fig 1.2. Legionella contamination in dental unit waterlines

Weiss, R A et al., (2004) stated that definitely, continued change in the environment and its organisms will result in continued change in infectious disease that the free-living microbes may find a human niche that suits their existence, such as the lung for L. *pneumophila* [35].

1.2. Factors associated with Legionellae occurrence

Multiple studies have investigated parameters that correlate to Legionella growth:

- Warm temperatures seems to be ideal for Legionella, this explain the significant contamination detected in low hot water tanks [36]. Legionella has the ability to survive in water for extremely long periods of time, long as a year, and may colonize water systems within temperature range between 20-50 °C [24]. Optimum growth temperature for L. *pneumophila* found between 25-42 °C [13,37]. Therefore, thermal control measure was commonly applied by health care facilities to avoid Legionella infection risk. That cold water should be stored and distributed below 20 °C, while hot water should be stored above 60 °C and circulated at a minimum return temperature of 51 °C [38].
- Selecting special plumbing pipes materials that can inhibit Legionella colonization such as copper ions, however the effectiveness of this strategy will not sustain after two years [39].

- Biofilm formation and growth in low nutrient environments are common factors that assist Legionella resistance of disinfectants in water systems [40,41]. Also, presence of amoebae promotes the growth of L. *pneumophila* and enhances its virulence [42].
- Low disinfectant residuals and aerosolization were also features associated with the source of legionella outbreaks [1].
- Most sporadic cases of LD outbreak are reported throughout the year but the most cases of epidemic infection seem to occur in late summer and early fall i.e., warm and damp climate promotes LD occurrence.
- The modern life style has introduced and designed warm, ventilated, humid 'artificial lungs' called air-conditioning systems that allowed Legionella bacteria to proliferate and become an opportunistic colonizer of the human lung [35].

1.3. Aim of research

This research aims to introduce the Anti-Bact Heat Exchanger (ABHE) system as an energy efficient method used for continuous disinfection of Legionella in HWS. To achieve the goal, mathematical model for the ABHE system is performed in addition to build simulation model for the ABHE system by Energy Equation Solver (EES) model. The EES-based model is validated experimentally and developed to investigate the effect of working parameters on the thermal performance of the ABHE system. As well, the EES-based model used to determine the optimum design of the plate heat exchanger (PHE) at specific working parameters in which waste heat recovery is maximized and the required area of the PHE is minimized.

1.4. Methodology and scientific approach

The methodology used in this work was (*i*) to investigate LD problem, source of infection, transition mode, factors that influence Legionella proliferation in water distribution system and overview different conventional methods used to control Legionella in HWS, (*ii*) to review the state-of the-art in terms of mathematical modelling of the ABHE system, (*iii*) to evaluate the performance of the ABHE system at specific working parameters and discover the key factors influencing thermal performance of the ABHE system, and (*iiii*) to develop and implement the mathematical model of the ABHE system in conjunction with the EES-based model in order to simulate the ABHE system.

Tasks (i) and (ii) were mainly conducted through literature reviews and specific subject courses to provide necessary context to the research. The scientific problem (iii) was accomplished by experimental tests of the ABHE system prototype. Then task (iiii) was fulfilled by the development of the computer program EES-based model which was built to simulate the ABHE system and validated by the experimental results. Further investigations were done by the EES-based model to reach the optimum design of the ABHE system at any given working parameters.

1.5. Significance of research

Legionella has been proven to exist in every place damp and warm. Due to the rapid increase in LD outbreaks worldwide accompanied with the fact that no vaccination against Legionella exists up to date, it is of great importance to invent new disinfection method or developing the existing ones. The conventional disinfection methods involved mainly chlorine, ozone, thermal treatment, UV system or combination of them. However, except the thermal disinfection method, all these methods significantly reduce but do not eliminate Legionella from amoebae, protozoa and/or a biofilm. Re-contamination of water distribution systems within days or weeks after applying conventional disinfection methods has been the subject of numerous studies.

While regulations and guidelines considered temperature control as a critical element for preventing Legionella growth the economic profit forces toward energy saving and considered it as a critical target. Re-contamination of Legionella in case of applying thermal treatment method caused due to applying the treatment sporadically to avoid intensive energy consumption and accordingly high costs. Furthermore, adding insulations to HWS pipes for minimizing heat losses under flowing conditions lead to sustained water to a longer period within optimal temperature range for L. *pneumophila* growth [37].

Addressing these technical drawbacks motivates the ongoing research to introduce the ABHE system as a robust disinfection method that have unique features in terms of providing continuously thermal disinfection of Legionella and in simultaneously saving energy by means of recovering waste heat, lowering the cost and saving environment by reducing greenhouse gas emissions.

The most important part in the ABHE system is the PHE where waste heat is recovered. Therefore, the current work focuses mainly on studying the effect of PHE design on the thermal performance of the ABHE system. Evaluating energy efficiency of the PHE depends on the characteristic features that relate to flow arrangements, flow rates, inlet and outlet temperatures, in addition to other critical parameters. Energy efficiency evaluation of the PHE has been the subject of multiple studies such as Zang,Y et,al., (2018) [43]. Wang, Y et al., (2018) stated that mathematical modeling is one of the most effective approaches to investigate the dynamic characteristics and control performances of plate heat exchangers [44].

The current work aimed to evaluate the energy efficiency of the PHE at different initial operation conditions such as flow rates, fluid properties and heat transfer area depending on the derived mathematical and hydraulic models. The experimental test of the ABHE system prototype enables validation of the EES-based model The EES-base model was developed to define the optimal design of the PHE at specific working parameters in which area of the PHE is minimized and the regeneration ratio is maximized. Furthermore, the developed EES-based model is used to optimize the design of the PHE by defining its optimal dimensions (i.e., the width and the length of the plate) in which the regeneration ratio is maximized, or the required area of the PHE is minimized. For this purpose, the conjugate directions optimization method was used to solve the unconstrained energy optimization problem, with the conversion tolerance of $1 \cdot 10^{-4}$.

2. Legionella disinfection

As Legionella is ubiquitous in aquatic habitats, it appears impossible to prevent its entry into man-made water systems [45]. The continuous increase in the reported cases of LD worldwide has prompted the development of various prevention measures. National and international guidelines in several countries have established technical guidance and strategies for controlling Legionella in water systems. Numerous studies have investigated different disinfectants for inactivation of Legionella. However, each of these methods has advantages and disadvantages. Legionella disinfection occurs chemically or thermally. Unlike other traditional pathogens, Legionella act as part of a complex microbial ecological web within free-living amoebae hosts and biofilm that guard Legionella proliferation, support its resist to thermal and chemical disinfection and in consequence become more infectious [25,46–48]. Re-colonization with Legionella occurs rapidly after discontinuing all types of treatment methods, except thermal treatment, and recovered to the initial concentration in the water and the biofilm within 4-5 days

[46]. Only thermal disinfection has been proven to destroy Legionella presents in protozoa and biofilms efficiently. Steinert et al. (1998) study concluded that the regrowth of Legionella was observed within two months after the first thermal decontamination [42].

Concerning microbial water quality, the study of Fewtrell L et al. showed that further household point-of-use water treatment (boiling, chlorination, etc.) in rural areas may reduce diarrheal illness by 39% [49].

2.1. Conventional disinfection methods

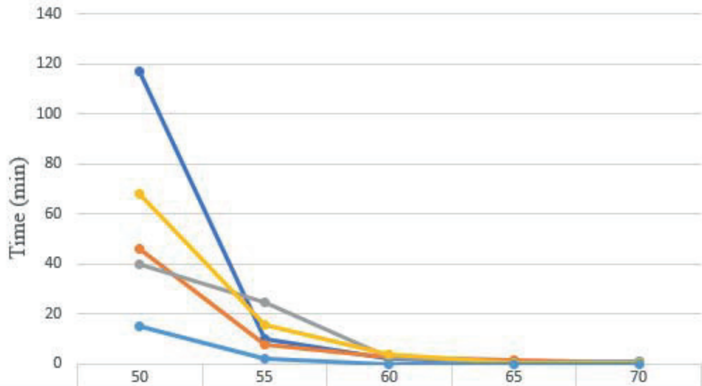
Among the chemical methods involving the use of metal ions (copper and silver), oxidation agents (halogen containing chlorine, bromine, etc., ozone and hydrogen peroxide), non-oxidation agents and the UV light, chlorine is known to be effective and widely used [50]. As mentioned earlier, such alternative treatments significantly reduce but do not eliminate pathogens from free-living amoebae, protozoa and/or a biofilm. This fact explains the occurrence of Legionella re-colonization in HWS within a few days or weeks after disinfection. Marchesi, I et al., (2011) has investigated the effectiveness of different methods used to control Legionella in hospital water system and found that superheating is not suitable for large buildings where temperatures >60 °C at each outlet cannot be constantly sustained. Shock hyper-chlorination can effectively deal with severe infection but must be achieved overnight leading to increased cost in addition to pipe corrosion. Point-of-care filters achieved 100% negative samples but the high costs about €1 million per year for 1000 outlets in patients' bathrooms and sinks make them unpractical for widespread application [26]. The study of Cervero-Aragó, S et al., (2015) showed that Legionella is more resistant to chlorine exposure than other bacteria [51].

2.2. Thermal disinfection method

To prevent Legionella contamination, temperatures are recommended to be maintained below 20 ^{o}C or higher than 50 ^{o}C. Kim, B et al., (2002) have stated that thermal disinfection is effective at temperatures >60 ^{o}C [50]. Practically, many countries have specified standards for control of Legionella in HWS. For example, EU guidelines stated that each water heater should deliver water at temperature of at least 60 ^{o}C, and in the range of 50–55 ^{o}C at tap outlets after 1 min of flushing. Heat shock and flush is applied periodically by means of increasing water temperatures in water storage tanks to above 70 ^{o}C and sustain it for one hour, then flushing all the outlets for 20- 30 minutes.

Obstacles that challenge the wide-ranging use of thermal disinfection method involve:

- Water temperatures of 60 ^{o}C prompts the risk of exposure to a full-thickness third degree burn in 6 s or less especially for younger and elderly people.
- Even though water is heated to 70 ^{o}C at the upper part of the storage tank, thermal stratification may lead to water temperatures within the range of L survival at the bottom of the storage tank and once the water is pumped to meet the heat demand during the peak load, L will start to colonize the HWS.
- One solution to avoid thermal stratification and stagnant water was the instantaneous heating devices. However in spite of its capability to minimize the proportion of L. *pneumophila* detected in HWS, the instantaneous heating devices can not eliminate L contamination since the treated hot water will be remixed with untreated cold water in mixture valve to avoid scalding.
- Heating water increase sanitary performance but simultaneously results in intensive energy consumption. Then, practically to reduce energy consumption the water storage tank was heated to 60 ^{o}C by an electric heater only once every 10 days. This means periodical thermal treatment and limitation in continuous action.
- Global trend to achieve energy and environmental conservation has prompt procedures that can significantly reduce energy consumption in HWS. For example, reducing the hot water temperature with 5.6 ^{o}C can reduce the energy consumption by 5% for electric water heaters. However, this reduction will result in developing an environment that enhances L multiplications.
- The worldwide drift toward utilizing renewable energy resources for energy and environmental conservation has introduced low temperatures for heating and cooling of buildings. The low heating temperatures and high cooling temperatures of buildings seem to offer an ideal habitat for Legionella pathogenic.



	50	55	60	65	70
Time (min) L. pneumophila sg. 1 ATCC 33152	117	10	2	0,8	0,9
Time (min) L. pneumophila sg. 1 env.	46	8	3	1,4	0,6
Time (min) L. pneumophila sg. 7 ATCC 33823	40	25	3	0,6	1,2
Time (min) L. pneumophila sg. 8 env.	68	16	4	0,8	0,7
Time (min) L. longbeachae ATCC 33462	15	2	0	0	0

Fig 2.1. Time required for a 4-log reduction of five Legionella strains at different temperatures[51]

Study of Cervero-Aragó, S et al., (2015) has investigated the effect of thermal treatment i.e. temperature and time on five Legionella species and concluded that the effectiveness of the thermal treatments increased as the temperatures and the exposure times increased, i.e. 60°C, 65°C and 70°C. The inactivation parameters showed narrow ranges as the temperature increased. Figure 3, shows the results obtained regarding the effect of thermal treatment, temperature and time, on the inactivation of Legionella [51] as Figure 2.1 shows. These results agreed with those reported by Kim, BR et al., (2002) and Bartram, J et al., (2007) [50,52].

Therefore, HWS with temperatures in range of 50–60 ^{o}C may contain a reservoir that incubate Legionella and if temperatures fall by only a few degrees, a rapid growth of L. *pneumophila* may occur leading to an increased risk of Legionella contamination. Therefore, those who aim to reduce hot water temperature to save environment, energy, cost and prevent scalding need to be aware of Legionella contaminations risk.

3. Anti-Bact heat exchanger System inspired by nature

Every technology inspired from nature possesses a superior and perfect design. Thus, numerous examples of how engineers extract useful ideas from nature and then apply them to problems are well established. Phil Gates expressed that the best inventions are copied from, or already in use by, other living things [53]. The current study introduce the ABHE system as a new technology (Patent SE.No. 0901111-5) inspired by nature and imitates the thermo-regulation process of a counter-current heat exchanger that exists in animals to adapt living in cold regions.

Animals are able to control their heat production and heat loss rates to maintain a nearly constant core temperature of 37 ^{o}C under a wide range of environmental conditions. The very effective regenerative heat exchangers that exist in the blood vessel system of bird's legs such as herons, fish, and marine mammals play a vital role in minimizing heat loss and in keeping the body warm in cold climate as Figure 3.1 shows. For example, while the core body temperature of a duck standing on ice is close to 37 ^{o}C, the bird's feet may be just above the freezing point 0 ^{o}C. That is because the arteries and veins are working in tandem to retain the heat. The warm arterial blood flows to the feet warms up the cold venous blood that flows back to the body. Figure 4 shows two types of counter current heat exchanger in both Canadian goose leg and in the porpoise flipper.

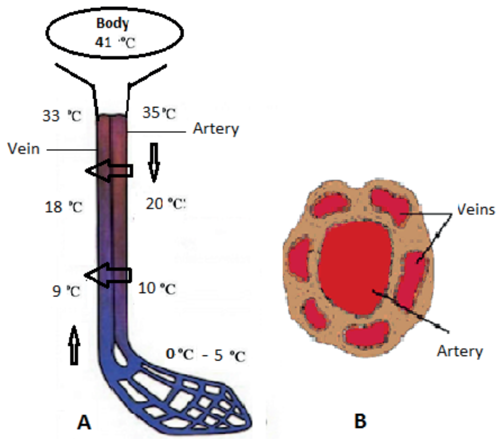


Fig 3.1. Two types of counter-current Heat Exchanger presents in (A), Canada goose can stand comfortably warm on ice and (B) Each artery is surrounded by veins in the porpoise flipper

3.1. Working principle of the Anti-Bact heat exchanger system

The ABHE system is a unique system that has robust features in terms of providing continuously thermally treated water accompanied with saving energy by recovering waste heat. The design of the ABHE system consists mainly of two units, firstly the PHE which represents the regeneration unit and secondly the disinfection unit where a fraction of energy is added to elevate the water temperature to the desired disinfection temperature as Figure 3.2 shows.

Through the PHE the heat is recovered from the treated water coming from the disinfection unit and efficiently used to heat up the supplied cold water. PHE is one of the most efficient types of heat transfer equipment that makes it possible to achieve temperature difference around ≈ 1 ^{o}C. The success of the PHE is a consequence of its unique set of advantages over other kinds of heat exchangers such as the extreme heat transfer rates, the ease of cleaning to meet health requirement, the great flexibility in altering the PHE thermal size by simply adding or removing some plates and the fouling tends to be significantly less. The heat recovery strongly relies on the size of the selected PHE that larger PHE results in a smaller temperature difference. However, increase PHE size results in increasing the cost of the ABHE system. Therefore, there is an optimal design of the PHE that maximizes the performance of the ABHE system and at the same time minimizes the required area of the PHE.

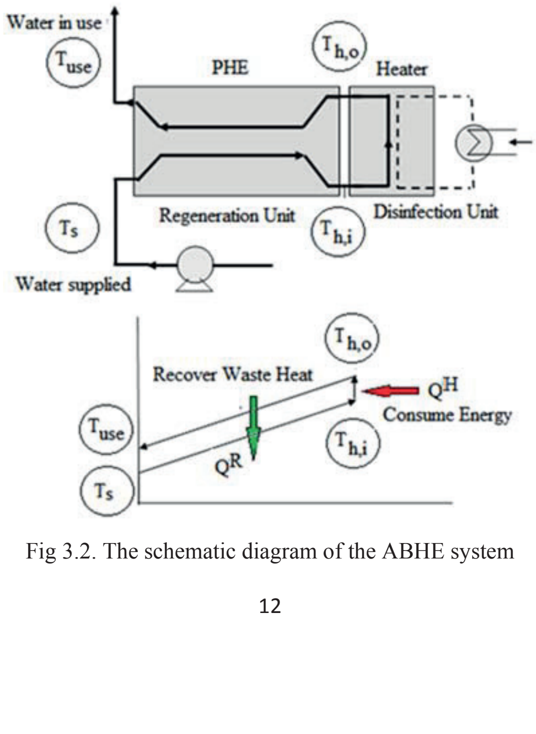


Fig 3.2. The schematic diagram of the ABHE system

3.2. Waste heat recovery by plate heat exchanger

Nowadays, the use of PHE has been increasing owing to their advantages of compactness and high heat transfer efficiency [54]. PHE play an important role in waste heat recovery, energy saving, emission reduction and transport processes where heat transfers from hot fluid to cold fluid. Waste heat recovery through PHE was the subject of several studies such as Mokhtar, M et al., (2017) and Wang, T et al., (2014) [55,56]. Through the PHE the waste heat is recovered and efficiently used to heat up the supplied cold water. The higher the heat transfer coefficient is in the PHE the lower is the temperature difference with possible difference approach of 1 ºC. The material of the plates is commonly stainless steel because of its excellent properties such as strength, easy to clean, ability to withstand high temperatures, and for its high-temperature corrosion resistance.

3.3. Energy source of disinfection Unit

The proportion of energy required in the disinfection unit can be supplied from any source of heat such as electrical, gas etc., or even from renewable energy sources such as solar energy. This gives wide range of possibility to use the available energy source and reduce the cost. Further investigation may concern study the life cycle cost of the ABHE system in case of using different energy sources.

4. Summary of appended papers

On the basis of the previous discussion of utilizing a thermal disinfection method by means of the ABHE system for Legionella disinfection in HWS, a model framework was developed and implemented for numerical analyses. The appended papers constitute documentation of this work, and the content of each paper is briefly summarized below:

Paper A: "Overview of legionella bacteria infection: control and treatment methods"

Human health hazard caused by Legionella pathogen and disinfection methods used to prevent Legionella risks was illustrated in this paper. The effect of water temperature on Legionella growth was discussed and the risk of exposure to LD outbreak in different water systems from low to high was presented. Water temperature is probably the most important or perhaps the only factor that can determine Legionella growth and multiplication. At temperatures higher than

55°C there is a breakpoint, but in some cases Legionella strains have been isolated from HWS up to 66 ºC. However, at temperatures above 70ºC they are destroyed almost instantly [50,52]. Furthermore, a summary on different disinfection methods used for control of Legionella in water distribution systems were illustrated. As Figure 4.1, shows, thermal disinfection (super heat and flush) was the most efficient among all other methods used to control Legionella in water distribution systems.

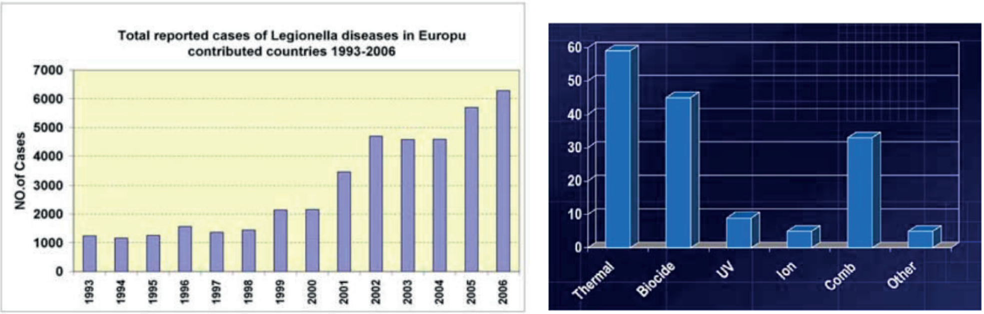


Fig 4.1. Water temperature in use as function of the required area of the PHE, pumping power and regeneration rate

Figure 4.1: Main results from ***Paper A*** where the total number of reported cases of LD in contributed countries between 1993 -2006 is shown (on left), and the effectiveness of different disinfection methods used to control Legionella in water distribution systems was shown in Figure 4.1 (on right).

Paper B: "Experimental and simulation validation of ABHE for disinfection of Legionella in hot water systems"

The main purpose of this study was to evaluate the performance of the ABHE system. A prototype of the ABHE was built with a configuration based on simplicity regarding design and construction. Mathematical modeling of the ABHE system was carried out to define the ABHE specification. A computer EES-based model was built to simulate the performance of the ABHE system. The purpose of the experiment was to achieve the following:

- Investigate the influence of supplied temperatures and flow rates on the thermal and hydraulic performance of the ABHE system.
- Find out the potential of waste heat recovery by means of the plate heat exchanger which represents the regeneration unit.

➢ Validate the EES model that was built to simulate the performance of the ABHE system. Results show that the experimental data is consistent with the results obtained by using the EES model. Consequently, the developed EES-based model can safely be used to simulate the ABHE for other working parameters or other setups that are not studied experimentally such as pressure drop and pumping power. The experimental results indicate that the thermal performance of the ABHE system is strongly dependent on the flow rate, while the supplied temperature has less effect. Higher flow rates enrich the turbulent flow which enhances the heat exchange and results in higher heat recovery and higher total heat transfer coefficient. However, increasing the flow rate also results in an increased pressure drop which consequently increases the consumed energy by the water pump to provide steady flow rates. The optimal design of the PHE and consequently the ABHE system can be achieved by adjusting the flow rates within the range that provide better performance of the PHE while avoiding unwelcoming increase in pressure drop. The maximum value of heat recovery is achieved at high flow rates and low supplied water temperatures. The supplied water temperature has no significant effect on the value of the total heat transfer coefficient.

The pumping power that was required to ensure constant flow rate in the ABHE system was much smaller than the heat recovery at different supplied temperatures. Consequently high saving in total cost is promising.

Experimental and simulation results from ***Paper B*** are shown in Figures 4.2 - 4.5 below.

