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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
ζ_0 ζ $\zeta_{1,0}$	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.

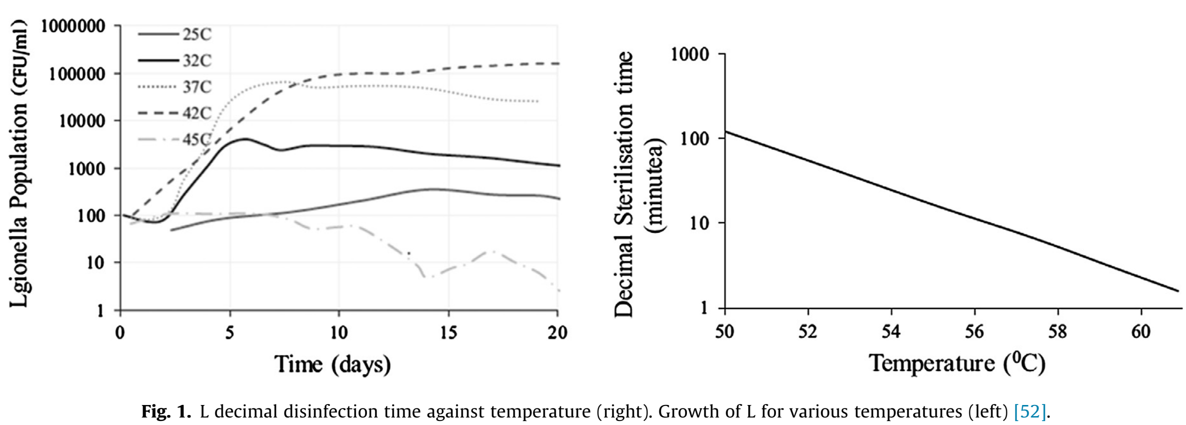


Fig. 1. L decimal disinfection time against temperature (right). Growth of L for various temperatures (left) [52].

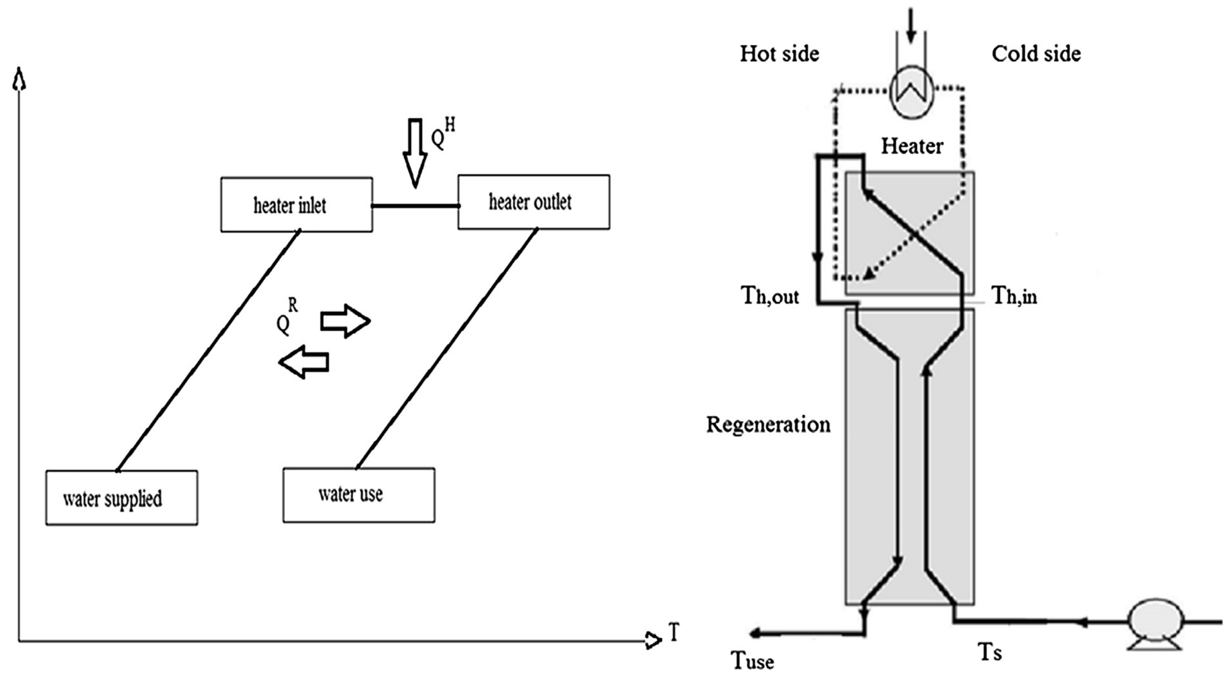


Fig. 2. Schematic diagram of the ABHE system used for L disinfection in HWS.