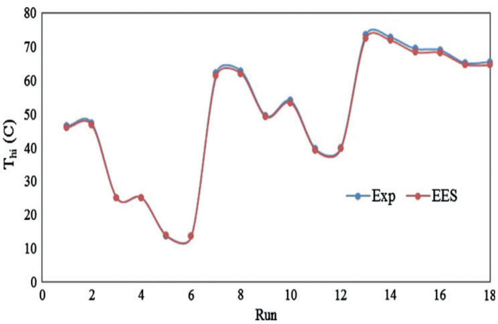


Fig4.2. Comparison between the inlet heater temperatures value as derived from experimental test and EES model

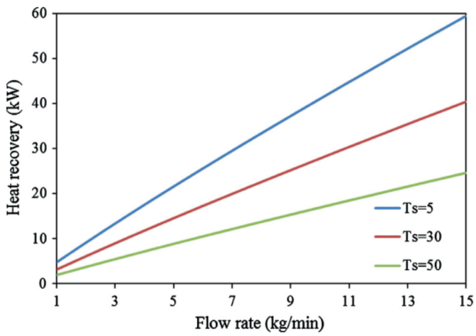


Fig 4.3. Heat recovery in PHE for different supplied water temperature at different flow rates

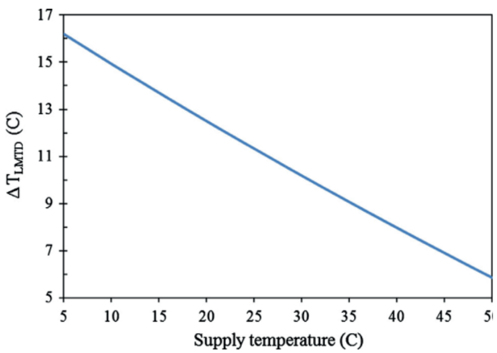


Fig 4.4. ΔT_{LMTD} in PHE as a function of the supplied water temperature

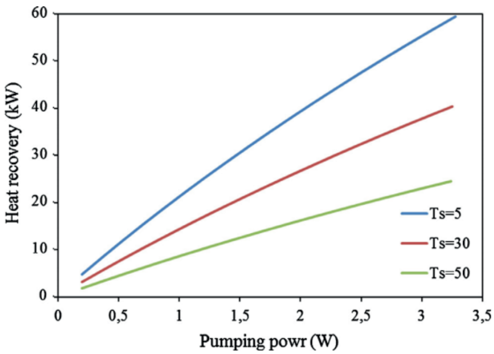


Fig 4.5. Heat recovery versus the pumping power at different supplied water temperature

Figures 4.3 and 4.4 resulted from the experimental test and Figure 4.2, indicates that the results of experimental test are trustworthy with the results obtained by using the EES-based model. The EES-based model was validated and then used for further investigation as shown in Figure 4.5, where the relation of pumping power versus heat recovery was clarified.

Paper C: "Effect of Working Parameters of the Plate Heat Exchanger on the Thermal Performance of the Anti-Bact Heat Exchanger System to Disinfect Legionella in Hot Water Systems"

The EES-based model was in this paper used to investigate the effect of different initial operation conditions on the thermal performance of the ABHE system. In addition, the EES-based model was used to determine the optimum design of the PHE at the given working parameters. Further study on the effect of the length and the width of the plates on the RR and the required area of the PHE was achieved. A small value of pumping power means a small pressure drop which lead to an efficient performance of the PHE. The results from ***paper C*** are shown in Figures 4.6 – 4.9 in addition to Tables 4.1.and 4.2, as following:

- An increase of temperature in use results in a reduced required PHE area and reduced pumping power but the recovered heat is also reduced as displayed in Figure 4.6.

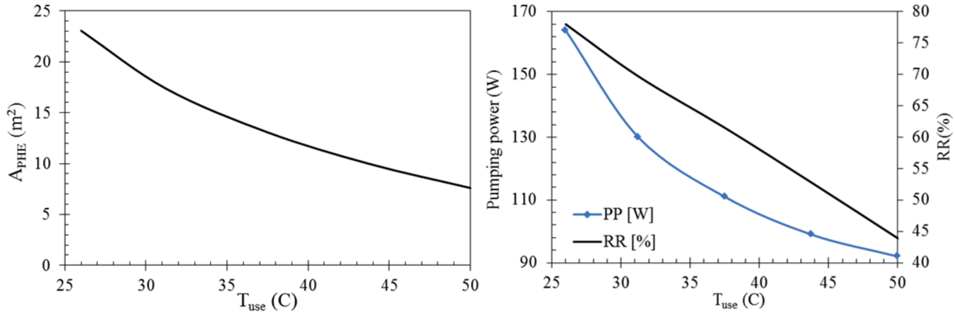


Fig 4.6. Water temperature in use as function of the required area of the PHE, pumping power and regeneration rate

➢ The effect of increasing disinfection temperature has similar effect of increasing supplied water temperature as Figure 4.7 shows.

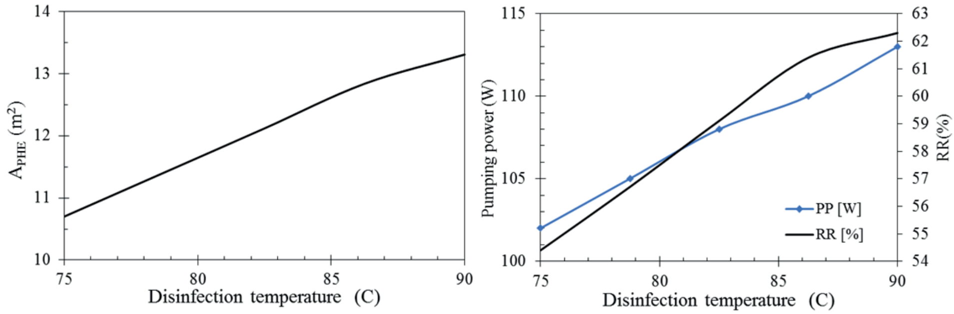


Fig 4.7. Disinfection water temperature as function of the required area of the PHE, pumping power and regeneration rate

➢ Increase supplied water temperature can enhance the thermal performance of the ABHE system by increasing the recovered heat, but in contrast it leads to increase in the required pumping power and required larger PHE area as Figure 4.8 displays.

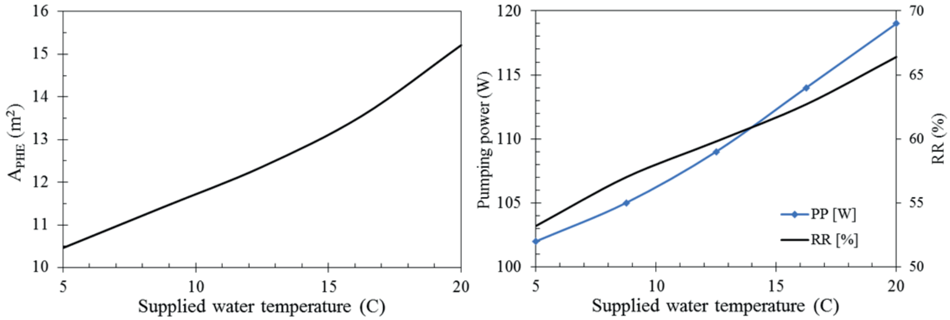


Fig 4.8. Supplied water temperature as function of the required area of the PHE, pumping power and regeneration rate

- Determination of the optimum design of the PHE that maximize the thermal performance of the ABHE system and at the same time minimize the required area of the PHE at a given PHE dimensions was shown in Figure 4.9.

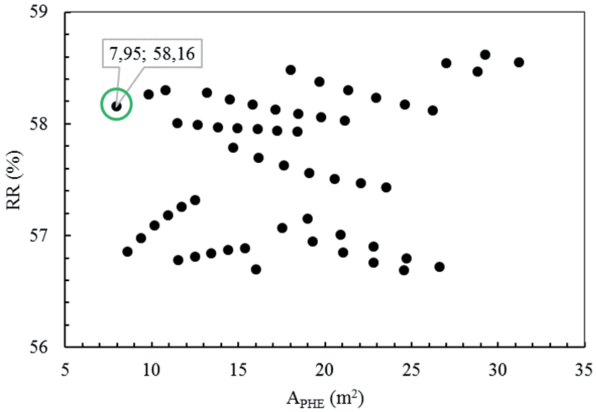


Fig 4.9. The required area of the PHE versus RR at the given initial operation condition, the circulated plot represent the optimum design of the ABHE system where the thermal

The developed EES-based model used also to optimize the design of the PHE by defining its optimal dimensions (i.e., the width and the length of the plate) in which the thermal performance of the ABHE system is maximized or the required area of the PHE is minimized. Consequently, high energy recovery and low cost of the ABHE system can be achieved. For this purpose, conjugate directions optimization method was used to solve the unconstrained energy optimization problems, with the conversion tolerance of 1.10^{-4}.

Table 4.1, shows the dimensions of the PHE in case the area of the PHE is required minimized.

Table 4.1. The dimensions of the PHE to minimize the required area of PHE

Criterion	T_s [^oC]	T_{use} [^oC]	T_d [^oC]	w [m]	L [m]	RR [%]	Optimal A_{PHE} [m^2]
Minimize area	10	40	80	0,15	0,5	56,8	7,83

While Table 4.2, shows the dimensions of the PHE in which the RR of the ABHE system is maximized.

Table 4.2. The dimensions of the PHE to optimize the RR of ABHE

Criterion	T_s [^oC]	T_{use} [^oC]	T_d [^oC]	w [m]	L [m]	A_{PHE} [m^2]	Optimal RR [%]
Maximize RR	10	40	80	0,18	0,62	11,45	58,3

5. Conclusion and Future Work

The goal of this work was to introduce the ABHE system as a robust disinfection method that mimics the natural system and provide continuous thermal treatment of water to prevent LD and simultaneously overcome the obstacles that limit the wide use of the thermal treatment method including high energy use and scalding exposure. The performed study shows great potential of utilizing the ABHE system. ABHE is an environmental friendly technology, safe, stable and compared to other periodical thermal treatment methods; the ABHE can successfully achieve continuous disinfection of Legionella and simultaneously enhance energy conservation by recovering the waste heat alongside the PHE, reduce greenhouse gas emissions and reduce the costs. The proportion of energy required in the disinfection unit can be supplied from different energy sources.

The development of the EES-based model, that is used to simulate the ABHE system, enables us to define the optimum design of the PHE. The EES-based model was validated experimentally and developed depending on a mathematical analysis of the ABHE system including the regeneration unit and the disinfection unit to provide a framework and a useful simulation tool to model the ABHE system at any given properties. Taking into account the geometrical parameters, flow arrangement and the initial operating conditions of the PHE, the EES model is used to optimize the PHE in which its area is minimized, and the RR of the ABHE system is maximized. Furthermore, the EES-based model is used to study the effect of the length and the width of the plates used in the PHE on the regeneration ratio and the required area of the PHE. The results obtained in this work show that the flow rates, supplied water temperature, water temperature in use, and disinfection temperature has different effect on the thermal performance of the ABHE system, beside the material and the geometrical parameters of the PHE. With the EES-based model it is possible to define the optimum design of the ABHE system in which thermal performance is maximized and area of PHE is minimized.

Additionally, this work forms a base where ABHE system can be designed to adjust any water distribution systems working at specific working parameters such as drinking water system, dental water lines, HWS, swimming pools and spa etc.

A suggestion for future work is utilizing different renewable energy resources as heat source in the disinfection unit and defines the life-cycle energy requirements of different heating sources such as gas, electric, solar or a combination of them. Utilizing the ABHE system in real HWS such as swimming pools is of interest.

6. References

[1] Clasen T, McLaughlin C, Nayaar N, Boisson S, Gupta R, Desai D, et al. Microbiological effectiveness and cost of disinfecting water by boiling in semi-urban India. American Journal of Tropical Medicine and Hygiene 2008;79.

[2] Gorham TJ, Yoo J, Garabed R, Mouhaman A, Lee J. Water access, sanitation, and hygiene conditions and health outcomes among two settlement types in rural far North Cameroon. International Journal of Environmental Research and Public Health 2017;14. doi:10.3390/ijerph14040441.

[3] Collier SA, Stockman LJ, Hicks LA, Garrison LE, Zhou FJ, Beach MJ. Direct healthcare costs of selected diseases primarily or partially transmitted by water. Epidemiology & Infection 2012;140:2003–13.

[4] Whiley H, Bentham R, Brown MH. Legionella Persistence in Manufactured Water Systems: Pasteurization Potentially Selecting for Thermal Tolerance. Frontiers in Microbiology 2017;8:1330.

[5] Falkinham III JO, Hilborn ED, Arduino MJ, Pruden A, Edwards MA. Epidemiology and ecology of opportunistic premise plumbing pathogens: Legionella pneumophila, Mycobacterium avium, and Pseudomonas aeruginosa. Environmental Health Perspectives 2015;123:749.

[6] Thacker SB, Bennett JV, Tsai TF, Fraser DW, McDade JE, Shepard CC, et al. An outbreak in 1965 of severe respiratory illness caused by the legionnaires' disease bacterium. Journal of Infectious Diseases 1978;138. doi:10.1093/infdis/138.4.512.

[7] Castillo NE, Rajasekaran A, Ali SK. Legionnaires' Disease: A Review. Infectious Diseases in Clinical Practice 2016;24. doi:10.1097/IPC.0000000000000401.

[8] Zhang Q, Zhou H, Chen R, Qin T, Ren H, Liu B, et al. Legionnaires' disease caused by Legionella pneumophila serogroups 5 and 10, China. Emerging Infectious Diseases 2014;20:1242.

[9] Buse HY, Ashbolt NJ. Differential growth of Legionella pneumophila strains within a range of amoebae at various temperatures associated with in-premise plumbing. Letters in Applied Microbiology 2011;53. doi:10.1111/j.1472-765X.2011.03094.x.

[10] Mekkour M, Khalil E, Driss B, Tai J, Cohen N, De Microbiologie D, et al. Legionella pneumophila: an environmental organism and accidental pathogen. Int J Sci Technol 2013;2:187–96.

[11] Cianciotto NP. Pathogenicity of Legionella pneumophila. International Journal of Medical Microbiology 2001;291:331–43.

[12] Karagiannis I, Brandsema P, der Sande M. Warm, wet weather associated with increased Legionnaires' disease incidence in The Netherlands. Epidemiology & Infection 2009;137:181–7.

[13] Cunha BA, Burillo A, Bouza E. Legionnaires' disease. The Lancet 2016;387:376–85.

[14] Almeida D, Cristovam E, Caldeira D, Ferreira JJ, Marques T. Are there effective interventions to prevent hospital-acquired Legionnaires' disease or to reduce environmental reservoirs of Legionella in hospitals? A systematic review. American Journal of Infection Control 2016;44:e183--e188.

[15] Beauté J, Robesyn E, de Jong B. Legionnaires' disease in Europe: all quiet on the eastern front? 2013.

[16] Welte T. Risk factors and severity scores in hospitalized patients with community-acquired pneumonia: prediction of severity and mortality. European Journal of Clinical Microbiology & Infectious Diseases 2012;31:33–47.

[17] Hines SA, Chappie DJ, Lordo RA, Miller BD, Janke RJ, Lindquist HA, et al. Assessment of relative potential for Legionella species or surrogates inhalation exposure from common water uses. Water Research 2014;56:203–13.

[18] Dunn CE, Rowlingson B, Bhopal RS, Diggle P. Meteorological conditions and incidence of Legionnaires' disease in Glasgow, Scotland: application of statistical modelling. Epidemiology & Infection 2013;141:687–96.

[19] Correia AM, Ferreira JS, Borges V, Nunes A, Gomes B, Capucho R, et al. Probable person-to-person transmission of Legionnaires' disease. New England Journal of

Medicine 2016;374:497–8.

[20] Heller R, Höller C, Süßmuth R, Gundermann K-O. Effect of salt concentration and temperature on survival of Legionella pneumophila. Letters in Applied Microbiology 1998;26:64–8.

[21] Sidari III FP, Stout JE, Vanbriesen JM, Bowman AM, others. Keeping Legionella out of water systems. American Water Works Association Journal 2004;96:111.

[22] Ditommaso S, Giacomuzzi M, Ricciardi E, Zotti CM. Efficacy of a Low Dose of Hydrogen Peroxide (Peroxy Ag+) for Continuous Treatment of Dental Unit Water Lines: Challenge Test with Legionella pneumophila Serogroup 1 in a Simulated Dental Unit Waterline. International Journal of Environmental Research and Public Health 2016;13:745.

[23] Fitzhenry R, Weiss D, Cimini D, Balter S, Boyd C, Alleyne L, et al. Legionnaires' Disease Outbreaks and Cooling Towers, New York City, New York, USA. Emerging Infectious Diseases 2017;23:1769.

[24] Buse HY, Schoen ME, Ashbolt NJ. Legionellae in engineered systems and use of quantitative microbial risk assessment to predict exposure. Water Research 2012;46:921–33.

[25] Cooper IR, Hanlon GW. Resistance of Legionella pneumophila serotype 1 biofilms to chlorine-based disinfection. Journal of Hospital Infection 2010;74:152–9.

[26] Marchesi I, Marchegiano P, Bargellini A, Cencetti S, Frezza G, Miselli M, et al. Effectiveness of different methods to control legionella in the water supply: ten-year experience in an Italian university hospital. Journal of Hospital Infection 2011;77:47–51.

[27] Von Baum H, Ewig S, Marre R, Suttorp N, Gonschior S, Welte T, et al. Community-acquired Legionella pneumonia: new insights from the German competence network for community acquired pneumonia. Clinical Infectious Diseases 2008;46:1356–64.

[28] Estrich CG, Gruninger SE, Lipman RD. Rates and predictors of exposure to Legionella pneumophila in the United States among dental practitioners: 2002 through 2012. The Journal of the American Dental Association 2017;148:164–71.

[29] Barbot V, Robert A, Rodier M-H, Imbert C. Update on infectious risks associated with dental unit waterlines. FEMS Immunology and Medical Microbiology 2012;65. doi:10.1111/j.1574-695X.2012.00971.x.

[30] Ma'ayeh SY, Al-Hiyasat AS, Hindiyeh MY, Khader YS. Legionella pneumophila contamination of a dental unit water line system in a dental teaching centre. International Journal of Dental Hygiene 2008;6.

[31] Rice EW, Rich WK, Johnson CH, Lye DJ. The role of flushing dental water lines for the removal of microbial contaminants. Public Health Reports 2006;121:270–4.

[32] Veronesi L, Capobianco E, Affanni P, Pizzi S, Vitali P, Tanzi ML. Legionella

contamination in the water system of hospital dental settings. Acta Biomedica de l'Ateneo Parmense 2007;78.

[33] Zanetti F, Stampi S, De Luca G, Fateh-Moghadam P, Sabattini MAB, Checchi L. Water characteristics associated with the occurrence of Legionella pneumophila in dental units. European Journal of Oral Sciences 2000;108.

[34] Arvand M, Hack A. Microbial contamination of dental unit waterlines in dental practices in Hesse, Germany: A cross-sectional study. European Journal of Microbiology and Immunology 2013;3:49–52.

[35] Weiss RA, McMichael AJ. Social and environmental risk factors in the emergence of infectious diseases. Nature Medicine 2004;10:S70.

[36] Mathys W, Stanke J, Harmuth M, Junge-Mathys E. Occurrence of Legionella in hot water systems of single-family residences in suburbs of two German cities with special reference to solar and district heating. International Journal of Hygiene and Environmental Health 2008;211:179–85. doi:10.1016/j.ijheh.2007.02.004.

[37] Bédard E, Fey S, Charron D, Lalancette C, Cantin P, Dolcé P, et al. Temperature diagnostic to identify high risk areas and optimize Legionella pneumophila surveillance in hot water distribution systems. Water Research 2015;71:244–56.

[38] Demirjian A, Lucas CE, Garrison LE, Kozak-Muiznieks NA, States S, Brown EW, et al. The Importance of Clinical Surveillance in Detecting Legionnaires' Disease Outbreaks: A Large Outbreak in a Hospital With a Legionella Disinfection System—Pennsylvania, 2011–2012. Clinical Infectious Diseases 2015;60:1596–602.

[39] der Kooij D Van, Veenendaal HR, Scheffer WJH. Biofilm formation and multiplication of Legionella in a model warm water system with pipes of copper, stainless steel and cross-linked polyethylene. Water Research 2005;39:2789–98.

[40] Ashbolt NJ. Environmental (saprozoic) pathogens of engineered water systems: understanding their ecology for risk assessment and management. Pathogens 2015;4:390–405.

[41] Falkinham JO, Pruden A, Edwards M. Opportunistic premise plumbing pathogens: increasingly important pathogens in drinking water. Pathogens 2015;4:373–86.

[42] Steinert M, Ockert G, Lück C, Hacker J. Regrowth of Legionella pneumophila in a heat-disinfected plumbing system. Zentralblatt Fur Bakteriologie 1998;288:331–42.

[43] Zhang Y, Jiang C, Shou B, Zhou W, Zhang Z, Wang S, et al. A quantitative energy efficiency evaluation and grading of plate heat exchangers. Energy 2018;142:228–33.

[44] Wang Y, You S, Zheng W, Zhang H, Zheng X, Miao Q. State space model and robust control of plate heat exchanger for dynamic performance improvement. Applied Thermal Engineering 2018;128:1588–604.

[45] Steinert M, Hentschel U, Hacker J. Legionella pneumophila: an aquatic microbe goes

astray. FEMS Microbiology Reviews 2002;26:149–62.

[46] Thomas V, Bouchez T, Nicolas V, Robert S, Loret JF, Levi Y. Amoebae in domestic water systems: resistance to disinfection treatments and implication in Legionella persistence. Journal of Applied Microbiology 2004;97:950–63.

[47] Declerck P, Behets J, Margineanu A, van Hoef V, De Keersmaecker B, Ollevier F. Replication of Legionella pneumophila in biofilms of water distribution pipes. Microbiological Research 2009;164:593–603.

[48] Thomas JM, Ashbolt NJ. Do free-living amoebae in treated drinking water systems present an emerging health risk? Environmental Science & Technology 2010;45:860–9.

[49] Fewtrell L, Kaufmann RB, Kay D, Enanoria W, Haller L, Colford Jr. JM. Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: A systematic review and meta-analysis. Lancet Infectious Diseases 2005;5. doi:10.1016/S1473-3099(04)01253-8.

[50] Kim BR, Anderson JE, Mueller SA, Gaines WA, Kendall AM. Literature review - efficacy of various disinfectants against Legionella in water systems. Water Research 2002;36:4433–44. doi:10.1016/s0043-1354(02)00188-4.

[51] Cervero-Aragó S, Rodr'\iguez-Mart'\inez S, Puertas-Bennasar A, Araujo RM. Effect of common drinking water disinfectants, chlorine and heat, on free Legionella and amoebae-associated Legionella. PloS One 2015;10:e0134726.

[52] Bartram J, Bartram J, Lee J V, Pond K, Surman-Lee S. Legionella and the prevention of legionellosis. World Health Organization; 2007.

[53] Gates P. Wild Technology: Inventions Inspired by Nature 1999.

[54] Klemes JJ, Arsenyeva O, Kapustenko P, Tovazhnyanskyy L. Compact heat exchangers for energy transfer intensification: low grade heat and fouling mitigation. CRC Press; 2015.

[55] Wang T, Luan W, Wang W, Tu S-T. Waste heat recovery through plate heat exchanger based thermoelectric generator system. Applied Energy 2014;136:860–5.

[56] Mokhtar M, Burns S, Ross D, Hunt I. Exploring multi-objective trade-offs in the design space of a waste heat recovery system. Applied Energy 2017;195:114–24.

Papers

Paper A

OVERVIEW OF ALEGIONELLA BACTERIA INFECTION, CONTROL AND TREATMENT METHODS

OVERVIEW OF LEGIONELLA BACTERIA INFECTION; CONTROL AND TREATMENT METHODS

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ABSTRACT

Since the first recognized outbreak of Legionnaires' disease (LD) in 1976, it has become an increasing problem around the world especially in poor countries. Legionella (L) causes an estimated 15,000 annual cases of pneumonia in USA, and leads to death in about 20% of the cases. L is found worldwide in both natural and artificial environments e.g. spa pools, cooling towers. It infects people by inhaled contaminated aerosols that can transmit several km. The optimal temperature for L growth is 20-45C. Control of L is therefore an important health issue. Many treatment methods are used; biocides, ionisation, ozone, UV-radiation, pressure, and thermal treatment. Only thermal treatment can completely eliminate L, which is killed almost instantly at 70C. Current paper gives an overview of the Legionella problem and treatment methods.

1. INTRODUCTION

Substandard water associated with the presence of bacteria called Legionella (L) is one of the major sources of infection diseases around the world. L bacteria (LB), which emerged in 1976 (Diederen, 2007), causes Legionnaires' disease (LD) (pneumonic legionellosis) and Pontiac fever (Kima et al., 2002), is identified as a collection of infections. Consequently L is known as one of tropical diseases spread through 'global warming' (Monckton, 2007) i.e. due to the human alteration of the environment (Bartram et al., 2007). It is considered responsible for epidemic and sporadic cases of pneumonia (Diederen, 2007 and Cloud et al., 2000) especially during summer and autumn because warm weather encourages proliferation of the bacteria in water. LD is normally acquired by inhalation of L from a contaminated environmental source (Borella et al., 20004 and Majid et al., 2007). L may be free-living or living within amoebae and other protozoa or within biofilms (Desia et al. 1999 and Pond 2005). There are currently more than 50 known species of L, twenty separate species of these organisms are occur in the respiratory tract (Diederen, 2007, Bartram et al., 2007 and Cloud et al., 2000).

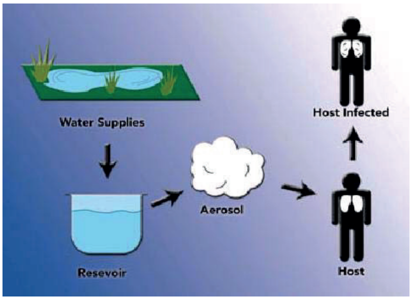

Fig.1. The cycle of infection with Legionella bacteria

L infection, see Fig 1, may occur directly from the environment to humans or by wound infections (Bartram et al., 2007 and Hoge et al., 1991) or even in buildings (hotels, hospitals, houses...) with municipal water (Donald, 2007). More than 50% of all houses using district heating systems were colonized by L, their significantly lower hot water temperature is thought to be the key factor leading to intensified growth of L (Mathys et al., 2007).

LD is not passed from person to person and does not occur by drinking water contaminated with LB. The risks occur when people inhale contaminated aerosols (Diederen, 2007, Brundrett, 2003, A.D.A.M, 1997 and Konishi et al., 2006). LB has been traced to contaminated aerosols generated at distances of up to 3.2km (Sartory et al., 2002). Particles of a size less than 5 µm can be deeply inhaled, and the individual could receive up to 1,000 or more LB at one time (Broadbent, 2003). This might happen during daily activities such as having a shower, toilet flushing. Humidifiers and nebulizers can also spread LB and have been reported as a source of infection in several cases (Bartram et al., 2007).

2. OCCURRENCE OF LEGIONELLA

LB can be found in both natural reservoirs such as water, soil and air see Fig 1, (Diederen, 2007, Hoge et al., 1991, EPA, 2001, Rathore, 2007 and Yi Yu et al., 2007). It is occurs in artificial aquatic environments e.g. spa pools, hot tubs, hot water storage tanks, cooling towers, cold and hot-water distribution systems, potable water, and industrial processes and equipment.

LB can be free floating or preferably attached to surfaces. Bio-films are complex microbial communities which offer protection and provide essential growth requirements for L. So, biofilm prevention is an important control measure against proliferation of L because they are difficult to remove from complex piping systems. Biofilms offers poor biocide penetration and L in such surfaces are therefore difficult to control.

Cases of LD have been reported in North and South America, Asia, Australia, New Zealand, Europe, and Africa. More than 80% of reported cases are sporadic through the year, while the rest occur during the summer and early fall (Rathore, 2007). Fig 2 shows the increase in reported cases of LD (Ricketts et al., 2007). Low temperature heating systems at temperatures 40-45C offers an ideal situation LB growth.

3. MORTALITY AND SURVIVAL

The case–fatality rate is 5-30% but can be as high as 80 % depending on risk factors such as age, cigarette smoking, alcoholism, and cancer (BRE, 2003). LD can strike at any age; Fig 3 shows that LD tends to occur in the middle age and elderly though it is more common in over ages over 50 (Laurance, 2007). The LD infection rate is 2-3 times greater among men than for women (Desia et al. 1999 and Rathore, 2007).

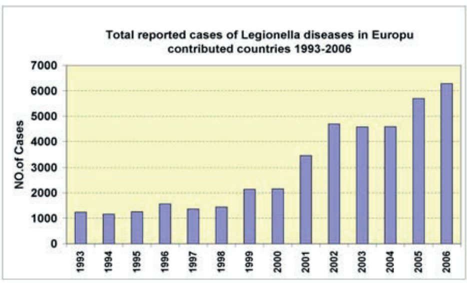

Figure 2. Total reported cases of Legionella diseases in contributed Europe countries 1993-2006

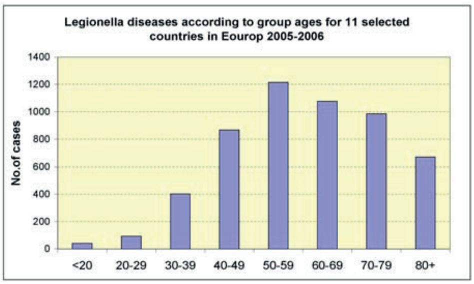

Figure 3. Legionella diseases according to group ages in 11 European countries 2005-2006

4. WATER TEMPERATURE AND LEGIONELLA GROWTH

LB proliferates and thrives in warm water and warm damp places (Bartram et al., 2007, Pond 2005 and Konishi et al., 2006). The temperature of the water is probably the most important or perhaps the only determinant factor for multiplication of L. Fig 4, (Diederen, 2007, Bartram et al., 2007, Mathys et al., 2007, Konishi et al., 2006, Rathore, 2007 and Cooke, 2004), shows that:

- The optimal growth temperature of LB is 20-45°C.
- LB is dormant below 20°C, but still alive.
- LB is completely killed at temperatures above 60°C (90% are killed within 2 min).

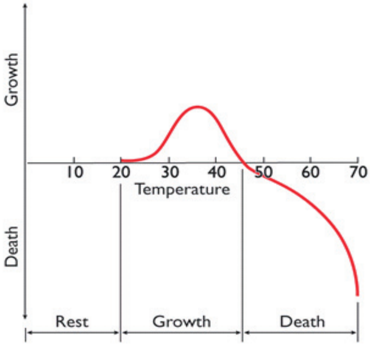

Figure 4. Influence of different temperatures on Legionella growth

There is little or no growth of bacteria below 20 ºC, but L will survive for long periods at low temperatures and proliferate when the temperature increases (Bartram et al., 2007). L is able to withstand temperatures of 50 °C for several hours though 90% are killed within 2 h (Cooke, 2004). At temperatures higher than 55°C there is a break point, but in some cases L strains have been isolated from hot-water systems up to 66 ºC. However, at temperatures above 70ºC they are destroyed almost instantly (Kima et al., 2002 and Bartram et al., 2007). Water systems are increasingly using water in the temperature range that enhances L growth. These systems can produce aerosols and thereby increasing spread of the LB. Fig 5 shows the high risks of LD outbreak in hot water systems at temperatures of 40-45, which are suitable for L multiply.

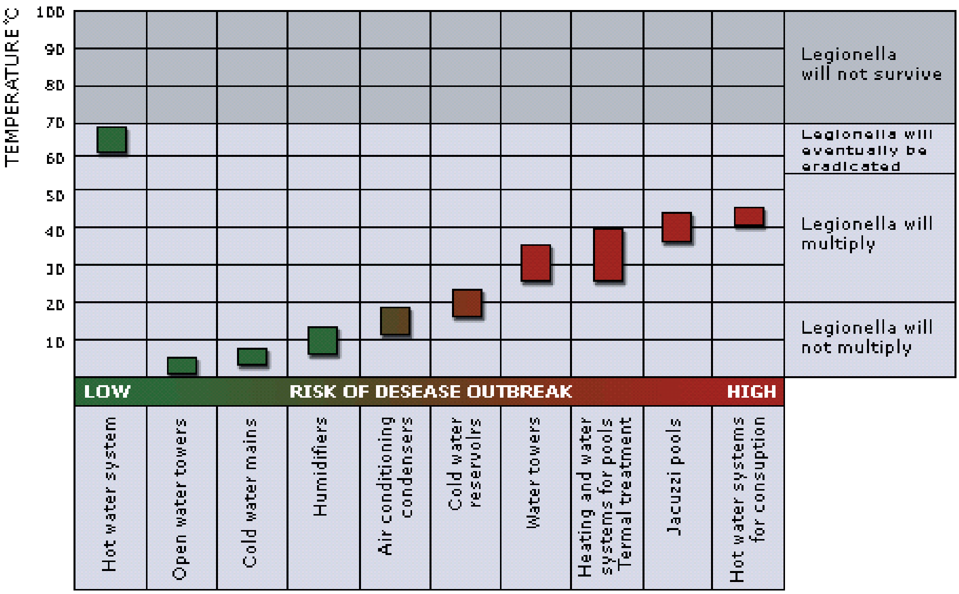

Figure 5. Influence of different Temperatures on the growth of or exposure to Legionella in many complex water systems

5. PREVENTION OF LEGIONELLA RISKS

Maintaining the temperature of hot and cold-water systems to prevent or minimize the growth of L is an important control measure to prevent the risk of L infection. Water systems should (Bartram et al., 2007):

- Avoid temperatures between 25-45 °C to prevent L colonization.
- Ideally, maintain cold water below 20 °C.
- Ideally, maintain hot water above 50 °C.

However, this is not possible always because of the nature of these systems i.e. control measures for reducing the proliferation of L must not increase the risk of scalding, particularly for children and elderly people (Bartram et al., 2007).

6. TREATMENT METHODS

There are several control methods available for disinfection of water distribution systems (Kima et al., 2002). The resistance of LB to disinfectants depends on the culture conditions (Cargill et al., 1992). Some methods have not always proven to give complete or permanent protection from recolonization of LB, but a combination of such methods may be the most effective way of managing water systems and preventing future outbreaks. These methods are classified into six groups according to the method's principle and are listed according to how commonly used they are, Fig 6 (BRE, 2003):

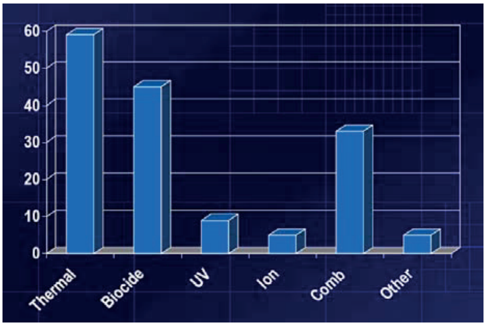

Figure 6. Control methods for disinfection of water distribution systems.

- Thermal (super heat and flush) (59%)
- Biocide (45%)
- Ultraviolet light sterilization (9%)
- Copper-Silver ionization (5.3%)
- Ozonation (8%)
- Other method of control in water system (3%)

Thermal disinfection (super heat and flush)

No other method than thermal treatment (super heat and flush) provides complete elimination and permanent protection from re-colonization of L. Thermal disinfection is the most commonly method in terms of controlling L in hot and cold water systems. Fig. 7 shows that the time necessary to kill LB is reduced by increasing temperature (Bartram et al., 2007). Elevation of water temperature to 70-80°C kills off LB within seconds (Donald, 2007, Brundrett, 2003 and EPA, 2001).

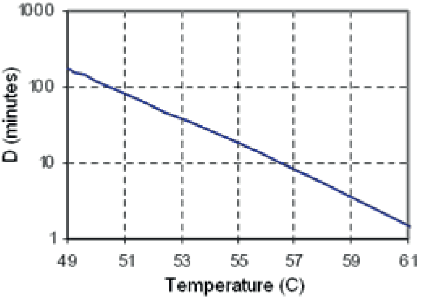

Figure 7. Time in minutes to kill 90% of the LB population.

Biocide (Chlorination)

Chlorination of water means raising chlorine levels in the system for one to two hours (EPA, 2001). Continuous chlorination requires the addition of chlorinated salts to the water.

Ultraviolet Light Sterilization

Ultraviolet light sterilization kills L by disrupting cellular DNA synthesis (EPA, 2001).UV radiation has not been widely used in drinking water disinfection because it leaves no residual to provide protection against potential downstream contamination. It has, however, been widely used in wastewater disinfection though studies indicate that UV radiation alone is insufficient to control LB. Therefore, e.g. periodic chlorination and heat pasteurization are used along with UV radiation for effective L control (Kima et al., 2002).

Copper-Silver Ionization

Copper-silver ionization distorts the permeability of the L cell, denatures proteins, and leads to lyses and cell death (EPA, 2001). Use of copper and silver ions indicated that 0.003 mg/L of Ag^{+} was sufficient to control the growth of Legionella in circulating warm water but it was difficult to eradicate Legionella from taps and showers (Kima et al., 2002).

Ozonation

Ozone which cannot be purchased, must be generated on site by ozonators, has been widely used in Europe to kill LB (EPA, 2001). Since the ozone does not stay in water sufficiently long to provide a residual effect against potential contamination in the distribution system, chlorine can be added after ozonation to provide the residual effect (Kima et al., 2002).

New Legionella Research at LTU

A new technology, which imitates a biological system, is currently being tested at LTU. It is a thermal chock treatment method that requires 90% less energy than conventional thermal treatment methods. It eradicates LB within seconds and can be heated by solar, biofuel, gas, electricity etc. The expected applications for this technology include domestic hot water, water disinfection in warm climate, and pasteurization of milk.

7. CONCLUSION

LB which was first identified in 1976 thrives in different aquatic environments. LB growth is sensitive essentially to the water temperature. Biofilms supports and offer protection for LB to stay alive even through severe conditions. LD is an increasing problem around the world and the increasingly common use of low temperature water systems provide ideal conditions for L. It should be noted that L is much more common in poor countries and that most cases of LD are not reported. The treatment methods of filtration, ozonation, and ultraviolet radiation serve to clarify the water and reduce the organic load. However no other method than thermal treatment (super heat and flush) provides both complete elimination and permanent protection from re-colonization of L. Thermal shock treatment at 70-80^{o}C for short periods (seconds) is the safest method to eliminate L. Improved surveillance for LD is essential for the rapid and timely control of disease outbreaks.

8. References

Diederen, B.M.W. (2007). Legionella spp. and Legionnaires' disease. Journal of infection (2008) 56,1-12.

Kima, B.R. Andersona, J.E. Muellera, S.A. Gainesb,W.A. Kendallb,A.M.(2002). Literature review—efficacy of various disinfectants against Legionella in water systems. Water Research 36 (2002) 4433–4444.

Monckton, C (2007). 35 Inconvenient Truths. Eco world- The global Environmental community. http://www.ecoworld.com/home/articles2.cfm?tid=446

Bartram, J., Chartier,Y., Lee, J., Pond, K., Surman-Lee, S.(2007). Legionella And The Prevention Of Legionellosis. World Health Organization.

Cloud, J.L., Carroll, K.C., Pixton, P., Erali, M., Hillyard, D. R. (2000). Detection of Legionella Species in Respiratory Specimens Using PCR with Sequencing Confirmation. Journal of Clinical Microbiology,2000, p. 1709-1712, Vol. 38, No. 5, 0095-1137

Borella, P., Montagna, T., Romano-Spica,V., Stampi, S., Stancanelli,G., Triassi ,M., Neglia, R., Marchesi, I., Fantuzzi, G., Tatò, D., Napoli, Ch., Quaranta,G., Laurenti, P., Leoni, E., De Luca, G., Ossi, C., Moro, M., Ribera, D., Alcalà, G.(2004). Legionella Infection Risk from Domestic Hot Water. Emerging Infectious Diseases (2004)Vol. 10, No. 3, www.cdc.gov/eid

Majid, S., Reza, N.M., Mohammad, b., Jamileh, G., Mahmood, J.T. (2007). Detection of Legionella Pneumophila by PCR-ELISA Method in Industrial Cooling Tower Water. Pakistan Journal of Biological Sciences, 10, 4015-4021.

Desai, R., Welsh, C., Summy, M., Farone, M., Newsome, A.L. (1999). The potential of in situ hybridization and an immunogold assay to identify Legionella associations with other microorganisms. Journal of Microbiological Methods, 37, 155-164

Pond.K (2005).Water Recreation and Disease Plausibility of Associated Infections: Acute Effects, Sequelae and Mortality. World Health Organization (WHO) 2005. www.who.int/water_sanitation_health/bathing/recreadischap2.pdf

Hoge, Ch.W. Breima, R.F. (1991). Advances in the Epidemiology and Control of *Legionella* Infections. Epidemiologic Reviews (1991) University School of Hygiene and Public Health, 13,1991

Donald Wise, PE. (2007). A 12-Step Program for Avoiding Liability for Hot Water System Injuries. Plumbing Systems & Design (2007). www.antiscald.com/12step.pdf

Mathys, W., Stanke, J., Harmuth, M., Junge-Mathys, E. (2007). Occurrence of Legionella in hot water systems of single-family residences in suburbs of two German cities with special reference to solar and district heating. International Journal of Hygiene and Environmental Health 211 (2008) 179-185.

Brundrett, G.(2003).Controlling Legionnaire’s Disease. Indoor Built Environ, 12,19–23

A.D.A.M. (1997). Pneumonia In-Depth Report. NY times health. http://health.nytimes.com/health/guides/disease/pneumonia/print.html

Konishi, T., Yamashiro, T., Koide, M., Nishizono, A. (2006) Influence of Temperature on Growth of Legionella pneumophila Biofilm Determined by Precise Temperature Gradient Incubator. Journal of Bioscience and Bioengineering 2006, Volume 101, Issue 6, Pages 478-484

Sartory, D.P., Bonnadonna, L., Delattre, J.-M., Gosling, P., Janda, M., van der Kooij, D. (2002). Guidelines for Drinking-Water Quality - Second Edition - Addendum Microbiological Agents in Drinking Water. World Health Organization

Broadbent, C. (2003). Legionella in hot water systems. ECOLIBRIUM™. www.airah.org.au/downloads/2003-04-03.pdf

Environmental Protection Agency (EPA). 2001 . Legionella: Drinking Water Health Advisory (2001). by EPA -822-B-01-005. http://www.epa.gov/waterscience/criteria/humanhealth/microbial/legionellaha.pdf

Rathore, H.M., Alvarez, A.(2007). Legionella Infection. Overview- eMedicine pediatrics;General Medicine. www.emedicine.com/ped/TOPIC1288.HTM - 98k

Yi Yu, P., Eason Lin, Y., Ru Lin, W.,Yun Shih, H., Ching Chuang, Y., Jy Ben, R., Kuei Huang, W., Shen Chen,Y., Ching Liu, Y., Yee Chang, F., Yong Yen, M., Chuan Liu, Ch., Chien Ko, W., Hsun Lin, H., Yuan Shi, Z. (2007). The high prevalence of Legionella pneumophila contamination in hospital potable water systems in Taiwan: implications for hospital infection control in Asia. International Journal of Infectious Diseases (2008) 12, 416—420.

Ricketts, K.D. Joseph, CA. (2007). Legionnaires' disease in Europe (2005-2006). Eurosurveillance, 12, 2007 http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=753

Legionellosis (Primarily Legionella Pneumophila Pneumonia) (2008). New Jersey Department of Health and Senior Services. www.state.nj.us/health/cd/manual/legionellosis.pdf

Laurance. J. (2007). Legionnaires' spreading across UK - Health News, Health. The INDEPENDENT, HEALTH & WELLBEING http://www.independent.co.uk/life-style/health-and-wellbeing/health-news/legionnaires-spreading-across-uk-460238.html

Cooke,R. P. D. (2004). Hazards of water. Journal of Hospital Infection, Volume 57, Issue 4, 2004, Pages 290-293

Cargill, KL., Pyle, BH., Sauer, RL., McFeters, GA.(1992). Effects of culture conditions and biofilm formation on the iodine susceptibility of Legionella pneumophila. Can J Microbiol1992;38:423–9.

BRE Environment for the Health and Safety Executive (HSE). (2003). Evaluation of HSC's ACOP and Guidance "Legionnaires disease: Control of legionella bacteria in water systems" (L8). http://www.hse.gov.uk/research/rrpdf/rr140.pdf

Paper B

Experimental and simulation validation of ABHE for disinfection of Legionella in hot water systems

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Research Paper

Experimental and simulation validation of ABHE for disinfection of *Legionella* in hot water systems

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HIGHLIGHTS

- ABHE system can supply a continues thermal treatment of water with saving energy.
- Mathematical and experimental validation of ABHE performance are presented.
- EES-based model is developed to simulate ABHE system.
- Energy saving by ABHE is proved for different initial working parameters.

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ABSTRACT

The work refers to an innovative system inspired by nature that mimics the thermoregulation system that exists in animals. This method, which is called Anti Bacteria Heat Exchanger (ABHE), is proposed to achieve continuous thermal disinfection of bacteria in hot water systems with high energy efficiency. In particular, this study aims to demonstrate the opportunity to gain energy by means of recovering heat over a plate heat exchanger. Firstly, the thermodynamics of the ABHE is clarified to define the ABHE specification. Secondly, a first prototype of an ABHE is built with a specific configuration based on simplicity regarding design and construction. Thirdly, an experimental test is carried out. Finally, a computer model is built to simulate the ABHE system and the experimental data is used to validate the model. The experimental results indicate that the performance of the ABHE system is strongly dependent on the flow rate, while the supplied temperature has less effect. Experimental and simulation data show a large potential for saving energy of this thermal disinfection method by recovering heat. To exemplify, when supplying water at a flow rate of 5 kg/min and at a temperature of 50 °C, the heat recovery is about 1.5 kW while the required pumping power is 1 W. This means that the pressure drop is very small compared to the energy recovered and consequently high saving in total cost is promising.