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

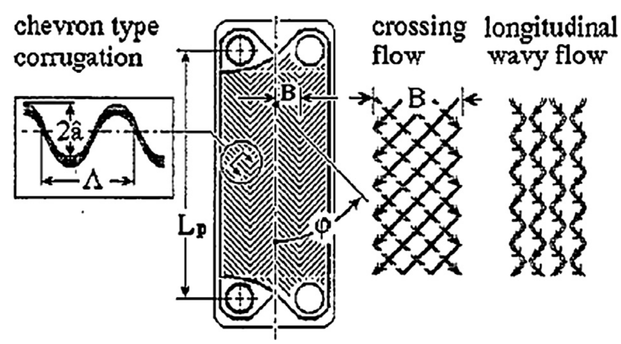


Fig. 3. Chevron-type heat exchanger plate, the angle φ and two flow patterns [62].

- 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

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

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

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

Then the heat capacity ratio C_r may be written as

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

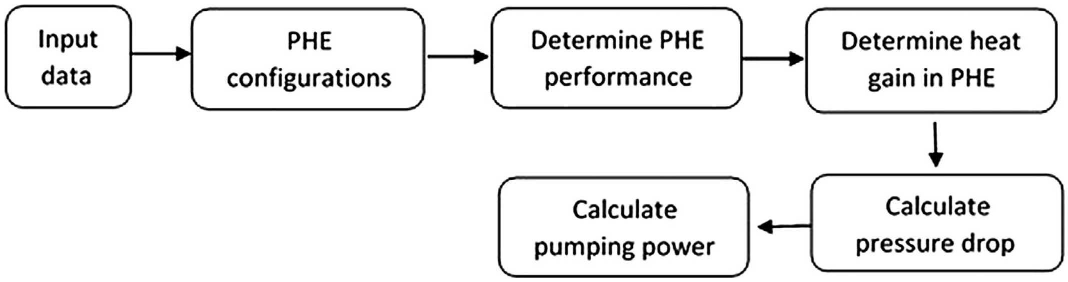


Fig. 4. Structure of the EES model designed to simulate the ABHE system.