1. Introduction

Nowadays, global driving forces are searching for more efficient, sustainable and economically viable technologies for energy conversion and utilization [1]. The growing global concerns toward providing water with high quality and simultaneously saving energy and environment have stimulated research on new innovative technologies. Bartram et al. proclaim that disease related to unsafe water, poor sanitation, and lack of hygiene are some of the most common causes of illness and death among the poor in developing countries [2]. Since the first detection of *Legionella* (L) in Philadelphia 1976, L is recognized to cause Legionellosis which is associated with two distinct forms: Legionnaires' disease (LD) and Pontiac fever [3,4]. Transmission of L occurs mainly by inhaling an infectious aerosol or by aspiration of contaminated potable water, therefore LD are believed to infect people through water systems that are linked to a variety of aerosol generating devices and respiratory equipment [5–11]. The mortality rate of Legionellosis is in range of 5–30% but can be as high as 80% depending on risk factors such as cigarette smoking, age and nosocomial acquisition, and in immunocompromised patients [12,13].The fact that vaccination against LD is not efficacious [14] makes the efforts

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Nomenclature

A	effective area, m^2
Ac	cross area of a channel, m^2
Ap	projected area of a single plate, m^2
B	back thickness of PHE, mm
C	heat capacity rate, W/K
C_p	specific heat capacity, J/kg °C
c_q	constant for *Nu* equation
Cr	heat capacity ratio
D_h	hydraulic diameter, m
F	correction factor
f	fanning friction factor
G	mass flux, kg/m^2 s
h	convection coefficient, W/m^2 °C
I	enthalpy, kJ/kg K
k	thermal conductivity of water, W/m^2 °C
L	length of the plate (port to port), m
$\dot{m}$	mass flow rate, kg/s
n	number of channels
N_p	total number of plates
N_{pass}	number of passes
q	constant for *Nu* equation
Q^H	heat load in heater, kW
Q^R	heat recovered, (regeneration), kW
T	temperature, °C
u	flow channel velocity, m/s
U	total heat transfer coefficient, W/m^2 °C
V	volumetric flow rate, m^3/sec
W	width of the plate, m
p	the wetted perimeter, m
pp	pumping power, W
ΔT_{LMTD}	logarithmic mean temperature difference
ΔP	pressure drop, kPa
ΔT_1	temperature difference at one end, °C
ΔT_2	temperature difference another end, °C
$\sum \Delta P_{Ni}$	distribution pressure drop, kPa

Greek symbols

α	channel spacing, gap, m
δ	plate thickness, m
$\zeta_0\ \zeta\ \zeta_{1,0}$	friction factors
η	pump efficiency
λ	thermal conductivity of a the plate, W/m °C
μ	dynamic viscosity of the fluid, kg/m s
μ_w	dynamic viscosity at wall temperature, kg/m s
ρ	fluid density, kg/m^3
φ	plate inclination angle, rad

Subscripts

c	cold water stream
g	gravity
h	hot water stream
h,i	temperature of the inlet heater
h,o	temperature of the outlet heater
m	mean temperature
max	maximum
min	minimum
s	supplied water temperature
t	total
use	temperature of water in use
w	wall
α	acceleration

Dimensionless numbers

Hg	Hagen number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Acronyms

ABHE	anti bact heat exchanger
EES	engineering equation solver
HWS	hot water systems
L	*Legionella*
L. pneumophila	*Legionella pneumophila*
LD	Legionnaires' disease
NTU	number of heat transfer unit
PHE	plate heat exchanger
RR	regeneration ratio

toward developing technologies and inventing a new water disinfection system of great importance.

It is well known that L, which is ubiquitous and has the ability to survive in water for extremely long periods of time, as a year, frequently colonize water systems at temperatures of 20–50 °C [15–17]. Therefore, temperatures are recommended to be maintained below 20 °C or higher than 50 °C. Practically, many countries have specified standards for control and minimization of L in hot water systems (HWS). For example, EU guidelines, such as those in UK, stipulate that each water heater should deliver water at a temperature of at least 60 °C, and in the range of 50–55 °C at tap outlets after 1 min of flushing to prevent the growth of L bacteria [6,10,17–19]. However, due to thermal stratification, heating a water tank to 60 °C is not enough for complete disinfection of L in HWS [17,20]. Numerous studies have been conducted showing that, to achieve an effective thermal disinfection and to prevent L re-contamination, superheating and flushing is frequently required. Periodical superheating and flushing is done by heating the hot water storage tanks to 70–77 °C for one hour followed by flushing water through all the outlets, faucets and shower heads for 20–30 min [21,22].

Numerous investigations on the efficiency of conventional disinfection methods in HWS, such as chlorine and ozone, have shown that such alternative treatments except the thermal disinfection method significantly reduce but do not eliminate pathogens from free-living amoebae, protozoa and/or a biofilm [23–26]. This fact explains the occurrence of L re-colonization in HWS within a few days or weeks after disinfection [26–28]. However, using thermal disinfection methods for controlling L is challenged by three factors; energy, health and environment, and water hygiene. In other words, thermal disinfection method has the following impediments:

- Heating water to at least 60 °C induces the risk of exposure to a full-thickness third degree burn in 6 s or less especially for younger and elderly people [29,30].
- Heating water is usually associated with thermal stratification in hot water storage tanks driven by gravitational effect [31]. Some studies even intend to enhance stratification and have employed this phenomenon to improve the efficiency of hot water storage tanks [32–34]. In fact, even though water is heated to approximately 70 °C in the upper part of the storage

tank, thermal stratification may lead to water at temperature within the range of L survival at the bottom of the storage tank. Then once the water is pumped to meet the heat demand during the peak load, L will start to colonize the HWS.

- In the study of Martinelli et al. it is shown that the proportion of *Legionella pneumophila* (*L. pneumophila*) detected in hot water reservoirs was higher than that observed in hot water instantaneous devices [35]. Then instantaneous heating devices can minimize but not eliminate L contamination since the hot water will remix later with untreated cold water to avoid scalding.
- Heating water increase sanitary performance but simultaneously results in intensive energy consumption. One action to decrease energy consumption is to raise the water storage tank temperature to 60 °C by an electric heater only once every 10 days at an energy cost of approximately 180 kW h per annum [10].
- The rapid population growth cause an intense increase in water and energy demand which is unwelcoming the idea of continuous heating water to a temperature of at least 60 °C for disinfect L in HWS. The study of Zhou et al. described how the large population growth in China generates multiple accumulated problems in the water power sectors involving high energy consumption, high emissions, high cost, daily and seasonal severe supply shortages [36].
- Heating water requires burn coal fuels, natural gas or electricity, which is consequently increasing greenhouse gas emissions [37]. For instance, in 2005 it was estimated that water-related carbon emissions were approximately 290 million metric tons [38]. In Australia, up to 28% of the greenhouse gas emissions were from the operation of HWS in 1998 [39]. While in China, due to the serious pollution emissions and environmental problems caused by high-energy consumptions with low energy-efficiency, several policies and regulations to achieve energy conservation and emission reduction were established [36,40].
- The vigorous global trend toward renewable energy resources as well as promoting smart energy management and conservation has introduced low temperatures for heating and cooling of buildings [40–42]. This low heating temperature seems to offer an ideal habitat for potentially pathogenic bacteria such as L.
- Enhancing energy and environment conservation means applying procedures that can significantly increase the energy efficiency of the systems. For example, a reduction of 5.6 °C will decrease the energy consumption with 5% for electric and gas water heaters. A reduction of 11.2 °C cuts energy use with 10% and 9% for electric and gas water heaters, respectively. This reduction in heating temperature will result in an environment with enriched L multiplications [43].

To conclude, HWS operating at 50–60 °C may contain a reservoir of population of L micro-organisms, and if the temperatures fall by only a few degrees there could be a rapid growth rate of *L. pneumophila* in the system after a short time of the disinfection, leading to an increased risk of human infection [44]. Therefore, those who aim to reduce hot water temperature to save environment, energy cost and prevent scalding, need to be aware of the risks of water contaminations.

The current study presents the Anti Bacteria Heat Exchanger system (ABHE) as a new thermal treatment method that is inspired by nature. The ABHE system is a solution for all obstacles that usually challenge the wide use of conventional thermal treatment methods. The advantages of the proposed ABHE system over the traditional thermal treatment method can be summarized as following

- The ABHE system can safely achieve thermal treatment of water at different desired disinfection temperatures. Even if the disinfection temperature is chosen to be of 90 °C, there will be no hazard of scalding since the high temperature will be recovered by the cold-water stream supplied on the other side of a plate heat exchanger (PHE). The heat exchange will occur inside the ABHE system and the disinfected water will be supplied to the customers at temperature of use with no scalding threats.
- The ABHE system can successfully increase the water sanitary performance while recovering the waste heat through an efficient regeneration unit.
- There is no thermal stratification in the ABHE system since the water is not stagnant or accumulated in a storage tank. In ABHE system the thermal treatment occurs continuously and not periodically as in conventional thermal treatments.
- The heat recovery and energy saving which is inherent in ABHE systems enables a reduction of fuel and electricity consumption and consequently reduced fuel cost. The notable global population growth encourages technologies such as the ABHE system that can provide clean water, save energy, and reduce fuel consumptions.
- The ABHE system can efficiently reduce the greenhouse gas emissions because saving waste energy with the ABHE system means saving a considerable portion of the required fuel.
- Using an ABHE system will enable low water temperature for heating in HWS without the hazard of exposure to L. With the ABHE system, the water will be fully disinfected and re-cooled to the desired temperature in different HWS.
- In contrast to the instantaneous heating devices, which usually heat small portion of water, the ABHE system is designed to disinfect all the water consumed by the users and feed it directly at the temperature of use.
- The current design of the ABHE system use an electric heater in the disinfection unit, while future work will promote the use of renewable energy such as solar energy as an environmental friendly heating resource.
- Instead of reducing hot water temperature to save energy, the ABHE system can achieve L disinfection at temperature of 90 °C and at same time saving the energy by means of heat recovery in PHE.
- The possibility of using different heating sources will broaden the utilization of the ABHE system. The heat resource can simply be adjusted depending on the availability of fuel source that will reduce the cost especially in developing countries.
- The design of the ABHE is flexible and can be adjusted for different supplied and used water temperatures. The PHE enables temperature differences between supplied and used water temperature of ≈1 degree. For instance, the ABHE system can be used in residential HWS, swimming pools, hospitals hotels, etc.

In this work, mathematical and experimental analyses of the ABHE system are carried out. The main purpose of the proposed system is to reduce energy consumption by means of recovering the heat alongside the regeneration unit. In this way, part of the energy that is required to achieve thermal disinfection is recovered by the PHEs while the other part, depending on the desired disinfectant temperature, is consumed by an electric heater located in the disinfection chamber.

2. Working principle of the ABHE system

The current study introduce the ABHE system as a new technology (Patent SE.No. 0901111-5) [45] inspired by nature and imitates the thermo-regulation process of the counter-current heat exchange that exist in some animals adapted to living in cold regions. Every technology inspired from nature possesses a superior and perfect design. Thus, numerous examples of how engineers extract useful ideas from nature and then apply them to problems are well established [46–48]. Phil Gates expressed that the best inventions are copied from, or already in use by, other living things [49]. The very effective regenerative heat exchangers that exist in the blood vessel system of human beings, bird's legs such as herons, fish, and marine mammals play a vital role in minimizing heat loss and in conserving the body warm in cold climate [50,51]. For instance, while the core body temperature of a duck standing on ice is close to 37 °C, the bird's feet may be just above the freezing point 0 °C. This is because the arteries and veins are working in tandem to retain the heat, the warm arterial blood that flows to the feet warms up venous blood that is flowing back to the body.

2.1. Description of ABHE

The ABHE system imitates the heat recovery system in the blood vessel of animals. The disinfection process of the ABHE system involves heating the water to a specific temperature for a specific time. As described earlier, temperature plays the key role in controlling the existence and growth of L in HWS. Fig. 1(left), shows that L frequently colonize HWS at temperatures of 20–50 °C with an optimal range of 32–42 °C, while at 70 °C they are killed instantly. This explains the possibility of controlling L by carefully monitoring the temperature in all water system [28]. Fig. 1(right) shows the decimal disinfection time of L at different temperatures. Faster disinfection can be achieved at higher temperature while lower temperature requires longer time.

The heat recovery in the ABHE system is carried out by a very efficient PHE representing the regeneration unit while L thermal disinfection is done in the electric heater that represents the disinfection unit. The working mechanism of the ABHE system is illustrated in the schematic diagram displayed in Fig. 2. The supplied cold water at T_s is heated up by the hot water coming from the water heater $T_{h,o}$ which is consequently cooled down to reach the desired temperature of use, T_{use}. In the disinfection unit, a fraction of energy is added to elevate the water temperature from the inlet heater temperature $T_{h,i}$ to the desired disinfection temperature T_d. The recovery of waste heat is inherent in the ABHE system because of the PHE structure features. Indeed, the higher the heat transfer coefficient is in the PHE the lower is the temperature difference, i.e. T_s can approach T_{use} with possible difference of 1 °C [31].

2.2. Description of PHE

Conservation of thermal energy using heat exchangers is of vital importance in sustainable development [53]. The current study intensively concerns the performance of the PHE because it represents the regeneration unit where the waste heat can be recovered. Since the first operational PHE invention in 1923 until recently, PHEs are used extensively in the process of food pasteurization. The principal advantages of such units are flexibility of flow arrangements, extremely high heat transfer rates, and ease of cleaning and sterilization to meet healthy and sanitary requirements [54]. The success of the PHE is a consequence of its unique and competitive set of advantages over other kinds of traditional heat exchangers such as the significant reduction in installation space requirement and the extreme heat transfer rates. For instance, the brazed PHE consists of a pack of pressed stainless steel plates held together by brazing with copper under vacuum. This simple design results in a light, compact, and cost effective heat exchanger. These features boost is used for process water heating, heat recovery and district heating systems. Table 1, shows that PHEs are very competitive and can offer several advantages over the traditional shell and tube heat exchanger [55]. For example, the close approach temperature difference operation makes the system more energy efficient, and this economic incentive is further supplemented by the much smaller space needed for the PHEs as compared to shell and tube heat exchangers [55].

Furthermore, the thermal hydraulic performance of the PHE is strongly promoted by the corrugation patterns, which exist on the adjoining plates. These corrugations interrupt the flow passages, enhance convective heat transfer coefficient, increase the effective surface area for the heat transfer, cause disrupting boundary layers, promote swirl flow and decrease fouling characteristics. In addition to corrugation patterns, a chevron type configuration enhances the heat transfer characteristics of the fluid flow [56–59] as can be seen in Fig. 3.

3. Methodology

The main purpose of this study is to evaluate the performance of the ABHE system. To fulfill this purposes, a prototype of an ABHE system have been built. A number of 18 experimental runs were carried out for a water-water single-phase and counter-current flow arrangement in order to investigate the influence from supplied temperatures and flow rates on the thermal and hydraulic performance of the ABHE. In addition, the experimental data were used to validate an Engineering Equation Solver (EES) model that was built to simulate the performance of the ABHE system. The EES model was then used to mimic the ABHE system at different operation conditions. The structure of the EES model is illustrated in Fig. 4. This methodology allows a better understanding of the performance of the ABHE system under varying operation conditions. In addition, the EES model enables studies of additional operation setups without doing experiments. Thus, the EES model was used to calculate the pressure drop and required pumping power.

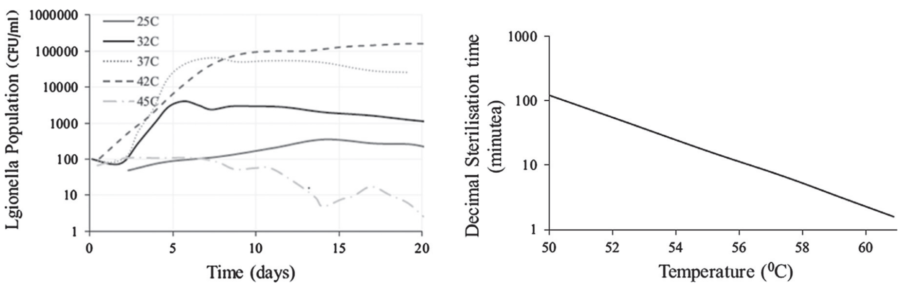


Fig. 1. L decimal disinfection time against temperature (right). Growth of L for various temperatures (left) [52].

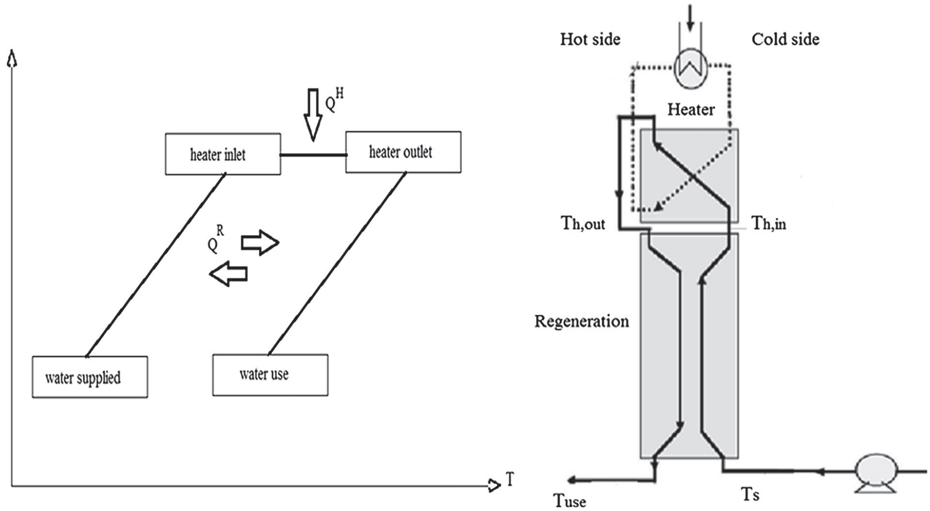


Fig. 2. Schematic diagram of the ABHE system used for L disinfection in HWS.

Table 1
Comparison of PHEs and shell and tube heat exchangers (from Plate Heat Exchanger: Design, Application and Performance, WIT Press, 2007, page 9) [55].

Specification	Gasket PHE	Shell and tube
Approach ΔT	~1 °C	~5 °C
Heat transfer ratio	~3–5	1
Maximum pressure	300 bar	60 bar
Temperature range	−25 to 600 °C	In excess of 650 °C
Fluid limitation	Subject only to material of construction	Subject only to material of construction. Not suitable for fouling duties.
Operating weight ratio	1	~3–10
Space ratio	1	~2–5
Multiple duty	Possible	Impossible
Welds	None	Welded
Leakage detection	Easy to detect	Difficult to detect
Disassembly time	~15 min	~60–90 min
Repair	Easy to replace plates and gaskets	Requires tube plugging = decreased capacity
Thermal size modification	Easily achieved by adding or removing plates	Difficult
Fouling ratio	~0.1–0.25	1
Normal size ranges for individual units	10 to 1000 m^2 (per shell, multiple shells can be used)	>1000 m^2
Thermal size	For the same effective heat transfer area, PHEs weight and volume are ~30% and 20% respectively less than Shell and tube due to high heat transfer coefficient in PHEs.	
Heat recovery	Up to 90% heat recovery in PHEs compared to 50% recovery for shell and tube heat exchanger	

4. Mathematical modeling of the ABHE system

To analyze the performance of the ABHE system, mathematical models were derived for both the regeneration unit and the disinfection unit. To do this the following assumptions have been made

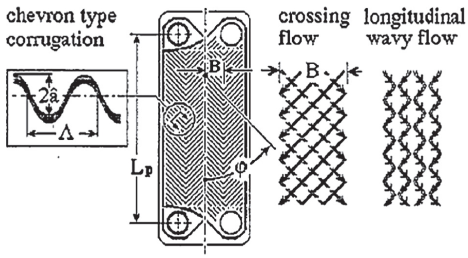


Fig. 3. Chevron-type heat exchanger plate, the angle φ and two flow patterns [62].

- Steady state operation.
- Heat loss to the surrounding is neglected.
- Uniform distribution of flow through the channels of pass.
- Fluids with Newtonian behavior.
- There is no phase change in any water streams.

4.1. Regeneration unit

The thermal model of water-water PHEs of a single pass and counter-current flow arrangement was calculated as described by Wang et al. [31]. The heat recovered from hot to cold water within the regeneration unit is given under the previous operation assumptions by the expression

$$Q^R = C_c \cdot (T_{h,i} - T_s) = C_h \cdot (T_{h,o} - T_{use}) \quad (1)$$

Since the mass flow is equal on both cold and hot water side, one finds

$$C_h = C_c = (\dot{m} \cdot C_p)_h = (\dot{m} \cdot C_p)_c \quad (2)$$

Then the heat capacity ratio C_r may be written as

$$C_r = \frac{C_{min}}{C_{max}} = \frac{C_c}{C_h} = \frac{C_h}{C_c} = 1 \quad (3)$$

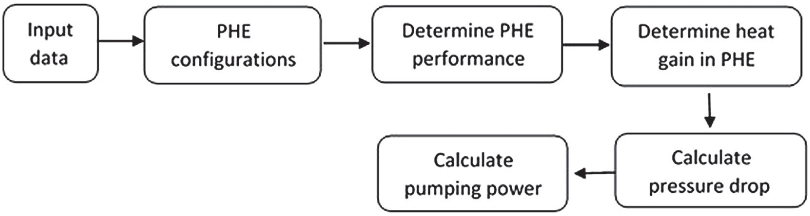


Fig. 4. Structure of the EES model designed to simulate the ABHE system.

The heat regeneration which is given in Eq. (1), can also be calculated by the following expression

$$Q^R = U \cdot A \cdot \Delta T_{LMTD} \cdot F \tag{4}$$

The total heat transfer coefficient U can be calculated depending on the temperature of the fluid, the flow pattern, the fouling factors, the thickness of the plate wall between the two streams and its thermal conductivity. The total heat transfer coefficient is then given by Eq. (5),

$$U = \frac{1}{\frac{1}{h_h} + \frac{\delta}{\lambda} + \frac{1}{h_c}} \tag{5}$$

The thermal properties in both the hot and the cold water streams are evaluated for the mean temperature as

$$T_{m,h} = \frac{T_{use} + T_{h,o}}{2} \quad \text{and} \quad T_{m,c} = \frac{T_s + T_{h,i}}{2} \tag{6a}$$

The plate wall temperature was considered as the average temperature of the cold and hot water streams on both sides as

$$T_w = \frac{T_s + T_{use} + T_{h,i} + T_{h,o}}{4} \tag{6b}$$

The Logarithmic mean temperature difference between the plate wall and water is defined as

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{7}$$

From energy conservation and in counter-current flow arrangement when $C_h = C_c$ one can see that $T_{h,i}–T_s = T_{h,o}–T_{use}$ and consequently $T_{h,o}–T_{h,i} = T_{use}–T_s$. Hence, by finding the limit of Eq. (7), when $\Delta T_1 = \Delta T_2$, the arithmetic mean temperature difference becomes [31]

$$\Delta T_{LMTD} = \Delta T_1 = \Delta T_2 = T_{h,o} - T_{h,i} = T_{use} - T_s \tag{8}$$

For the case of a single pass and counter-current flow arrangement the correction factor $F = 1$ [31].

The effective heat transfer area in PHEs can be obtained by multiplying the projected area of a single plate $A_p = w{\cdot}L$ by the total number of plates as follows

$$A = (N_p - 2) \cdot A_p \tag{9}$$

Two plates are subtracted from the total number of the plates because the first and the last plates have fluid only on one side so that they are not effective in transferring heat [38].