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

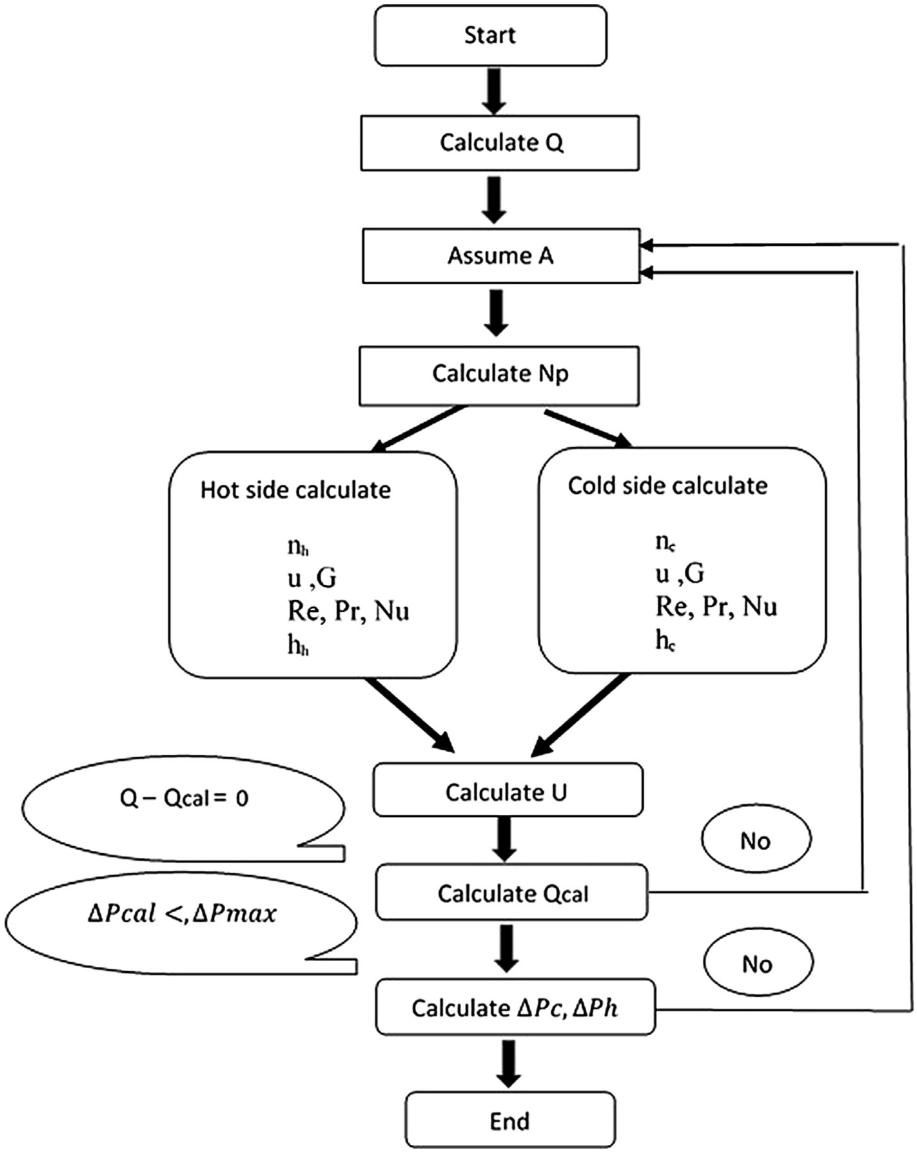


Fig. 5. Schematic diagram for obtaining the required number of plates in PHE.

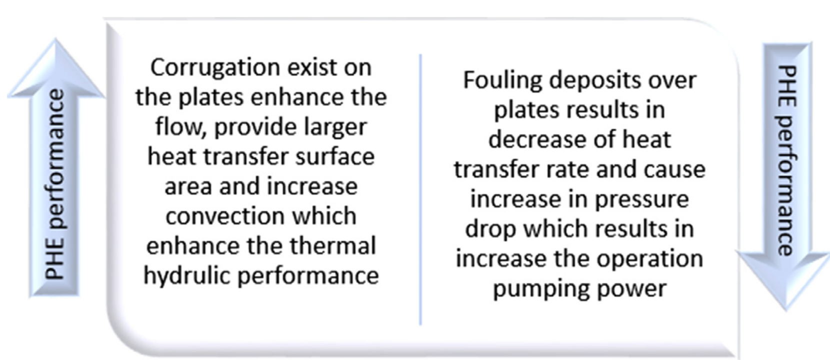


Fig. 6. Effects of fouling and corrugation on PHE performance.

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.