By using the Logarithmic mean temperature difference method, which is widely employed for design PHEs, the same heat flow given in Eq. (1), can be given by

$$\begin{aligned} U \cdot A \cdot \Delta T_{LMTD} \cdot F &= (N_P - 2) \cdot U \cdot A_p \cdot \Delta T_{LMTD} \cdot F \\ &= C_h(T_{h,o} - T_{use}) = C_c(T_{h,i} - T_s) \end{aligned} \tag{10}$$

To determine the required area of the PHE, the total heat transfer coefficients must be calculated. The dimensionless numbers *Re*, *Pr* and *Nu* for a single-phase flow in the counter-current flow arrangement of PHEs can be obtained from

$$Pr = \frac{C_p \cdot \mu}{k} \tag{11}$$

$$Re = \frac{\rho \cdot u \cdot D_h}{\mu} \tag{12}$$

$$Nu = \frac{h \cdot D_h}{k} \tag{13}$$

The flow velocity u in a single channel can be expressed as

$$u = \frac{G}{\rho} \tag{14a}$$

$$u = \frac{\dot{m}}{A_c \cdot n \cdot \rho} \tag{14b}$$

The number of channels n in the hot and the cold water streams in PHE can be given by

$$n_h = \frac{N_P - 2}{2} \tag{15a}$$

and

$$n_c = \frac{N_P}{2} \tag{15b}$$

The hydraulic diameter D_h is defined as [43]

$$D_h = \frac{4 \cdot A_c}{p} \tag{16a}$$

Here, P is the wetted perimeter. For a rectangular cross section, $P = 2a + 2w$, A_c is the flow cross area and defined as $A_c = a \cdot w$. Then the hydraulic diameter can be defined as

$$D_h = \frac{2 \cdot (a.w)}{(a + w)} \tag{16b}$$

If $a \ll w$, then the hydraulic diameter can be considered as $D_h \approx 2a$. In case the flow is laminar $R_e < 2000$, the factors ζ_0 and $\zeta_{1,0}$ are given by [35,56]

$$\zeta_0 = \frac{64}{R_e} \tag{17}$$

$$\zeta_{1,0} = \frac{597}{R_e} + 3.385 \tag{18}$$

While, if the flow is turbulent $R_e \geqslant 2000$, then the factors ζ_0 and $\zeta_{1,0}$ can be given by

$$\zeta_0 = \frac{1}{(1.8\ln(R_e) - 1.5)^2} \tag{19}$$

$$\zeta_{1.0} = \frac{39}{R_e^{0.289}} \quad (20)$$

The friction factor ζ is obtained from

$$\frac{1}{\sqrt{\zeta}} = \frac{\cos\varphi}{\left(0.18\cdot\tan\varphi + 0.36\cdot\sin\varphi + \frac{\zeta_0}{\cos\varphi}\right)^{0.5}} + \frac{1-\cos\varphi}{\sqrt{\zeta_1}} \quad (21)$$

Where the factor ζ_1 is given by

$$\zeta_1 = 3.8\cdot\zeta_{1,0} \quad (22)$$

The dimensionless Hagen number (Hg) has proven to be very useful and works for both natural and forced convection flow. Depending on the physical properties of water, Hg is defined by

$$Hg = \frac{\zeta\cdot R_e^2}{2} = \rho\left(\frac{\Delta P}{L}\right)\cdot\left(\frac{D_h^3}{\mu^2}\right) \quad (23a)$$

When $R_e \leqslant 2300$, Hg number reads simply as

$$H_g = 32R_e \quad (23b)$$

Then, Nusselt number is obtained as following

$$Nu = c_q P_r^{1/3}(\mu/\mu_w)^{1/6}[2Hg\cdot\sin(2\varphi)]^q \quad (24)$$

The arithmetic and geometric mean values of the constants c_q and q are 0.122 and 0.374 respectively [56].

4.1.1. Hydraulic modeling

The pressure drop is directly related to the size of the PHE. Higher pressure drop means that more energy is consumed by the water pump. Practically, there is an opposite interest during the process of PHE design. The process engineers prefer to keep the pressure drop as small as possible to reduce pumping cost, while heat exchanger designers aim to minimize heat transfer area which is often achieved by relative higher pressure drop. The total pressure drop can be calculated by [31]

$$\Delta P_t = \Delta P_f + \Delta P_g + \Delta P_a + \sum \Delta P_{Ni} \quad (25)$$

$$\Delta P_f = \frac{2\cdot f\cdot\rho\cdot u^2\cdot L}{D_h} = 2\cdot f\cdot\left(\frac{L}{D_h}\right)\cdot\left(\frac{G^2}{\rho}\right)$$

$$\sum \Delta P_{Ni} = 1.5\cdot\left(\frac{G^2}{2\rho}\right)\cdot N_{pass} \quad (26a)$$

$$\Delta P_g = \pm\rho\cdot g\cdot L$$

The total pressure drop ΔP_t is the sum of several fractions of pressure drop. Hence, ΔP_f is the frictional pressure drop, ΔP_g is the pressure drop due to the gravity and $\sum\Delta P_{Ni}$ is the sum of all other pressure losses due to inlet and outlet flow distribution. The pressure drop due to flow acceleration ΔP_a is usually negligible for single-phase flows [31]. The '+' sign is for vertical up flow and the '–' sign is for vertical down flow. The fanning friction factor value can be given by the empirical correlation depending on the plate surface corrugation pattern, Re, and the fluid properties. The fanning friction factor for chevron plates of 45° may be expressed as

$$f = \begin{cases} 0.3025 + \frac{91.75}{R_e} & 1800 > R_e > 150 \\ 1.46R_e^{-0.177} & 30,000 > R_e > 1800 \end{cases} \quad (26b)$$

Practically, to determine the number of plates needed depends on many parameters such as physical properties of fluids, flow channel velocity, channel geometry, allowable pressure drop, plate spacing, plate thickness, plate size and plate material. Fig. 5 shows that to obtain an appropriate number of plates at a specific heat duty, several iterations must be made before the final acceptable design is determined. The design of the EES model, described in Fig. 4, was based on the schematic diagram presented in Fig. 5. In the EES model, to obtain a proper number of plates in the PHE, the estimated value of the total heat transfer coefficient Q should equal the calculated value. The calculated value of the total pressure drop should, in its turn, be smaller than the maximum allowable pressure drop in the PHE.

4.1.2. Pumping power

Power must be supplied to the pump to drive the flow through the PHE at a certain flow rate. A reduction in pumping power results in less capital and operational costs [31]. The pumping power is proportional to the PHE pressure drop and can be defined by [1,43]

$$pp = \frac{V\Delta P}{\eta} = \frac{\dot{m}\Delta P}{\rho\eta} \quad (27)$$

The volumetric flow rate can be calculated from ($V = \dot{m}/\rho$). A smaller proportion of the pumping power to the recovery heat means a better performance of the ABHE system. If the ratio is insignificant, then the total PHE surface area will be the only design factor [60]. In addition, fouling can cause a noticeable increase in the pressure drop and consequently an increase in the required pumping power which causes an increase of the operation cost [31,61]. Fouling and corrugation on adjoining plates have an opposite effect on the PHE performance as shown in Fig. 6.

4.2. Disinfection unit

In the current work an electric heater is used in the disinfection unit to elevate water temperature to the desired disinfection temperature. The heat load is defined by the following

$$Q^H = \dot{m}(I_o - I_i) \quad (28)$$

That I_o and I_i are the enthalpy of the water at the outlet and inlet of the heater, respectively. In ABHE system the water flow rate is the same in both hot and cold water streams. The heat regeneration ratio RR indicates the energy saving in ABHE system and can be defined by

$$RR = \frac{Q^R}{Q^R - Q^H} \quad (29)$$

5. Experimental equipment description (setup)

A prototype of an ABHE has been built and designed to test the performance of the ABHE system under different operation condition. Fig. 7, shows the schematic of the experimental setup which mainly consists of two units. Firstly, the regeneration unit that is built from a pack of 30 compact plates made of 316 stainless steel with a 45° chevron pattern to promote turbulence. The PHE is of type IC8T × 30H/1P and typically used in single family houses connected to district heating. Secondly, the disinfection unit comprises a standard insulated cylinder boiler with an electric heater of capacity 3 kW. In this unit, intensive energy is added to elevate water temperature to the desired disinfection temperature $T_d = T_{h,o}$. The pipes used in the system are made from copper and has a diameter of 22 mm. Primarily one circulation water pump was added to the ABHE device to avoid fluctuations in the flow rates. However, the chosen water pump did not have the ability to control the flow rate and, therefore, the flow rate was controlled via a tap water feeder. So, the water pump effect is not a factor in the experimental setup. A water tank was supplied to the prototype to diminish the fluctuation of water flow rate throughout the experiment process. Flow rate measurements were carried

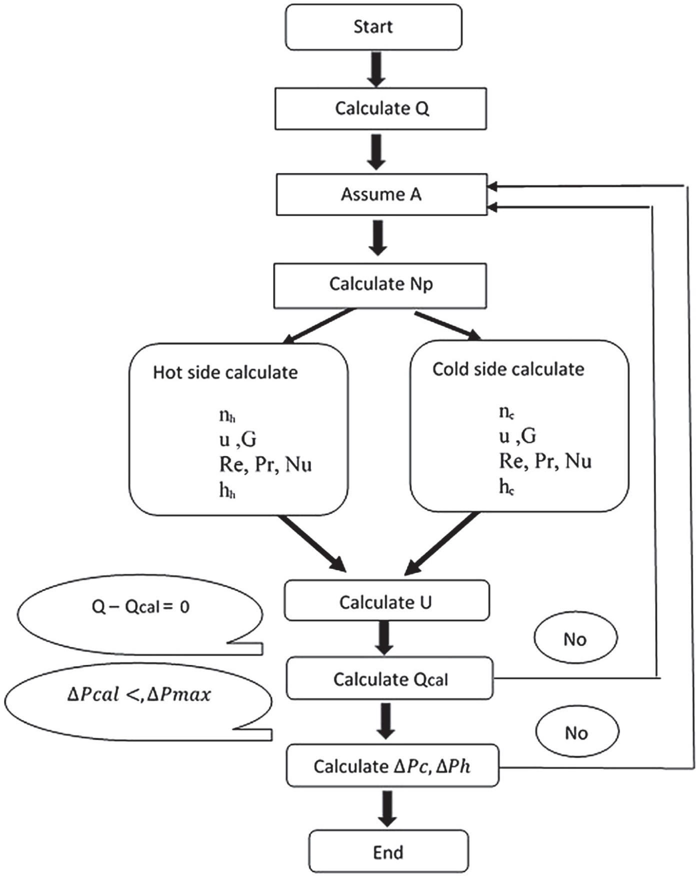


Fig. 5. Schematic diagram for obtaining the required number of plates in PHE.

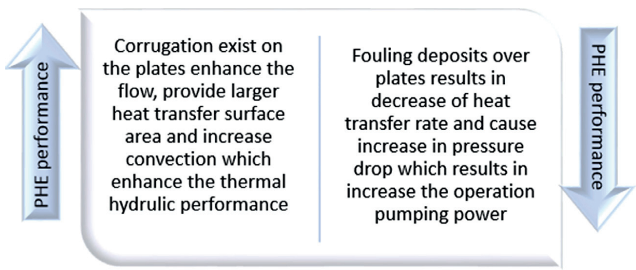


Fig. 6. Effects of fouling and corrugation on PHE performance.

out by measuring the weight of the water as a function of time. No pressure sensor was used. However, the pressure drops in the hot and cold side were estimated with the EES model. Four thermostats (temperature gauges) were logged internally and used to record water temperatures in 4 locations; supplied water T_s, water in use T_{use}, inlet heater $T_{h,i}$ and outlet heater $T_{h,o}$. The main purpose with the experiments is to evaluate the effect of different operation conditions on the heat recovery in the PHE and consequently the effectiveness of the ABHE system in both disinfecting L and saving energy compared to the conventional thermal treatment methods.

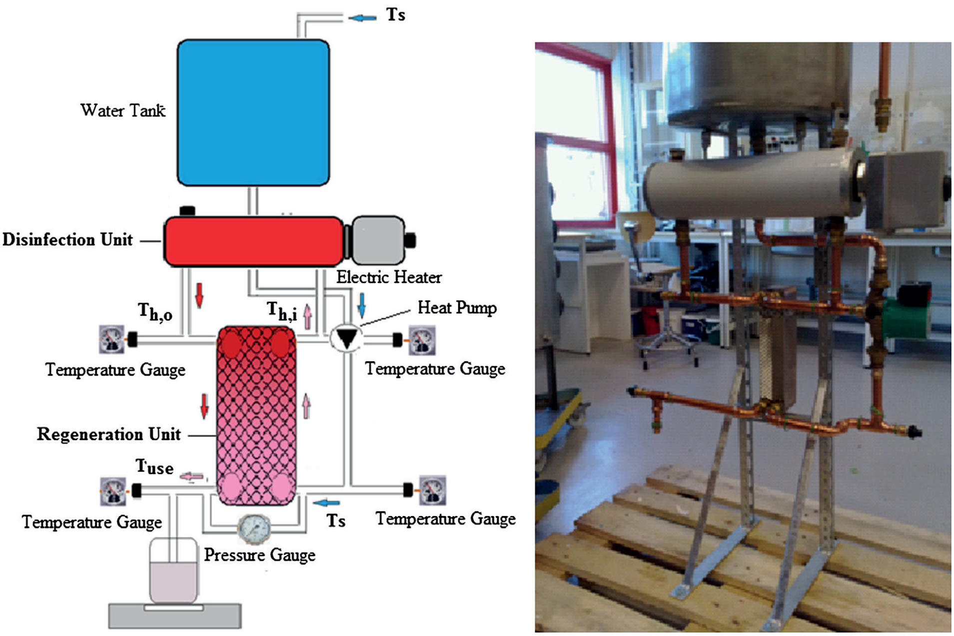


Fig. 7. Schematic of the ABHE system tested experimentally (left) by the prototype (right).

In the ABHE system, the heat is exchanged in PHE between the hot and cold water streams. Water in each side has specific thermal properties in term of temperatures, pressure drop, convection heat transfer coefficient, etc. In each run during the experimental test, the supplied water temperature and flow rate were listed when steady state conditions were reached.

The geometry parameters of the single pass PHE IC8T type, and the specification of the PHE used in the experiment are defined in Table 2. All data including the PHE dimensions, working operation specification and number of plates in both cold and hot sides was established from the technical documents taken from the manufacturer company of the PHE. Table 2, shows the flow arrangement on both hot and cold water streams where the hot side exchanges the heat with the cold side.

6. Experimental test

The performance of ABHE system was tested in the experiment by using three levels of flow rate at three different supplied water temperatures for a total of 18 runs. A single pass of water-water counter-current flow arrangement with total of 30 plates, 15 plates on the cold side and 14 plates on the hot side are carried out in the experiment. Water flow rate in range 3–12 kg/min was tested and the supplied water temperature was varied in range of 4–50 °C. A circulation water pump was added initially to the ABHE device but excluded later because it did not have the ability to control the flow rate. The flow rate was controlled via tap water feeder. Therefore, the water pump effect does not exist in the experimental analyses. The experimental results are taken after the flow rate and supplied temperature had reached steady state at different scenarios. By using the EES model, simulations of ABHE were achieved. EES model was used to determine the required pumping power. The model was also used to show the effect of flow rate on the pumping power for different supplied water temperatures.

7. Results and discussion

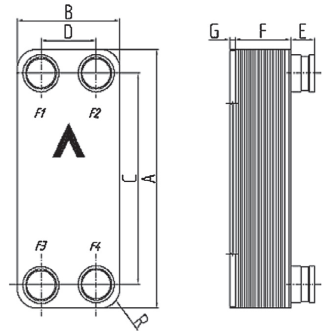
By using the ABHE prototype (see Fig. 7), the experiment was conducted for 18 runs at flow rates in the range of 3–12 kg/min and for supplied water temperatures in the range of 4–50 °C. The experimental results were used to validate the developed EES model. Results from the experiment and the EES model at the same initial operation parameters are listed in Table 3.

A comparison between the measured values of the inlet heater temperature $T_{h,i}$ and the calculated ones obtained by the EES model are displayed in Fig. 8. As shown, the experimental data is consistent with the results obtained by using the EES model. Consequently, the developed EES model can safely be used to simulate the ABHE for other working parameters or other setups that are not studied experimentally such as pressure drop and pumping power.

Analyses of the experimental data as well as the results obtained with the EES model show that parameters such as water flow rate and supplied water temperature affect the thermal performance of the ABHE. Fig. 9 shows the effect of the water flow rate on the total heat transfer coefficient of the PHE at different supplied water temperature. As shown in Fig. 9, the total heat transfer coefficient is strongly influenced by the flow rate. This is because the flow pattern in the PHE (e.g., laminar or turbulent flow) depends on the speed of the fluid which is increased by increasing the flow rate through the PHE. On the other hand, the total heat transfer coefficient of the PHE is slightly increased with increased supplied water temperature. This is due to the fact that increasing the water temperature results in changing the thermal properties

Table 2
Main characteristic dimensions, flow arrangement and specification of the water-water PHE IC8Tx30H/1P used in ABHE experimental test.

Characteristic	IC8T plate
Plate length (port-to-port), m	0.278
Plate width (available to flow), m	0.073
Plate thickness, m	0.0006
Mean channel spacing, m	0.0018
Port diameter, m	0.016
Total heat transfer area, m^2	0.644
Plate material	AISI 316
Thermal conductivity, W/m °C	0.667
Back thickness, m	0.0717
Number of passes	1



Specification		Measurements (mm)		Tolerance
Max working pressure	16 bar	A	315	± 2
Min/max temperature, °C	0/135	B	73	± 1
Max number of plates	40	C	278	± 1
Total number of plates	30	D	40	± 1
Number of plates in cold side	15	E	12.1	± 1
Number of plates in cold side	14	F	2 + 2.24 × (NP − 2)	± 0.005
Hold-up volume: inner circuit	(NP/2 − 1 1) × 0.039L	G	7	± 1
		R	16	

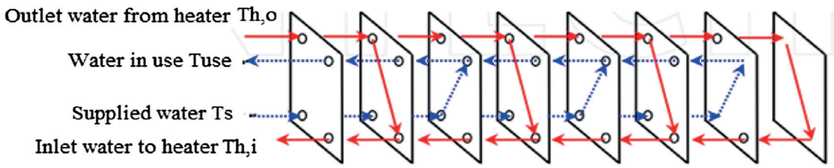


Table 3
Results of the experimental test and comparison the inlet heater temperature by the experimental test and the EES model. Pressure drop and pumping power by EES model.

Experimental test						EES calculations		
Run	Flow rate kg/min	Temperature, °C				$T_{h,i}$, °C	ΔP, kPa	*PP*, W
		Hot side		Cold side				
		Th,o	Tuse	T_s	$T_{h,i}$			
1	3.275	59.1	18.5	5.4	45.99	46.4	10.17	0.7724
2	3.25	59.2	18	5.4	46.59	47.2	10.17	0.7665
3	5.925	32.1	11.9	4.8	25	25	10.28	1.4076
4	5.9	32.1	11.8	4.8	25.1	25.1	10.28	1.4007
5	9.95	17.9	8.5	4.4	13.79	13.7	10.42	2.393
6	10.02	17.7	8.4	4.4	13.69	13.6	10.42	2.4096
7	3.7	72.6	38.8	27.5	61.3	62.2	10.1	0.8724
8	3.72	73.4	38.9	27.5	62	62.8	10.1	0.8771
9	5.475	55.2	36.3	30.2	49.1	49.4	10.16	1.2946
10	5.525	60.5	38.4	31.2	53.3	53.9	10.14	1.3063
11	12.07	43.1	34.2	30.3	39.2	39.5	10.32	2.8927
12	12.07	43.3	34.5	30.7	39.5	39.9	10.32	2.8927
13	7.125	78.3	59.5	53.6	72.41	73.4	10.05	1.6858
14	7.175	77.6	59.4	53.7	71.91	72.8	10.06	1.698
15	8.4	73.5	59.2	54.1	68.41	69.4	10.09	1.9917
16	8.4735	73.1	58.9	54	68.21	69	10.09	2.0096
17	11.52	68.4	58.9	55.2	64.7	65.2	10.16	2.7474
18	11.56	68.5	58.9	54.9	64.5	65.5	10.16	2.7571

of it and, consequently, enhances the heat transfer. However, the flow rates have a more significant effect on the total heat transfer coefficient than the supplied water temperature.

From the definition of the heat recovery, one can expect that the flow rate affects the total heat transfer coefficient and the heat recovery of ABHE in a similar manner. As shown in Fig. 10, increas-

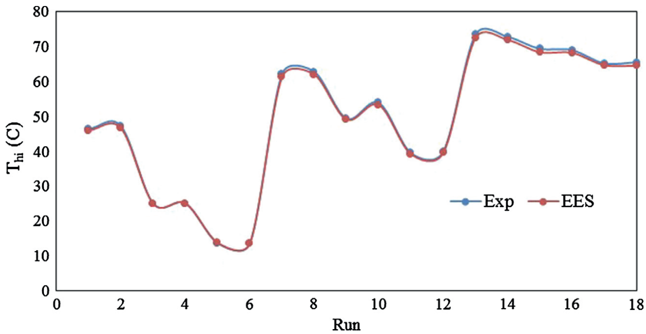


Fig. 8. Comparison between the inlet heater temperatures value as derived from experimental test and EES model.

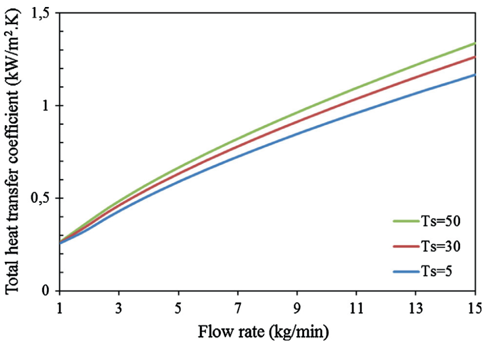


Fig. 9. Total heat transfer coefficient in PHE for different supplied water temperatures °C at different flow rates.

ing the flow rate results in increased the heat recovery. However, Figs. 9 and 10, show that supplied water temperature affects the total heat transfer coefficient and heat recovery in opposite way, i.e. higher supplied water temperature results in higher total heat transfer coefficient and lower heat recovery and vice versa.

The supplied water temperature affects the value of the ΔT_{LMTD}, which has a direct influence on the value of the heat recovery in the PHE. Fig. 11, shows that lower supplied water temperature leads to a higher value of ΔT_{LMTD} that decreases the total heat transfer coefficient and increases the heat recovery in the PHE. By the EES model and for a given disinfection temperature (i.e. $T_{h,o} = 80$ °C) at the PHE surface area given in Table 2, increasing the supplied water temperature leads to a reduce in ΔT_{LMTD}, value as illustrated in Fig. 11. In this way, the reduction in the heat recovery due to increasing supplied temperature in Fig. 10, can be justified.

As shown earlier, ABHE can achieve thermal disinfection of L and in same time reduce energy consumption by means of heat recovery in PHE. However, adding PHE to the system leads to an increase in pumping power due to the increased pressure drop. The next analysis, therefore, aims at finding the overall assessment of the PHE design. This can be fulfilled by comparing the benefit of adding the ABHE (in term of heat recovery) with disadvantage of using PHE (in term of pumping power). Fig. 12, shows the recovered heat Q^R versus the required pumping power at different supplied water temperatures. It is worth to mention that a proper design of the PHE results in a smaller required pumping power compared to the recovered heat. A small value of pumping power means a small pressure drop which lead to an efficient performance of the PHE. As shown in Fig. 12, it is obvious that the required pumping power is much smaller than the heat recovery

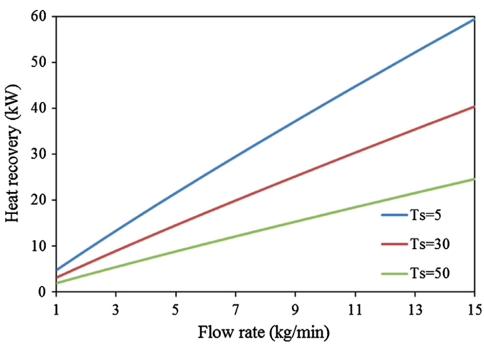


Fig. 10. Heat recovery in PHE for different supplied water temperature °C at different flow rates.

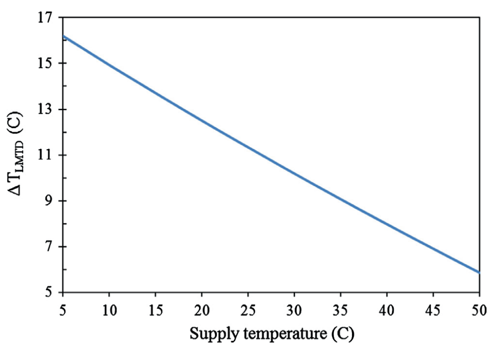


Fig. 11. ΔT_{LMTD} in PHE as a function of the supplied water temperature.

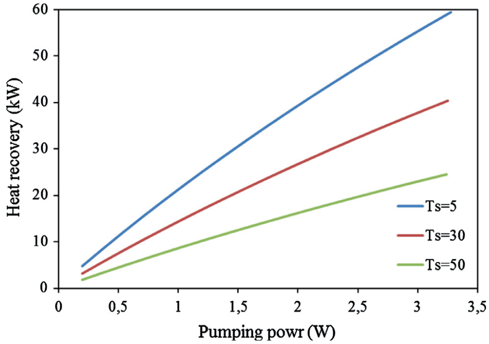


Fig. 12. Heat recovery versus the pumping power at different supplied water temperature °C.

and, thus, adding the ABHE system is of great advantage in term of energy saving.

The significant results of the current work can be summarized as following:

- Since the PHE has a fixed area and the heat transfer occurs within the same fluid (water-water), the temperature difference between the hot and cold sides is a function of the heat added by the electric heater. In this experiment, the heater is setup at constant power meaning that the water is heated less with increasing flow rates. Future studies may instead consider a fixed temperature, equal to the desired disinfection temperature, at the outlet of the heater. The PHE may then be designed for specific flow rates, supplied water temperatures and temperature in use.
- From the experimental study, flow rate and supplied water temperature appear to be the main factors that impetus the performance of the ABHE system.
- Higher flow rates enrich the turbulent flow which enhances the heat exchange and results in higher heat recovery and higher total heat transfer coefficient. However, increasing the flow rate also results in an increased pressure drop which consequently increases the consumed energy by the water pump to provide steady flow rates.
- Higher supplied water temperature enhances the total heat transfer coefficient, which results in reduced ΔT_{LMTD} value and consequently, reduces the benefit of ABHE in term of heat recovery.
- The optimal design of the PHE and consequently the ABHE system can be organized by means of adjusting the flow rates within the range that provide better performance of the PHE while avoiding unwelcoming increase in pressure drop.
- The maximum value of heat recovery is achieved at high flow rates and low supplied water temperatures.
- The supplied water temperature has no significant effect on the value of the total heat transfer coefficient.

8. Conclusion

ABHE is an energy efficient technology inspired by nature and used to achieve both L disinfection in HWS and energy savings by means of heat recovery. The ABHE system is mainly composed of a regeneration unit (PHE) and a disinfection unit (heater). The current study presents an experimental test to evaluate the performance of the ABHE and the effectiveness of the PHE in terms of heat recovery at different supplied water temperatures and different flow rates. An Engineering Equation Solver (EES) model was derived and validated to simulate the ABHE system at steady state conditions. The built model was then used to evaluate the performance of the ABHE system in terms of heat recovery, effectiveness, pressure drop and required pumping power at any given working parameters.

As result, the experimental tests and EES model show a high potential of recovering heat and hence saving energy. The effect of changing supplied water temperature on the total heat transfer coefficient and heat recovery was not significant. The flow rate has the greatest influence on the ABHE performance. The total heat transfer coefficient increases with increasing flow rates. In addition, the pumping power is relatively small compared to the recovered heat implying that less energy is required to overcome the pressure drop in the PHE as compared to the gain in heat transfer and consequently less operation costs.

Compared to other periodical thermal treatment methods, the ABHE can successfully achieve continuous disinfection of L in HWS and simultaneously save energy by recovering the waste heat alongside the PHE. The proportion of energy required in the disinfection unit can be supplied from different energy resources such as electric and solar energy.

The performed study shows great potential of utilizing the ABHE system in different applications. ABHE is an environmental friendly technology, safe, stable and offer enhanced energy conservation, reduced emissions, reduced costs as well as supplying clean water with high-quality. Future studies could concern utilizing different renewable energy resources as heat source in the disinfection unit and define the life-cycle energy requirements of different heating sources such as gas, electric, solar or a combination of them. Also, the application of the proposed ABHE system in a real HWS such as swimming pools, residential and commercial buildings would be of interest in future studies as well as using Computational Fluid Dynamic (CFD) models for exploring the ABHE performance at different initial operation conditions.

References

[1] T. Wang, W. Luan, W. Wang, S. Tu, Waste heat recovery through plate heat exchanger based thermoelectric generator system, Appl. Energy 136 (2014) 860–865.

[2] J. Bartram, K. Lewis, R. Lenton, A. Wright, Focusing on improved water and sanitation for health, Lancet (London, England) 365 (2005) 810–812.

[3] D.W. Fraser, D.C. Deubner, D.L. Hill, D.K. Gilliam, Nonpneumonic, short incubation-period legionellosis (Pontiac fever) in men who cleaned A steam-turbine condenser, Science 205 (1979) 690–691.

[4] J. Lacey, J. Dutkiewicz, Bioaerosols and occupational lung-disease, J. Aerosol Sci. 25 (1994) 1371–1404.

[5] A.H. Woo, A. Goetz, V.L. Yu, Transmission of *Legionella* by respiratory equipment and aerosol generating devices, Chest 102 (1992) 1586–1590.

[6] M.B. Synder, M. Siwicki, J. Wireman, D. Pohlod, M. Grimes, S. Bowmanriney, et al., Reduction in *Legionella-Pneumophila* through heat flushing followed by continuous supplemental chlorination of hospital hot water, J. Infect. Dis. 162 (1990) 127–132.

[7] K. Nygard, O. Werner-Johansen, S. Ronsen, D.A. Caugant, O. Simonsen, A. Kanestrom, et al., An outbreak of legionnaires disease caused by long-distance spread from an industrial air scrubber in Sarpsborg, Norway, Clin. Infect. Dis. 46 (2008) 61–69.

[8] M.E. Schoen, N.J. Ashbolt, An in-premise model for *Legionella* exposure during showering events, Water Res. 45 (2011) 5826–5836.

[9] D. Van der Kooij, H.R. Veenendaal, W.J. Scheffer, Biofilm formation and multiplication of *Legionella* in a model warm water system with pipes of copper, stainless steel and cross-linked polyethylene, Water Res. 39 (2005) 2789–2798.

[10] M. Lucas, P. Martínez, C.G. Cutillas, P.J. Martínez, J. Ruiz, A.S. Kaiser, et al., Experimental optimization of the thermal performance of a dry and adiabatic fluid cooler, Appl. Therm. Eng. 69 (2014) 1–10.

[11] M. Lucas, J. Ruiz, P.J. Martínez, A.S. Kaiser, A. Viedma, B. Zamora, Experimental study on the performance of a mechanical cooling tower fitted with different types of water distribution systems and drift eliminators, Appl. Therm. Eng. 50 (2013) 282–292.

[12] K. Rajkowski, Thermal inactivation of four human pathogens on catfish, 10, 2009, 1.

[13] P. Dennis, D. Green, B. Jones, A note on the temperature tolerance of *Legionella*, J. Appl. Bacteriol. 56 (1984) 349–350.
[14] M.A. Horwitz, S.C. Silverstein, Interaction of the legionnaires-disease bacterium (*Legionella-Pneumophila*) with human phagocytes. 2. Antibody promotes binding of *L-Pneumophila* to monocytes but does not inhibit intracellular multiplication, J. Exp. Med. 153 (1981) 398–406.
[15] B.H. Keswick, C.P. Gerba, S.M. Goyal, Occurrence of enteroviruses in community swimming pools, Am. J. Public Health 71 (1981) 1026–1030.
[16] M. Lacroix, Electric water heater designs for load shifting and control of bacterial contamination, Energy Convers. Manage. 40 (1999) 1313–1340.
[17] I. Campbell, A.S. Tzipori, G. Hutchison, K.W. Angus, Effect of disinfectants on survival of cryptosporidium oocysts, Vet. Rec. 111 (1982) 414–415.
[18] G. Sanden, B. Fields, J. Barbaree, J. Feeley, Viability of *Legionella pneumophila* in choline-free water at elevated temperatures, Curr. Microbiol. 18 (1989) 61–65.
[19] P. Charles, E. Jame, T. Jeanetle, Evaluation of Microbial Removal/Inactivation by the Innowave 240 r, 1997
[20] C. Zwiener, S.D. Richardson, D.M. De Marini, T. Grummt, T. Glauner, F.H. Frimmel, Drowning in disinfection byproducts? Assessing swimming pool water, Environ. Sci. Technol. 41 (2007) 363–372.
[21] B. Kim, J. Anderson, S. Mueller, W. Gaines, A. Kendall, Literature review—efficacy of various disinfectants against *Legionella* in water systems, Water Res. 36 (2002) 4433–4444.
[22] K. Furuhata, T. Takayanagi, N. Danno, S. Okada, F. Kiya, Contamination of hot water supply in office buildings by *Legionella pneumophila* and some countermeasures, [Nihon koshu eisei zasshi], Japanese J. Publ. Heal. 41 (1994) 1073–1083.
[23] J. Kusnetsov, E. Iivanainen, N. Elomaa, O. Zacheus, P.J. Martikainen, Copper and silver ions more effective against legionellae than against mycobacteria in a hospital warm water system, Water Res. 35 (2001) 4217–4225.
[24] E.F.P. Callizo, J.D. Sierra, J.M.S. Pombo, C.E. Baquedano, B.P. Huerta, Evaluation of the effectiveness of the Pastormaster method for disinfection of legionella in a hospital water distribution system, J. Hosp. Infect. 60 (2005) 150–158.
[25] R. Heller, C. Holler, R. Sussmuth, K.O. Gundermann, Effect of salt concentration and temperature on survival of *Legionella pneumophila*, Lett. Appl. Microbiol. 26 (1998) 64–68.
[26] P. Muraca, J.E. Stout, V.L. Yu, Comparative-assessment of chlorine, heat, ozone, and UV-light for killing *Legionella-Pneumophila* within a model plumbing system, Appl. Environ. Microbiol. 53 (1987) 447–453.
[27] M. Steinert, G. Ockert, C. Luck, J. Hacker, Regrowth of *Legionella pneumophila* in a heat-disinfected plumbing system, Zentralblatt Fur Bakteriologie-International J. Med. Microbiol. Virol. Parasitol. Infect. Diseases 288 (1998) 331–342.
[28] S. Saby, A. Vidal, H. Suty, Resistance of *Legionella* to disinfection in hot water distribution systems, Water Sci. Technol. 52 (2005) 15–28.
[29] S. Park, S. Kim, I. Ju, J. Cho, S. Ha, Thermal inactivation of murine norovirus-1 in suspension and in dried mussels (*Mytilus edulis*), J. Food Saf. 34 (2014) 193–198.
[30] G. Maheshwari, R. Jannat, L. McCormick, D. Hsu, Thermal inactivation of adenovirus type 5, J. Virol. Methods 118 (2004) 141–146.
[31] B. Sundén, R.M. Manglik, Plate Heat Exchangers: Design, Applications and Performance, Wit Press, 2007.
[32] H. Mehling, L.F. Cabeza, S. Hippeli, S. Hiebler, PCM-module to improve hot water heat stores with stratification, Renewable Energy 28 (2003) 699–711.
[33] M. Mazman, L.F. Cabeza, H. Mehling, M. Nogues, H. Evliya, H.Ö. Paksoy, Utilization of phase change materials in solar domestic hot water systems, Renewable Energy 34 (2009) 1639–1643.
[34] L.F. Cabeza, M. Ibáñez, C. Sole, J. Roca, M. Nogués, Experimentation with a water tank including a PCM module, Sol. Energy Mater. Sol. Cells 90 (2006) 1273–1282.
[35] F. Martinelli, A. Caruso, L. Moschini, A. Turano, C. Scarcella, F. Speziani, A comparison of *Legionella pneumophila* occurrence in hot water tanks and instantaneous devices in domestic, nosocomial, and community environments, Curr. Microbiol. 41 (2000) 374–376.
[36] K. Zhou, S. Yang, Demand side management in China: the context of China's power industry reform, Renew. Sustain. Energy Rev. 47 (2015) 954–965.
[37] H. Martin, Drop and Heat Transfer in Plate Heat Exchangers, VDI Heat Atlas, Springer, 2010, pp. 1515–1522.
[38] J. Lines, Asymmetric plate heat-exchangers, Chem. Eng. Prog. 83 (1987) 27–30.
[39] R.H. Crawford, G.J. Treloar, Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia, Sol. Energy 76 (2004) 159–163.
[40] K. Zhou, S. Yang, C. Shen, S. Ding, C. Sun, Energy conservation and emission reduction of China's electric power industry, Renew. Sustain. Energy Rev. 45 (2015) 10–19.
[41] M. Kharseh, L. Altorkmany, How global warming and building envelope will change buildings energy use in central Europe, Appl. Energy 97 (2012) 999–1004.
[42] K. Zhou, C. Fu, S. Yang, Big data driven smart energy management: from big data to big insights, Renew. Sustain. Energy Rev. 56 (2016) 215–225.
[43] T. Bergman, A. Lavine, F. Incropera, Fundamental of Heat and Mass Transfer, 2007.
[44] J. Rogers, A.B. Dowsett, P.J. Dennis, J.V. Lee, C.W. Keevil, Influence Of temperature and plumbing material selection on biofilm formation and growth of *Legionella-Pneumophila* in a model potable water-system containing complex microbial-flora, Appl. Environ. Microbiol. 60 (1994) 1585–1592.
[45] B. Nordell, L. Altorkmany, Vätskedesinficerare omfattande en värmeväxlare (Disinfect fluid including a heat exchanger Disinfect fluid including a heat exchanger), SE 0901111-5, 2011.
[46] Y. Bar-Cohen, Biomimetics: Nature-Based Innovation, CRC Press, 2011.
[47] G. John, D. Clements-Croome, G. Jeronimidis, Sustainable building solutions: a review of lessons from the natural world, Build. Environ. 40 (2005) 319–328.
[48] K. Hargroves, M. Smith, Innovation inspired by nature: biomimicry, Ecos 2006 (2006) 27–29.
[49] P. Gates, Wild Technology: Inventions Inspired by Nature, Kingfisher, 1999.
[50] N.K. Schmidt, D. Jackson, Countercurrent heat exchange in the respiratory passages, Science 144 (1964) 567.
[51] A.P. Fraas, Heat Exchanger Design, John Wiley and Sons Inc., 1989.
[52] P.M. Armstrong, M. Uapipatanakul, I. Thompson, D. Ager, M. McCulloch, Thermal and sanitary performance of domestic hot water cylinders: conflicting requirements, Appl. Energy 131 (2014) 171–179.
[53] A. Dufour, O. Evans, T. Behymer, R. Cantu, Water ingestion during swimming activities in a pool: a pilot study, J. Water Health 4 (2006) 425–430.
[54] P. Teunis, I. Ogden, N. Strachan, Hierarchical dose response of *E. coli* O157: H7 from human outbreaks incorporating heterogeneity in exposure, Epidemiol. Infect. 136 (2008) 761–770.
[55] L. Causer, T. Handzel, P. Welch, M. Carr, D. Culp, R. Lucht, et al., An outbreak of Cryptosporidium hominis infection at an Illinois recreational waterpark, Epidemiol. Infect. 134 (2006) 147–156.
[56] H. Martin, A theoretical approach to predict the performance of chevron-type plate heat exchangers, Chem. Eng. Process. 35 (1996) 301–310.
[57] A. Muley, R. Manglik, H. Metwally, Enhanced heat transfer characteristics of viscous liquid flows in a chevron plate heat exchanger, J. Heat Transfer 121 (1999) 1011–1017.
[58] R.M. Manglik, Plate heat exchangers for process industry applications: enhanced thermal-hydraulic characteristics of chevron plates, Proc. Enhan. Multiph. Heat Transfer. (1996) 267–276.
[59] A. Durmuş, H. Benli, İ. Kurtbaş, H. Gül, Investigation of heat transfer and pressure drop in plate heat exchangers having different surface profiles, Int. J. Heat Mass Transf. 52 (2009) 1451–1457.
[60] X. Liu, J. Niu, An optimal design analysis method for heat recovery devices in building applications, Appl. Energy 129 (2014) 364–372.
[61] G.F. Hewitt, S.J. Pugh, Approximate design and costing methods for heat exchangers, Heat Transfer Eng. 28 (2007) 76–86.
[62] K. Gunkel, H.J. Jessen, The problem of urea in bathing water, Zeitschrift Gesamte Hygiene und ihre Grenzgebiete 34 (1988) 248–250.

Paper C

Effect of Working Parameters of the Plate Heat Exchanger on the Thermal Performance of the Anti-Bact Heat Exchanger System to Disinfect Legionella in Hot Water Systems

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Effect of Working Parameters of the Plate Heat Exchanger on the Thermal Performance of the Anti-Bact Heat Exchanger System to Disinfect Legionella in Hot Water Systems

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Abstract

The objective of the current study is to analyze the effect of different working parameters on the thermal performance of the Anti-Bact Heat Exchanger system (ABHE). The ABHE system is inspired by nature and implemented to achieve continuous disinfection of Legionella in different human-made water systems at any desired disinfection temperature. In the ABHE system, most of the energy is recovered using an efficient plate heat exchanger (PHE). A model by Engineering Equation Solver (EES) is set-up to figure out the effect of different working parameters on the thermal performance of the ABHE system. The study shows that higher supplied water temperature can enhance the regeneration ratio (RR), but it requires a large PHE area and pumping power (PP) which consequently increase the cost of the ABHE system. However, raising the temperature in use results in a reduced PHE area and PP, which accordingly reduce the cost of the ABHE system. On the other hand, the EES model is used to study the effect of the length and the width of the plates used in the PHE on the RR and the required area of the PHE. Finally, taking into account the geometrical parameters, flow arrangement and the initial operating conditions of the PHE, the EES model is used to optimize the PHE in which its area is minimized, and the RR of the ABHE system is maximized.

Keywords: Legionella; thermal disinfection; simulation; thermal performance; plate heat exchanger

Nomenclature

A	effective area, m^2
Ac	cross area of a channel, m^2
Ap	projected area of a single plate, m^2
B	back thickness of PHE, mm
C	heat capacity rate, W/K
C_p	specific heat capacity, J/kg.^{o}C
c_q	constant for Nu equation
Cr	heat capacity ratio
D_h	hydraulic diameter, m
F	correction factor
f	fanning friction factor
G	mass flux, kg/m^2.sec
h	convection coefficient, W/m^2.^{o}C
I	enthalpy, kJ/kg.K
k	thermal conductivity of water, W/m^2.^{o}C
L	length of the plate (port to port), m
m	mass flow rate, kg/sec
n	number of channels
N_p	total number of plates
N_{pass}	number of passes
q	constant for Nu equation
Q^H	heat load in heater, kW
Q^R	heat recovered, (regeneration), kW
T	temperature, ^{o}C
u	flow channel velocity, m/sec
U	total heat transfer coefficient, W/m^2.^{o}C
V	volumetric flow rate, m^3/sec
W	width of the plate, m
p	the wetted perimeter, m
pp	pumping power, W
ΔT_{LMTD}	logarithmic mean temperature
ΔP	pressure drop, kPa
ΔT_1	temperature difference at one end, ^{o}C
ΔT_2	temperature difference another end, ^{o}C
$\sum\Delta P_{Ni}$	distribution pressure drop, kPa

Greek symbols

α	channel spacing, gap, m
δ	Plate thickness, m
ζ_0 ζ $\zeta_{1,0}$	friction factors
η	pump efficiency
λ	thermal conductivity of a the plate, W/m.^{o}C
μ	dynamic viscosity of the fluid, kg/m.sec
μ_w	dynamic viscosity at wall temperature, kg/m.sec
ρ	fluid density, kg/m^3
φ	plate inclination angle, rad

Subscripts

c	cold water stream
g	gravity
h	hot water stream
$h_{,i}$	temperature of the inlet heater
$h_{,o}$	temperature of the outlet heater
m	mean temperature
max	maximum
min	minimum
s	supplied water temperature
t	total
use	temperature of water in use
w	wall
α	acceleration

Dimensionless numbers

H_g	Hagen number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Acronyms

ABHE	anti bact heat exchanger
EES	engineering equation solver
HWS	hot water systems
L	Legionella
L. *pneumophila*	Legionella pneumophila
LD	Legionnaires' disease
NTU	number of heat transfer unit
PHE	plate heat exchanger
RR	regeneration ratio

1. Introduction

Providing clean water, saving energy and environment is universal challenges affecting people throughout the world. Problems of water scarcity, waterborne disease, energy source shortage and environmental pollution are expected to become worse in the coming decades. Approximately 3.1% of annual deaths and 3.7% of the annual health burden worldwide are attributed to unsafe water, sanitation and hygiene [1]. During the last decades, waterborne pathogens had a devastating effect on public health due to emerging new infectious agents that drive efforts to decontaminate waters previously considered clean [2]. Legionella (L) is an important waterborne bacterium that poses a significant health risk to people exposed to the organism in aerosolized water droplets from contaminated water systems [3]. The discovery of Legionnaires' disease (LD), deadly pneumonia [4-6], has proven that all aquatic environments can be contaminated by this ubiquitous Gram-negative rod. The study by Rogers et al. (1994) showed that up to 85% of the warm water systems might contain this pathogen [7].