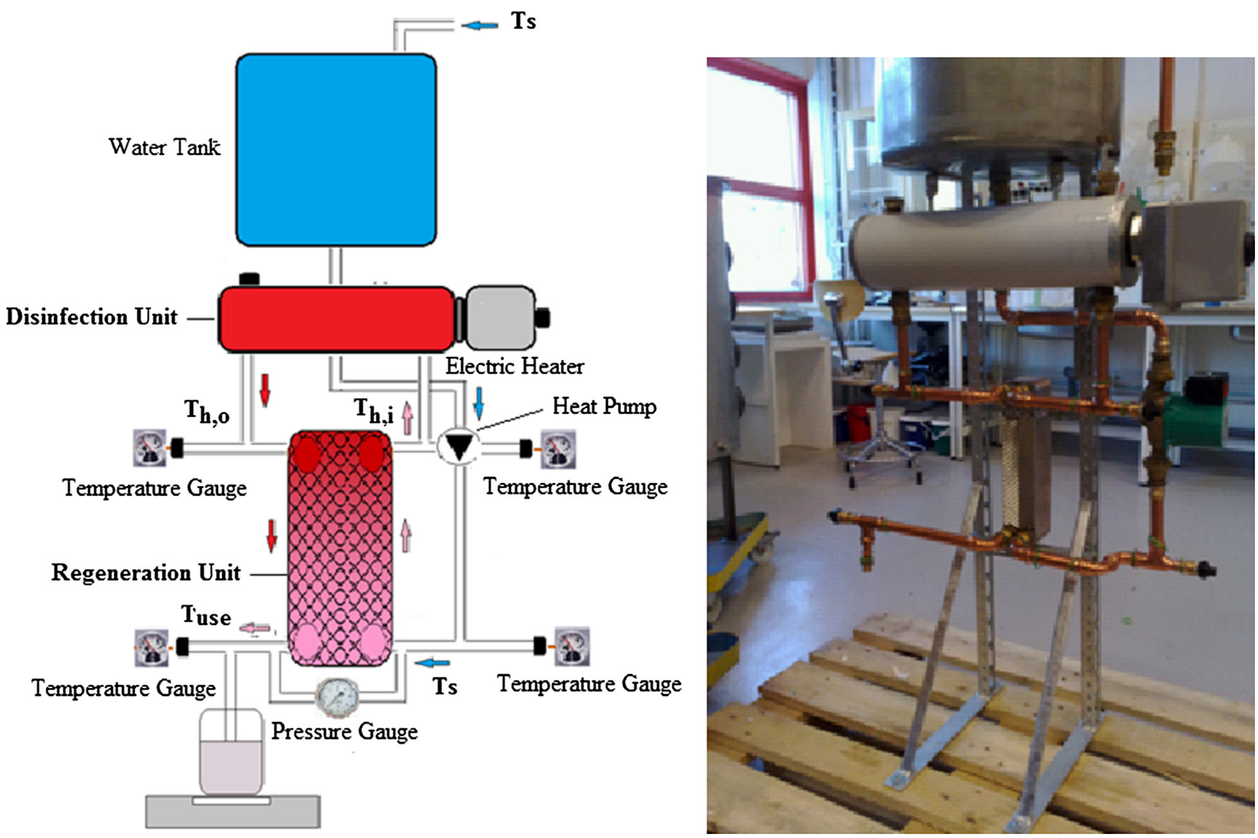


Fig. 7. Schematic of the ABHE system tested experimentally (left) by the prototype (right).

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

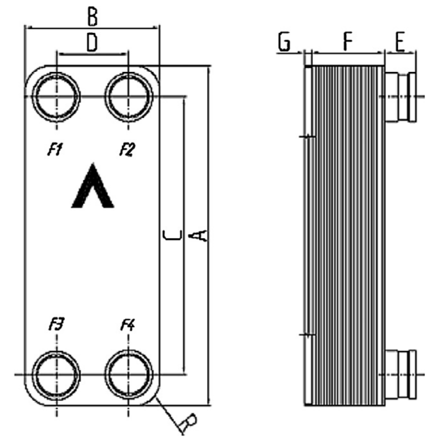
By using the ABHE prototype (see Fig. 7), the experiment was conducted for 18 runs at flow rates in the range of 3–12 kg/min and for supplied water temperatures in the range of 4–50 °C. The experimental results were used to validate the developed EES model. Results from the experiment and the EES model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

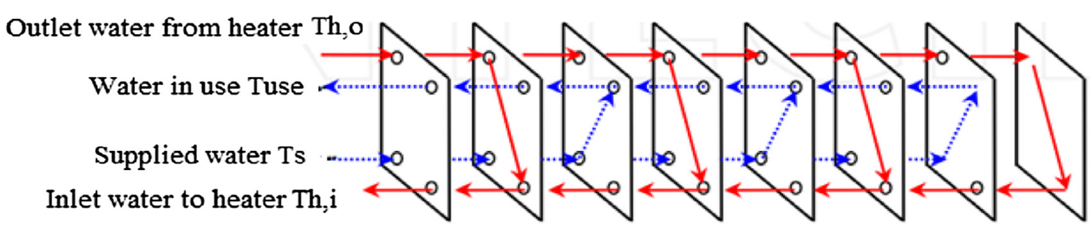


Table 3
Results of the experimental test and comparison the inlet heater temperature by the experimental test and the EES model. Pressure drop and pumping power by EES model.

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-

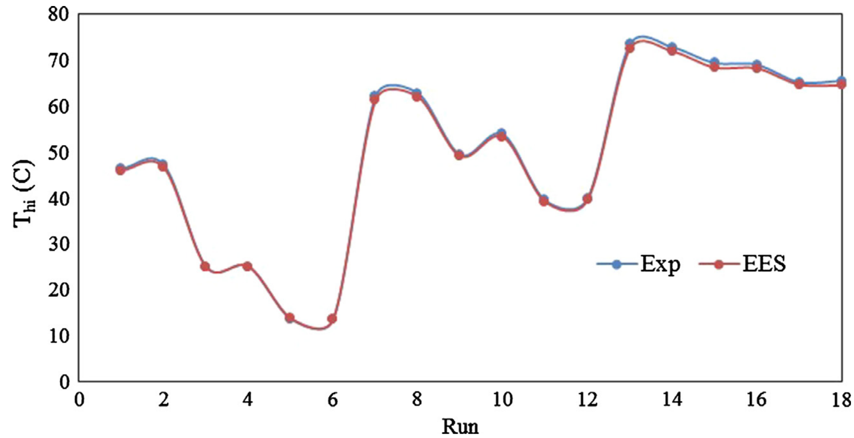


Fig. 8. Comparison between the inlet heater temperatures value as derived from experimental test and EES model.