Various disinfection methods against L involving ozone, chlorine, copper-silver ionization, thermal and UV systems were established and tested in terms of corrosion, cost, safety, and utility [8-10]. Except for thermal disinfection, Thomas et al. (2004) observed a rapid re-colonization by L after stopping all types of treatment methods. L recovered to the initial concentration in the water and the biofilm within 4-5 days [11]. While Protozoa plays the significant role in the transmission of this bacterium, the *Acanthamoeba* cysts together with the biofilm can protect it for long periods from the action of the disinfectants [12]. This embedded community explains the limitation of the conventional disinfection methods and the occurrence of re-colonization in water systems within days or weeks. Therefore, disinfecting water has become increasingly more challenging especially for long-term control.

Only thermal disinfection has been proven to destroy L present in protozoa and biofilms efficiently, and simultaneously destroys several cell components. Steinert et al. (1998) study concluded that the regrowth of L was observed within two months after the first thermal decontamination [12]. The regrowth of L was due to the sporadic use of the thermal disinfection method because of the intensive energy requirement and the high cost. Addressing these problems motivates researchers to improve the existing water disinfection methods and inventing robust new ones. A robust disinfection method should have unique features in terms of providing long-term disinfected water, minimizing the use of chemicals in the purified water, using less energy, lower cost as well as saving the environment by reducing greenhouse gas emissions.

A previous study has introduced the Anti-Bact Heat Exchanger (ABHE) system as a unique system has robust features in terms of providing continuously thermally treated water accompanied with saving energy by recovering the waste heat. In recent decades, multiple studies have been focusing on waste heat recovery in building for conserving energy in different topics, like Polly et al. (2010) [13], Mokhtar et al. (2017) [14], Bertrand (2017) [15], Wang et al. (2014) [16] and Wong et al (2010) [17]. The earlier study tested the prototype of the ABHE system experimentally to verify the performance of the ABHE system at different supplied water temperature (Ts) and flow rates [18].

Optimization of the PHE was a subject of multiple studies like Hadidi (2015) [19], Zhou et al. (2014) [20], Xie et al. (2008) [21]. Gut et al. (2004) [22] and Wang et al. (2003) [23]. The current study, therefore, investigates the effect of different initial working parameters on the thermal performance of the ABHE system, to define the optimal design of the plate heat exchanger (PHE) that maximize the thermal performance of the ABHE system and minimize the required area of the PHE and accordingly lowering the cost.

2. Conventional Thermal Treatment Method and ABHE System

Successful strategies to control L should certainly take into account all factors that potentially influence L growth and persistence such as temperature, water stagnation, the influence of biofilm, the existence of sediment and nutrients. Temperature has the key role and is the most important environmental factors that control L activities and evolution [24-28]. L colonize water systems at temperatures of 20-50°C, with an optimal growth range of 32–42 ºC, while at 70 ºC they are killed virtually instantly [24,29].Samples taken by Martinelli et al. (2000) showed that hot water systems in homes, hospitals and public baths with hot water tanks ≤ 50 ºC or instantaneous devices < 60 ºC were five times more likely to contain Legionella *pneumophila* [30]. The risk of LD outbreak in different human-made water systems at their ideal working temperatures is illustrated in Fig. 1. Boiling water is the oldest and the most convenient thermal treatment method used to obtain water free of biological contaminants [31,32].Boiling water can kill or deactivate all classes of waterborne pathogens, including those who have shown resistance to chemical disinfection and viruses that are too small to be mechanically removed by microfiltration [33]. However, the intensive increase in water and energy demand due to the rapid population growth un welcomes the idea of continuous heating of water to 70 ºC for complete disinfect of L in hot water systems. Therefore, to avoid the risk of L contamination in conventional systems the water should be heated to at least 60ºC at the top of the hot water storage tank. Superheat and flush is achieved periodical by heating water tank to 70-77ºC and sustain it for one hour, then flush all the outlets and faucets for 20-30 minutes [34]. The short duration of superheat and flush for 5 minutes failed to eliminate L and recontamination occur after ten days [35]. It is worth mention that, tap water scalds are life-threatening injuries; the mortality rates reported in adults are of 15-46% and in children between 8 and 12.5% [36].

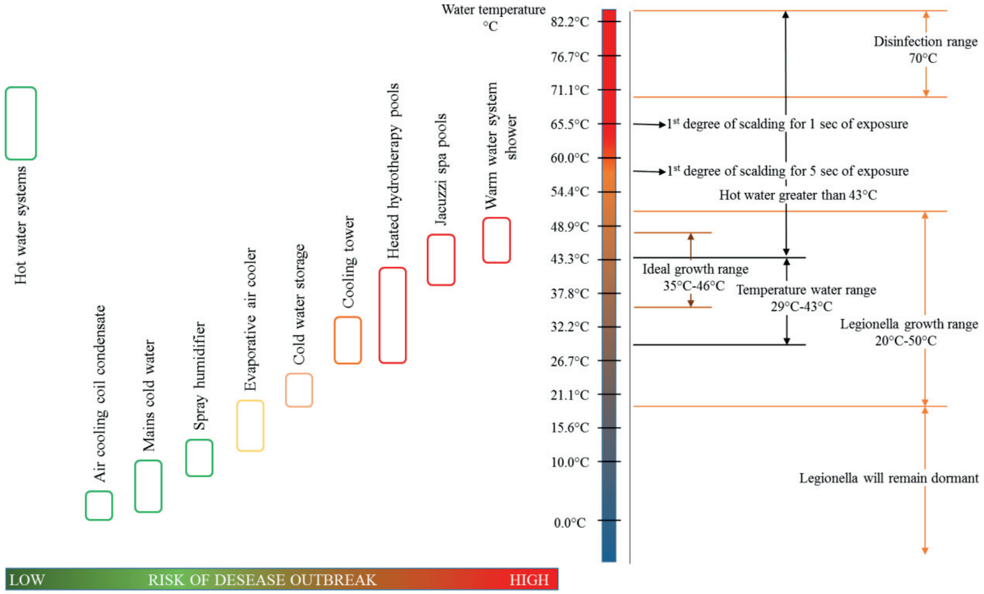

Fig 1. Water temperature and risk of Legionella outbreak in different water systems (left)[1]. Legionella growth, thermal disinfection of Legionella and risk of scalding at hot temperatures (right)

Scalds caused by hot tap water account for between 2500 and 4500 hospital admissions each year in the US with an average of 57 deaths per year [37]. The study of Tse et al. (2006) found that the usual temperature of home water heaters at 60°C can severely burn a young child's skin in less than 5 seconds [38]. The time is cut approximately in half for each rise in temperature of 1°C

[1] Modified from CIBSE TM 13:2002. Minimizing the risk of Legionnaires' disease.

[37] as Fig. 1 shows. Legislations to prevent hot water scalding were adapted by lowering the tap water temperature in homes from 60 ºC to around 49-50 ºC [37-41]. A possible solution is to install a thermostatic mixing valve or tempering valve, so the hot tap water can be adjusted in the range of 32-45^{o}C to fit different daily activities [37,42]. It is worth mention that, the cold water which is used to maintain hot water temperature in the mixing valve may contain dormant L and once it mixed with the hot water, the resulted water will be temperate and in the range that enhances L proliferation.

Most disinfection methods used to control L in water systems are insufficient for long-term disinfection. Nowadays, engineers extract useful ideas from nature and then apply them to solve problems [43]. Phil Gates has expressed that best inventions are copied from, or already in use by, other living things [44]. The new system called ABHE was developed to disinfect L in a sustainable, environmentally friendly and energy efficient manner [45]. The ABHE system is inspired by nature and imitates the very efficient regenerative heat exchangers that exist in the blood vessel system of animals [46,47]. For example, the unique heat exchanger in the legs and feet of waterfowl plays a vital role in minimizing heat loss and in conserving the body warm during cold climates as shown in Fig. 2. So while the core body temperature of a duck standing on ice is near 37^{o}C the bird's feet may be just above the freezing point [47]. The ABHE system consists mainly of a PHE which represents the regeneration unit, connected to the disinfection unit where any source of heat can be used (electrical heater, gas heater or any other heat sources), see Fig 2. Through the PHE the waste heat is recovered and efficiently used to heat up the supplied cold water. The material of the plates is commonly stainless steel because of its excellent properties such as strength, easy to clean, ability to withstand high temperatures, and for its high-temperature corrosion resistance [48]. A fraction of energy is added to the disinfection unit to increase the water temperature to the desired disinfection temperature (T_d). The PHE can be designed to recover heat from the treated water and make it leave the PHE at a temperature close to the initial temperature, i.e., the temperature in use (T_{use}≈Ts). PHE is one of the most efficient types of heat transfer equipment. The success of the PHE is a consequence of its unique set of advantages over other kinds of heat exchangers such as the extreme heat transfer rates, the ease of cleaning to meet health requirement, the great flexibility in altering the PHE thermal size by simply adding or removing some plates and the fouling tends to be significantly less.

The heat recovery, i.e., the difference between T_{use} and T_s, strongly relies on the size of the selected PHE. The larger PHE results in a smaller temperature difference. However, increase PHE size results in increasing the cost of the ABHE system. Therefore, there is an optimal design of the PHE that enable maximizes the performance of the ABHE device and simultaneously minimize the required area of the PHE.

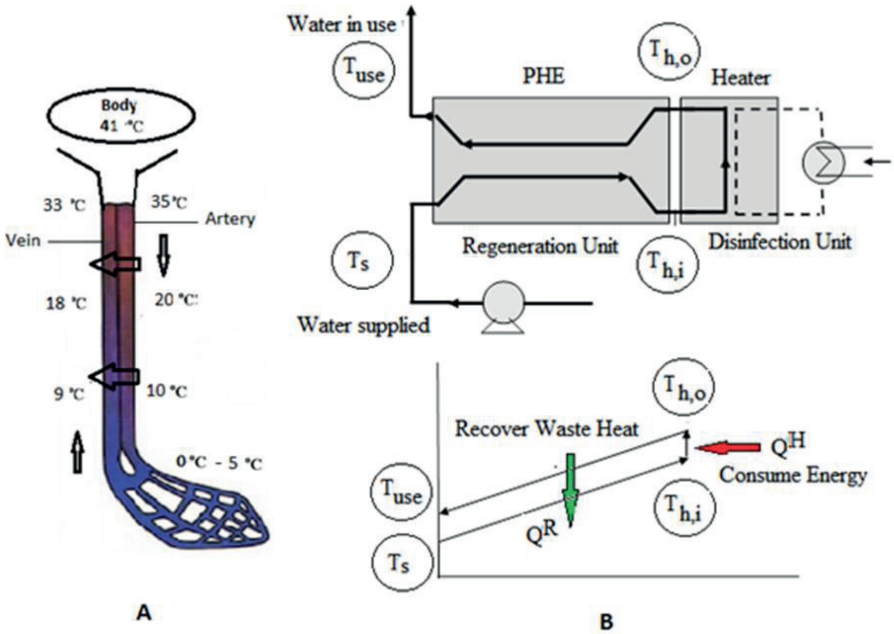

Fig 2. Schematic diagram of (A) countercurrent heat exchanger presents in Canada goose and (B) the ABHE system used for L disinfection in hot water systems

3. Methodology

The study investigates the effect of different working parameters, including the flow rate, the supplied water temperature, the water temperature in use, the disinfection temperature, and the dimensions of the PHE on the thermal performance of the ABHE systems. For this purpose, an Engineering Equation Solver (EES) model, which was validated in a previous work conducted by the authors [18] is developed further in the current work to determine the optimal design of the PHE. Fig **3** shows the structure of the EES-based model. The methodology used to design the optimum water- water single-phase PHE by the EES-based model was illustrated previously [18].

The optimal design of the PHE is the one that results in maximum performance of the ABHE. For any given operation parameters, mentioned above, the model is used to define the required PHE area, the pressure drop, the power of pumping needed, the required capacity of the electric heater, and the benefit of using the ABHE system. Conjugate directions optimization method [49] was used, which is a conventional method to solve unconstrained energy optimization problems, with the conversion tolerance of $1 \cdot 10^{-4}$, to define the optimal design of the PHE. This way the energy performance of the ABHE is maximized.

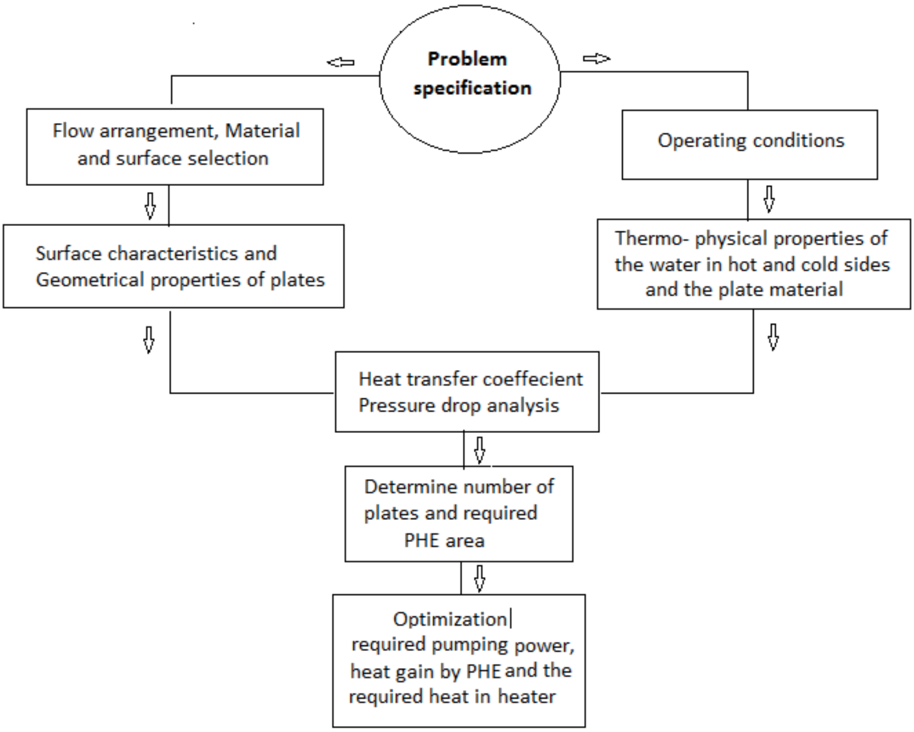

Fig 3. Structure of the EES-based model used to simulate the ABHE system

4. Physical Modeling of the ABHE System

The thermal modeling of the ABHE system with both the regeneration unit and the disinfection unit was performed in a prior study [18] by applying the following assumptions:

- Steady-state conditions.
- Heat loss to the surrounding is neglected.
- Uniform distribution along the flow channel.

- Incompressible and Newtonian fluids.
- There is no phase change in any water streams.

4.1 The Regeneration Unit

The thermal model of a water-water PHE of a single-phase and countercurrent flow arrangement was achieved to determine the overall heat transfer coefficient U, the required number of plates Np and the total area of the PHE.

The following expression gives the waste heat recovery:

$$Q^R = C_c \cdot \left(T_{h,i} - T_s\right) = C_h \cdot (T_{h,o} - T_{use}). \tag{1}$$

Since the mass flow in the cold and hot water side is equal, one can find that

$$C_h = C_c = (\dot{m} \cdot C_p)_h = (\dot{m} \cdot C_p)_c \tag{2}$$

Moreover, the heat capacity ratio C_r may be written as

$$C_r = \frac{C_{min}}{C_{max}} = \frac{C_c}{C_h} = \frac{C_h}{C_c} = 1 \tag{3}$$

The heat regeneration, which is given in Eq. (1), can also be calculated by the following expression

$$Q^R = U \cdot A \cdot \Delta T_{LMTD} \cdot F \tag{4}$$

moreover, the total heat transfer coefficient U can be calculated from

$$U = \frac{1}{\frac{1}{h_h}+\frac{\delta}{\lambda}+\frac{1}{h_c}}. \tag{5}$$

The thermal properties in the hot and cold water streams are evaluated at the mean temperature as follows

$$T_{m,h} = \frac{T_{use}+T_{h,o}}{2} \quad \text{and} \quad T_{m,c} = \frac{T_s+T_{h,i}}{2} \tag{6}$$

The Logarithmic mean temperature difference between the plate wall and water is defined as

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\frac{\Delta T_1}{\Delta T_2}}. \tag{7}$$

From energy conservation and in a countercurrent flow arrangement when $C_h = C_c$ the arithmetic mean temperature difference becomes

$$\Delta T_{LMTD} = \Delta T_1 = \Delta T_2 = T_{h,o} - T_{h,i} = T_{use} - T_s \tag{8}$$

Moreover, for a single pass and countercurrent flow arrangement the correction factor F =1.

The effective heat transfer area in PHEs can be obtained by multiplying the projected area of a single plate A_p= $w L$ by the total number of plates as follows

$$A = (N_p - 2).A_p \quad (9)$$

Two plates are subtracted from the total number of the plates because the first and the last plates have fluid only on one side so that they are not effective in transferring heat.

To determine the required area of the PHE, the overall heat transfer coefficients must be derived. The convection heat transfer coefficients are evaluated using the dimensionless numbers Re, Pr, and Nu. For a turbulent countercurrent flow in single-phase PHEs, the dimensionless numbers are given by:

$$Pr = \frac{C_p \cdot \mu}{k} \quad (10)$$

$$Re = \frac{\rho \cdot u \cdot D_h}{\mu} \quad (11)$$

$$Nu = \frac{h \cdot D_h}{k} \quad (12)$$

The flow velocity u in a single channel can be expressed as

$$u = (G/\rho) = \frac{\dot{m}}{A_c \cdot n \cdot \rho} \quad (13)$$

Moreover, the number of channels n in the hot and cold water streams within the PHE is expressed as

$$n_h = (N_p - 2)/2 \quad \text{and} \quad n_c = N_p/2 \quad (14)$$

The hydraulic diameter D_h can be derived from

$$D_h = 4.A_c/p \quad (15)$$

Here, P is the wetted perimeter. For a rectangular cross-section, $P = 2a + 2w$, A_c is the flow cross area and defined as $A_c = a\ w$. If $a \ll w$, the hydraulic diameter can be written as $D_h \approx 2a$.

In the case of laminar flow $R_e < 2000$, the factors ζ_0 and $\zeta_{1,0}$ are given by

$$\zeta_0 = \frac{64}{R_e} \quad (16)$$

$$\zeta_{1,0} = \frac{597}{R_e} + 3{,}385 \quad (17)$$

While, if the flow is turbulent $R_e \geq 2000$, then the factors ζ_o and $\zeta_{1,o}$ can be given by

$$\zeta_0 = \frac{1}{(1{,}8 \ln(R_e) - 1{,}5)^2} \quad (18)$$

$$\zeta_{1,0} = \frac{39}{{R_e}^{0{,}289}} \quad (19)$$

The friction factor ζ is obtained from

$$\frac{1}{\sqrt{\zeta}} = \frac{\cos\varphi}{\left(0{,}18 \cdot \tan\varphi + 0{,}36 \cdot \sin\varphi + \frac{\zeta_0}{\cos\varphi}\right)^{0{,}5}} + \frac{1-\cos\varphi}{\sqrt{\zeta_1}} \qquad (20)$$

Where the factor ζ_1 is given by

$$\zeta_1 = 3{,}8 \cdot \zeta_{1,0} \qquad (21)$$

The dimensionless Hagen number (Hg) has proven to be very useful and works for both natural and forced convection flow. Depending on the physical properties of water, Hg is defined by

$$\mathrm{Hg} = \frac{\zeta \cdot \mathrm{R_e}^2}{2} = \rho\left(\frac{\Delta P}{L}\right) \cdot \left(\frac{{D_h}^3}{\mu^2}\right) \qquad (22.a)$$

When $R_e \leq 2300$, Hg number merely reads as

$$H_g = 32 R_e \qquad (22.b)$$

Then, Nusselt number is obtained by following

$$Nu = c_q P_r^{\frac{1}{3}} (\mu / \mu_w)^{\frac{1}{6}} [2Hg \cdot \sin(2\varphi)]^q \qquad (23)$$

The arithmetic and geometric mean values of the constants c_q and q are 0,122 and 0,374 respectively. The relation between the channel spacing a and the thickness of the plate can be expressed as

$$a = \frac{1}{2}\left(\frac{L}{N_p + 1} - \delta\right) \qquad (24)$$

It is worth mentioning that Alfa Laval, which is a well-known producer of PHE, uses amplitude term to find out the proper type of PHE in case that all temperatures of the hot and cold water streams are known. The amplitude Φ can be calculated by:

$$\Phi = \frac{Q^R}{\Delta T_{LMTD}} \qquad (25)$$

Table 1 shows the proper and smaller size of PHE given by Alfa Laval according to Φ-value.

Table 1. Selecting the type of PHE based on Φ-value

Max Φ-value	3	16	30	80	95	185	300	1300
Smallest size of PHE	CB14	CB27	CB52 M3	CB77	M6	CB200	M10	M15 CB300

Hydraulic Modeling

The total pressure drop in a PHE of single-phase flow involves several frictions and head loss elements including frictional pressure drop ΔP_f, the gravitational pressure drop ΔP_g and the additional flow distribution pressure drop $\sum \Delta P_{Ni}$ [50].

$$\Delta P_t = \Delta P_f + \Delta P_g + \Delta P_a + \sum \Delta P_{Ni} \quad (27)$$

$$\Delta P_f = \frac{2 \cdot f \cdot \rho \cdot u^2 \cdot L}{D_h} = 2 \cdot f \cdot \left(\frac{L}{D_h}\right) \cdot \left(\frac{G^2}{\rho}\right)$$

$$\sum \Delta P_{Ni} = 1.5 \cdot \left(\frac{G^2}{2\rho}\right) \cdot N_{pass} \quad (28.a)$$

$$\Delta P_g = \pm \rho \cdot g \cdot L$$

The '+' sign is for vertical up the flow, and the '- 'sign is for vertical downflow. The pressure drop due to flow acceleration ΔP_a is usually negligible for single-phase flows. The Fanning friction factor f value is a function of the plate surface corrugation pattern, flow Reynolds number, and the fluid properties. For chevron plates of 45^{o} value of f can be given by

$$f = \begin{cases} 0.3025 + \dfrac{91.75}{\mathrm{R_e}} & 1800 > \mathrm{R_e} > 150 \\ 1.46\ \mathrm{R_e}^{-0.177} & 30000 > \mathrm{R_e} > 1800 \end{cases} \quad (28.b)$$

Pressure drop affects the size of the PHE directly, the higher the pressure drop, the bigger the area of the PHE. Keeping pressure drop as small as possible is preferable to reduce pumping cost. However, relatively higher pressure drop allows minimizing the heat transfer area which accordingly reduces the operating costs.[50].

Pumping Power

Fouling in PHEs increase pressure drop and pumping power (PP) which cause an increase in operation cost [51]. The required PP to overcome the flow resistance and ensure constant flow rate in PHE can be given by [16,52]

$$PP = \frac{V\,\Delta P}{\eta} = \frac{\dot{m}\,\Delta P}{\rho\,\eta} \quad (29)$$

The volumetric flow rate V can be calculated as ($V=\dot{m}/\rho$). ΔP is the total pressure drop, and η is the pump efficiency which is almost 0.95 for water fluid. A smaller proportion ratio of the required PP to the recovered heat means a better performance and effectiveness of the PHE. If the ratio of the PP to heat transfer rate in PHE is insignificant, then the surface area of the PHE will be the only design factor [53].

4.2 Disinfection Unit

The thermal modeling of the disinfection unit involves calculating the required energy consumed by an electric heater. The electric heater is used to elevate water temperature in the heater to the desired T_d. The heat load is then defined as

$$Q^H = \dot{m}(I_o - I_i) \tag{28}$$

I_o and I_i are the enthalpies of the water at the outlet and the inlet of the heater respectively. The flow rate is the same alongside hot and cold water streams

Now, taking into account the required energy in the disinfection unit Q^H and the waste heat recovered in the regeneration unit Q^R the heat regeneration ratio (RR) is then defines by Eq. (29).

$$RR = \frac{Q^R}{Q^R - Q^H} \tag{10}$$

The RR helps to evaluate the ABHE system in term of saving energy entirely.

5. Results and Discussions

The EES-based model was built to simulate the performance of the ABHE system at any working conditions. Table 2 shows the nominal working conditions, which are used as a base for the derivations and the corresponding required area of the PHE that is used in the ABHE system. In this example, it is shown that for T_s of 10 °C, specific T_d of 80 °C and T_{use} of 40 °C, the required area of the PHE is 11.65 m^2.

Table 2. The nominal assumed working parameters and corresponding required are of PHE

$\dot{m}$	T_s	T_{use}	T_d	w	L	U_c	A_{PHE}	N	RR	PP
[kg/s]	[°C]	[°C]	[°C]	[m]	[m]	W/m^2.K	[m^2]	[-]	[%]	[W]
5	10	40	80	0.192	0.619	2411	11.65	100	57.5	106

Firstly, as previously mentioned, the RR in the ABHE system depends on the size of the PHE, which affects the total cost of the ABHE system. Therefore, the following discussions illustrate the relationship between different working parameters and the required area of the PHE. Indeed, the needed area of the PHE and, consequently, the cost of the ABHE rely on the flow rate of the water through the ABHE system as exemplified in Fig. 4, for the working conditions specified in Table 2.

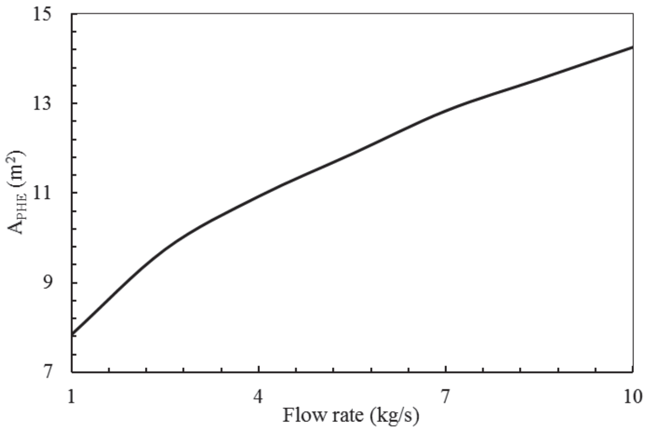

Fig. 4. The required area of the PHE along with the flow rate to achieve the working conditions specified in Table 2.

To investigate the performance of the ABHE system, the EES-based model was run for different working parameters including T_{use}, T_d, and T_s. The effect of T_{use} on the required area of the PHE, the RR, and the PP is illustrated in Fig. 5. As shown for the specified working conditions (see Table 2), increasing the T_{use} results in reduced RR value which minimizing the benefit of the ABHE system. However, increasing the T_{use} results in a reduced area of the PHE and pumping power, which reduce the capital and the operating costs of the ABHE system. Therefore, the T_{use} should be chosen carefully.

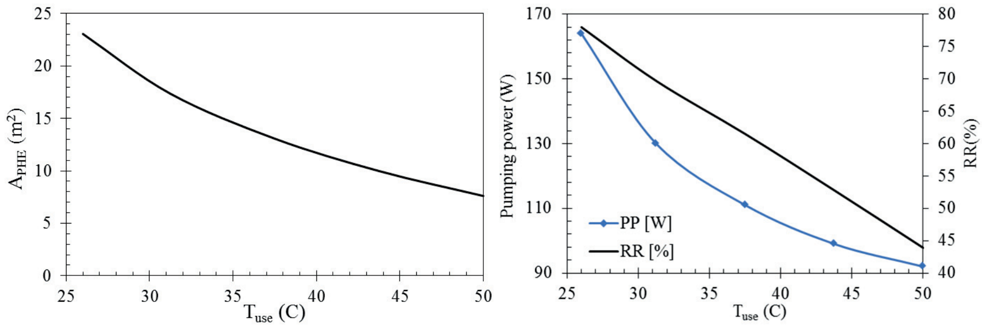

Fig. 5. The effect of the T_{use} on the RR and the required area of the PHE.

The analysis was repeated to investigate the effect of the Td on the performance of the ABHE system and the design of the PHE. As shown in Fig. 6, the T_d has opposite effect compared to the impact of the T_{use}. Increasing the T_d leads to an increased benefit of the ABHE system in term of increased RR. However, it increases the required area of the PHE and the PP, which affects the capital and operation costs of the ABHE system. Consequently, it can be concluded that the T_d also needs to be selected with care.

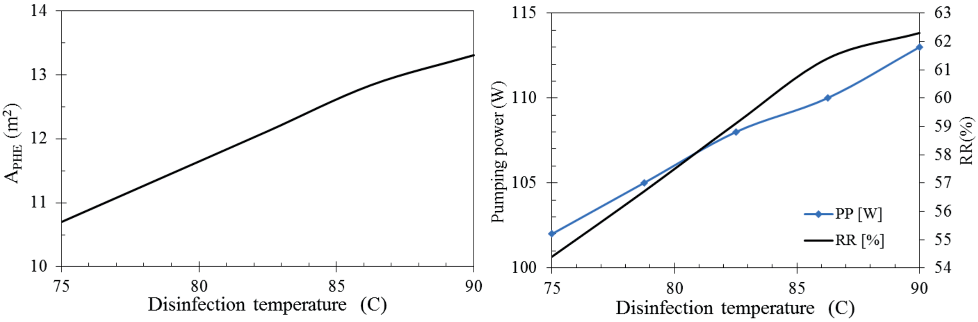

Fig. 6. The effect of the T_d on the pumping power, RR and the required area of the PHE

The effect of T_s on the performance of the ABHE system RR, the required PP and the required area of the PHE was shown in Fig. 7. The T_s has similar effects as the T_d. Namely, increasing T_s will lead to increase the RR, the PP as well as the required area of the PHE which leads to increase ABHE system operational costs.

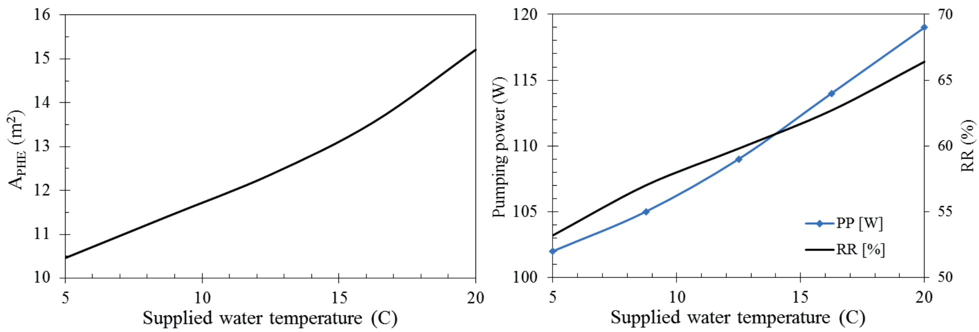

Fig. 7. The effect of the T_s on the PP, RR and the required area of the PHE.

Summary of effect different working parameters such as T_s, $T_{d,}$ and T_{use} on the thermal performance of the ABHE system including RR, PP, and area of PHE are shown in Fig. 8.

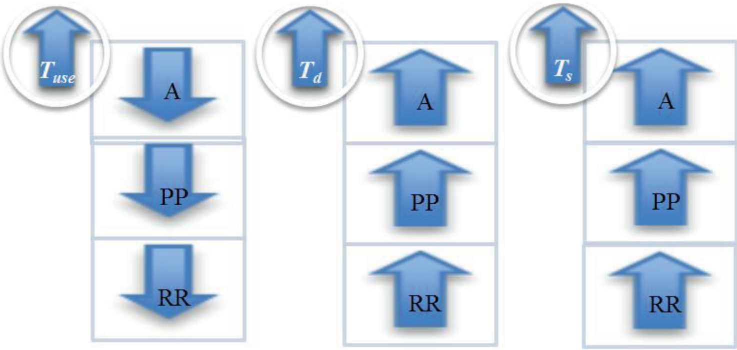

Fig. 8. Effect of different working parameters on the thermal performance of the ABHE system including RR, PP, and area of PHE

Secondly, to investigate the effect of the length and the width of the plate used in the PHE on the RR and the required area of the PHE, the simulation by the EES-based model was run for different width and length dimensions. In this study, the considered sizes of the PHE vary from 150-500 mm for the width and 500 to 800 mm for the length. Fig. 9, shows the relation of the RR in the ABHE system along with the required area of the PHE to fulfill the conditions that listed earlier in Table 2, for different width and length of the PHE. The simulation showed that (with 150 mm width and 500 mm length) the RR of 58% and the required area of the PHE of 7.95 m^2 are seen to be the optimum design of the PHE under the specific conditions that listed in Table 2.

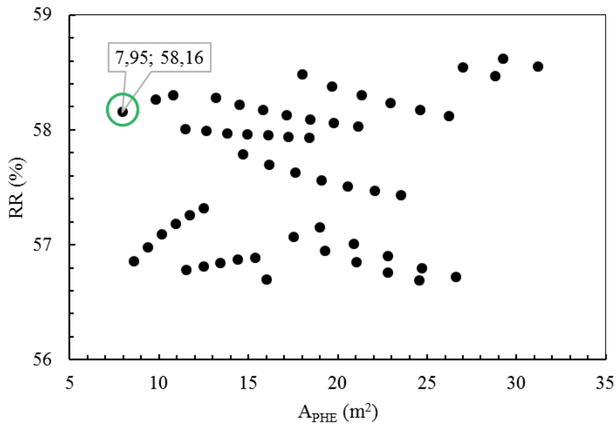

Fig. 9. The required area of the PHE versus RR to fulfill the conditions in Table 2 for different width and length of the PHE.

Then, this simulation enables to select the optimum design of the PHE that provides possible higher RR and in same time smaller required area of the PHE at a given PHE dimensions. Furthermore, the developed EES-based model can also be used to optimize the design of the PHE by defining its optimal dimensions (i.e., the width and the length of the plate) in which the RR is maximized, or the required area of the PHE is minimized. For this purpose, conjugate directions optimization method was used to solve the unconstrained energy optimization problems, with the conversion tolerance of $1 \cdot 10^{-4}$. Table 3, shows the optimal dimensions of the PHE in which the area of the PHE is minimized

Table 3. The dimensions of the PHE to minimize the required area of PHE

Criterion	T_s [°C]	T_{use} [°C]	T_d [°C]	w [m]	L [m]	RR [%]	Optimal A_{PHE} [m^2]
Minimize area	10	40	80	0,15	0,5	56,8	7,83

While **Error! Not a valid bookmark self-reference.**, shows the dimensions of the PHE in which the RR of the ABHE system is maximized. Consequently, high energy recovery and low cost of the ABHE system can be achieved.

Table 4. The dimensions of the PHE to optimize the RR of ABHE

Criterion	T_s [°C]	T_{use} [°C]	T_d [°C]	w [m]	L [m]	A_{PHE} [m^2]	Optimal RR [%]
Maximize RR	10	40	80	0,18	0,62	11,45	58,3

6. Conclusion

Hot water systems are commonly contaminated with ubiquitous L causing acute human diseases. The continuous increase in the reported cases of LD outbreaks makes disinfecting water more challenging. Practically the effectiveness of the conventional treatment methods used to control L in hot water systems is proven to be inadequate in the eradication of L. The ABHE system is a robust and straightforward technique with high energy efficiency since it mimics systems already developed by nature with the most top ability and most straightforward integrated process. Heat recovery is achieved in the ABHE system using the heat exchanger.

In the current study, an EES-based model was developed to simulate the ABHE system. This requires the consideration of working parameters, including the PHE geometric parameters (i.e., the length and the width), the flow rate, the T_s, the T_{use}, and the T_d. The developed EES-based model was also used to optimize the PHE design by maximize the thermal performance of the

ABHE system RR and minimize the required area of the PHE at any given conditions. The performed simulations showed that:

- The ABHE system has excellent capability to reduce the energy consumption to achieve L disinfection for different T_d.
- The working conditions have a significant effect on the required area of the PHE, which consequently affects the capital cost and the thermal performance of the ABHE system.
- The effect of the working parameters on the pumping power, due to adding the PHE to the water cycle, is insignificant.
- The area of the PHE in the ABHE system strongly affects the RR, namely the benefit of using the ABHE system.

Another important conclusion can be drawn is that selecting the dimensions of the plates (i.e., the length and the width) used in the PHE has a significant impact on the performance of the ABHE system.

7. References

[1] N.J. Ashbolt, Microbial contamination of drinking water and disease outcomes in developing regions, Toxicology. 198 (2004) 229-238.

[2] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Marinas, A.M. Mayes, Science and technology for water purification in the coming decades, Nature. 452 (2008) 301-310.

[3] W.D. Flanders, K.H. Kirkland, B.G. Shelton, Effects of holding time and measurement error on culturing Legionella in environmental water samples, Water research. 62 (2014) 293-301.

[4] J. Lacey, J. Dutkiewicz, Bioaerosols And Occupational Lung-Disease, Journal of Aerosol Science. 25 (1994) 1371-1404.

[5] J. Blostein, Shigellosis from swimming in a park pond in Michigan, Public health reports (Washington, D.C.: 1974). 106 (1991) 317-322.

[6] Centers for Disease Control and Prevention (CDC), Prevalence of parasites in fecal material from chlorinated swimming pools--United States, 1999, MMWR.Morbidity and mortality weekly report. 50 (2001) 410-412.

[7] J. Rogers, A.B. Dowsett, P.J. Dennis, J.V. Lee, C.W. Keevil, Influence Of Temperature And Plumbing Material Selection On Biofilm Formation And Growth Of Legionella-Pneumophila In

A Model Potable Water-System Containing Complex Microbial-Flora, Applied and Environmental Microbiology. 60 (1994) 1585-1592.

[8] J. Kusnetsov, E. Iivanainen, N. Elomaa, O. Zacheus, P.J. Martikainen, Copper and silver ions more effective against legionellae than against mycobacteria in a hospital warm water system, Water Research. 35 (2001) 4217-4225.

[9] E.F.P. Callizo, J.D. Sierra, J.M.S. Pombo, C.E. Baquedano, B.P. Huerta, Evaluation of the effectiveness of the Pastormaster method for disinfection of legionella in a hospital water distribution system, Journal of Hospital Infection. 60 (2005) 150-158.

[10] R. Heller, C. Holler, R. Sussmuth, K.O. Gundermann, Effect of salt concentration and temperature on survival of Legionella pneumophila, Letters in Applied Microbiology. 26 (1998) 64-68.

[11] V. Thomas, T. Bouchez, V. Nicolas, S. Robert, J. Loret, Y. Levi, Amoebae in domestic water systems: resistance to disinfection treatments and implication in Legionella persistence, Journal of applied microbiology. 97 (2004) 950-963.

[12] M. Steinert, G. Ockert, C. Luck, J. Hacker, Regrowth of Legionella pneumophila in a heat-disinfected plumbing system, Zentralblatt Fur Bakteriologie-International Journal of Medical Microbiology Virology Parasitology and Infectious Diseases. 288 (1998) 331-342.

[13] G.T. Polley, M. Picón-Núñez, J.d.J. López-Maciel, Design of water and heat recovery networks for the simultaneous minimisation of water and energy consumption, Applied Thermal Engineering. 30 (2010) 2290-2299.

[14] M. Mokhtar, S. Burns, D. Ross, I. Hunt, Exploring multi-objective trade-offs in the design space of a waste heat recovery system, Applied Energy. 195 (2017) 114-124.

[15] A. Bertrand, R. Aggoune, F. Maréchal, In-building waste water heat recovery: An urban-scale method for the characterisation of water streams and the assessment of energy savings and costs, Applied Energy. 192 (2017) 110-125.

[16] T. Wang, W. Luan, W. Wang, S. Tu, Waste heat recovery through plate heat exchanger based thermoelectric generator system, Applied Energy. 136 (2014) 860-865.

[17] L.T. Wong, K.W. Mui, Y. Guan, Shower water heat recovery in high-rise residential buildings of Hong Kong, Applied Energy. 87 (2010) 703-709.

[18] L. Altorkmany, M. Kharseh, A. Ljung, T.S. Lundström, Experimental and simulation validation of ABHE for disinfection of Legionella in hot water systems, Applied Thermal Engineering. 116 (2017) 253-265.

[19] A. Hadidi, A robust approach for optimal design of plate fin heat exchangers using biogeography based optimization (BBO) algorithm, Applied Energy. 150 (2015) 196-210.

[20] G. Zhou, E. Wu, S. Tu, Optimum selection of compact heat exchangers using non-structural fuzzy decision method, Applied Energy. 113 (2014) 1801-1809.

[21] G.N. Xie, B. Sunden, Q.W. Wang, Optimization of compact heat exchangers by a genetic algorithm, Applied Thermal Engineering. 28 (2008) 895-906.

[22] J.A. Gut, J.M. Pinto, Optimal configuration design for plate heat exchangers, International Journal of Heat and Mass Transfer. 47 (2004) 4833-4848.

[23] L. Wang, B. Sunden, Optimal design of plate heat exchangers with and without pressure drop specifications, Applied Thermal Engineering. 23 (2003) 295-311.

[24] J.M. Kusnetsov, E. Ottoila, P.J. Martikainen, Growth, respiration and survival of Legionella pneumophila at high temperatures, Journal of Applied Bacteriology. 81 (1996) 341-347.

[25] T.D. Brock, Life At High-Temperatures, Science. 230 (1985) 132-138.

[26] J. Darelid, S. Lofgren, B.E. Malmvall, Control of nosocomial Legionnaires' disease by keeping the circulating hot water temperature above 55 degrees C: experience from a 10-year surveillance programme in a district general hospital, Journal of Hospital Infection. 50 (2002) 213-219.

[27] L. Hruba, The Colonization Of Hot Water Systems By Legionella, Annals of Agricultural and Environmental Medicine. 16 (2009) 115-119.

[28] M. Best, A. Goetz, V.L. Yu, Heat Eradication Measures For Control Of Nosocomial Legionnaires-Disease - Implementation, Education, And Cost-Analysis, American Journal of Infection Control. 12 (1984) 26-30.

[29] M. Lacroix, Electric water heater designs for load shifting and control of bacterial contamination, Energy Conversion and Management. 40 (1999) 1313-1340.

[30] F. Martinelli, A. Caruso, L. Moschini, A. Turano, C. Scarcella, F. Speziani, A comparison of Legionella pneumophila occurrence in hot water tanks and instantaneous devices in domestic, nosocomial, and community environments, Current microbiology. 41 (2000) 374-376.

[31] A. Gadgil, Drinking water in developing countries, Annual Review of Energy and the Environment. 23 (1998) 253-286.

[32] T.F. Clasen, D.H. Thao, S. Boisson, O. Shipin, Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam, Environmental science & technology. 42 (2008) 4255-4260.

[33] M. Vital, Growth of pathogenic bacteria in freshwater and their competition with the autochthonous bacterial flora. (2010).

[34] B. Kim, J. Anderson, S. Mueller, W. Gaines, A. Kendall, Literature review—efficacy of various disinfectants against Legionella in water systems, Water research. 36 (2002) 4433-4444.

[35] Y. Chen, Y. Liu, S.S. Lee, H. Tsai, S. Wann, C. Kao, et al., Abbreviated duration of superheat-and-flush and disinfection of taps for Legionella disinfection: lessons learned from failure, American Journal of Infection Control. 33 (2005) 606-610.

[36] S. Cerovac, A.H. Roberts, Burns sustained by hot bath and shower water, Burns. 26 (2000) 251-259.

[37] D.W. Huyer, S.H. Corkum, Reducing the incidence of tap-water scalds: strategies for physicians, CMAJ : Canadian Medical Association journal = journal de l'Association medicale canadienne. 156 (1997) 841-844.

[38] T. Tse, C.H. Poon, K. Tse, T. Tsui, T. Ayyappan, A. Burd, Paediatric burn prevention: an epidemiological approach, Burns. 32 (2006) 229-234.

[39] H. Gole, R. Kimble, K. Stockton, Bathroom scald burns in Queensland Children, Burns. (2016).

[40] T.C. Erdmann, K.W. Feldman, F.P. Rivara, D.M. Heimbach, H.A. Wall, Tap water burn prevention: the effect of legislation, Pediatrics. 88 (1991) 572-577.

[41] E. Clouatre, R. Pinto, J. Banfield, M.G. Jeschke, Incidence of hot tap water scalds after the introduction of regulations in Ontario, Journal of burn care & research : official publication of the American Burn Association. 34 (2013) 243-248.

[42] M. Peck, A.C. Brewer, M. Pressman, E. Blank, A. Mickalide, Hot tap water legislation in the United States, Journal of burn care & research : official publication of the American Burn Association. 31 (2010) 918-925.

[43] J.E. Ongerth, R.L. Johnson, S.C. Macdonald, F. Frost, H.H. Stibbs, Back-country water treatment to prevent giardiasis, American Journal of Public Health. 79 (1989) 1633-1637.

[44] C. Lallana, W. Krinner, T. Estrela, C.S. Nixon, J. Leonard, J. Berland, Sustainable water use in Europe,Office for Official Publications of the European Communities, 2001.

[45] B. Nordell, L. Altorkmany, Vätskedesinficerare omfattande en värmeväxlare (Disinfect fluid including a heat exchangerDisinfect fluid including a heat exchanger), SE 0901111-5 (2011).

[46] N.K. Schmidt, D. Jackson, Countercurrent heat exchange in the respiratory passages, Science. 144 (1964) 567.

[47] A.P. Fraas, Heat Exchanger Design,John Wiley and Sons, Inc, 1989.

[48] H. Mehling, L.F. Cabeza, S. Hippeli, S. Hiebler, PCM-module to improve hot water heat stores with stratification, Renewable Energy. 28 (2003) 699-711.

[49] C.T. Kelley, Iterative methods for optimization,SIAM, 1999.

[50] B. Sundén, R.M. Manglik, Plate heat exchangers: design, applications and performance,Wit Press, 2007.

[51] G.F. Hewitt, S.J. Pugh, Approximate design and costing methods for heat exchangers, Heat Transfer Engineering. 28 (2007) 76-86.

[52] T. Bergman, A. Lavine, F. Incropera, Fundamental of Heat and Mass Transfer, (2007).

[53] X. Liu, J. Niu, An optimal design analysis method for heat recovery devices in building applications, Applied Energy. 129 (2014) 364-372.