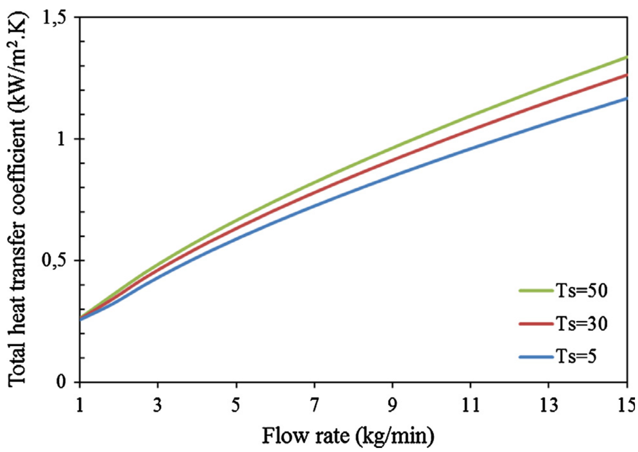


Fig. 9. Total heat transfer coefficient in PHE for different supplied water temperatures °C at different flow rates.

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

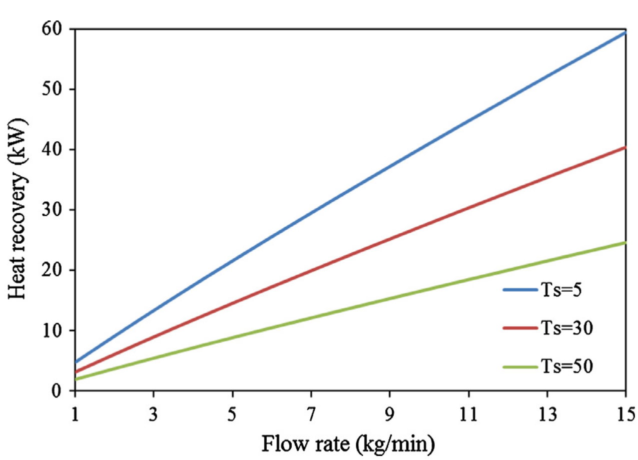


Fig. 10. Heat recovery in PHE for different supplied water temperature °C at different flow rates.

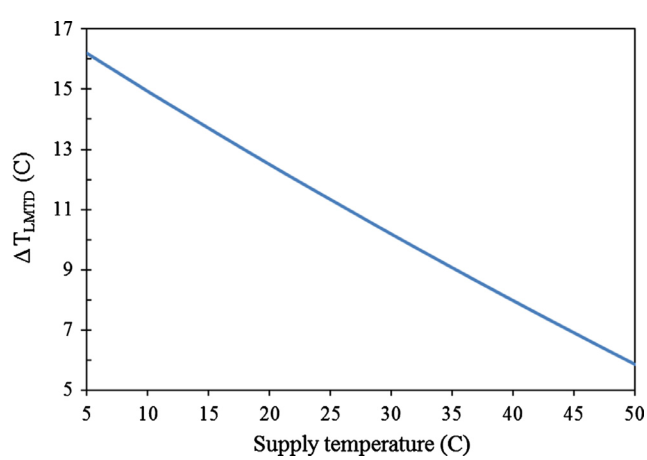


Fig. 11. ΔT_{LMTD} in PHE as a function of the supplied water temperature.

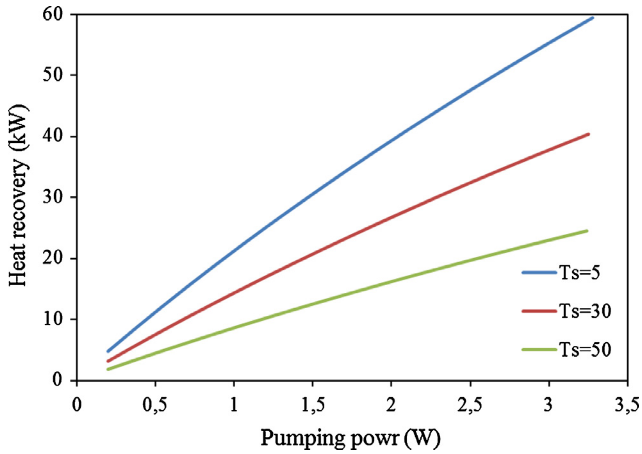


Fig. 12. Heat recovery versus the pumping power at different supplied water temperature °C.

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.

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