EXPERIMENTAL STUDY OF SHOWER GREYWATER THERMAL ENERGY RECOVERY

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EXPERIMENTAL STUDY OF SHOWER GREYWATER THERMAL ENERGY RECOVERY

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I certify that in my opinion the thesis submitted by Ibrahim Ali M. ELJETLAWI titled "EXPERIMENTAL STUDY OF SHOWER GREYWATER THERMAL ENERGY RECOVERY" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

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Ibrahim Ali M. ELJETLAWI

ABSTRACT

M. Sc. Thesis

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Fossil fuels depletion and increase in energy costs, rise the importance of little improvements in our daily life energy consuming systems efficiency. Compared with the heavy energy consuming systems, domestic energy wasting system improvements cause little amount of savings for per case, but it also provides big amount of earnings in the size of community. Shower greywater is an example of the household size energy wasting potential. This experimentally done study cares with the saving of the greywater heat to the tap water preheating before heating to shower in a water heater. Three different type of heat exchangers that are tube in tube, helical coil, and brazed plate were attached in two different positioning which are horizontal and vertical case to a household size shower experimentation setup. The experimentations were done for a half an hour shower period with 40 ºC water set temperature. The size of annual possible energy saving for four people family by the horizontally attached heat exchangers that are tube in tube, helical coil, and brazed plate approximately about

39.31 kWh, 247.1 kWh and 315.7 kWh. In case of vertical attachment of the heat exchangers saving account about 108.57 kWh, 378.14 kWh and 418.7 kWh. The rates of saving are also 2.56%, 16.13% and 20.61% for the horizontal and 7.09%, 24.69% and 27.34% for the vertical attachment of the heat exchangers. Maximum reachable economic size of saving is $ 42.7/year, and attachment of a heat exchanger for per shower costs $ 87 with its all equipment's. The minimum payback period can be estimated about minimum 2 years. Environmentally, minimum benefit of this saving is equivalent to the release of 32.43 kg less carbon emission.

ÖZET

Yüksek Lisans Tezi

DUŞ ATIK SUYU TERMAL ENERJİSİNİN GERİ KAZANIMI DENEYSEL ÇALIŞMASI

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Fosil yakıtların tükenmesi ve enerji maliyetlerinin artması, günlük yaşamda enerji tüketen sistemlerin verimliliğindeki küçük gelişmelerin önemini artırmaktadır. Ağır enerji tüketen sistemlerle karşılaştırıldığında, evsel enerji tüketiminde gerçekleştirilen iyileştirmeler vaka başına az miktarda tasarruf sağlarken, toplum boyutunda büyük miktarda kazanç sağlar. Duş atık suyu, ev tipi enerji israf noktalarına bir örnektir. Bu deneysel olarak gerçekleştirilen çalışma, bir su ısıtıcısında şebeke suyunun duş suyu olarak ısıtılmadan önce atık duş suyu ısısı ile ön ısıtılmasını ele alır. İç içe borulu, spiral borulu ve plakalı ısı eşanjörü olmak üzere üç farklı tip ısı eşanjörü yatay ve dikey olmak üzere iki farklı konumlandırma ile ev tipi boyutlarında bir duş deney düzeneğine bağlandı. 40 ℃ sıcaklığa ayarlanmış duş suyu sıcaklığı ve yarım saatlik bir duş sürecinde için deneyler gerçekleştirildi. Yıllık sağlanabilmesi muhtemel enerji tasarrufu miktarı dört kişilik bir aile için iç içe borulu, spiral borulu ve plakalı ısı

eşanjörünün yatay konumlu bağlanması için yaklaşık 39,31 kWh, 247,1 kWh ve 315,7 kWh olarak, dikey konumlu bağlanmaları durumu için ise 108,57 kWh, 378,14 kWh ve 418,7 kWh olarak hesaplanmıştır. Tasarrufların oransal miktarı eşanjörlerin yatay konumlandırılmaları durumu için %2,56, %16,13 ve %20,61 olarak, dikey konumlandırılmaları durumu için ise %7,09, %24,69 ve %27,34 olarak belirlenmiştir. Tasarrufun erişilebilir maksimum miktarı 42,7 $/yıl'dır ve her bir duş için ısı eşanjörü ve ekipmanları maliyeti 87 $'dır, minimum geri ödeme süresi 2 yıl olarak belirlenmiştir. Çevresel olarak, kazanımın minimum faydası yılda 32,43 kg daha az karbon emisyonu salınımına eşittir.

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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

$\dot{Q}$: heat exchange rate

$\dot{m}$: mass flow rate

c_p : specific heat transfer coefficient

ΔT : temperature difference

A : heat transfer surface area

U : overall heat transfer coefficient

ΔT_{LMTD}: logarithmic mean temperature difference

$\dot{Q}_{pw}$: heat transfer rate to preheat water

$\dot{Q}_{gw}$: heat transfer rate from greywater

$T_{gw,in}$: greywater heat exchanger inlet temperature

$T_{gw,out}$: greywater heat exchanger exit temperature

$T_{pw,in}$: preheating water heat exchanger inlet temperature

$T_{pw,out}$: preheating water heat exchanger exit temperature

d_i : inner diameter of tube

d_o : outer diameter of tube

A_i : inner heat exchange surface area

A_o : outer heat exchange surface area

h_i : inner side convection coefficient

h_o : outer side convection coefficient

k : thermal conductivity

L : tube length

ABBREVITIONS

PHEs   : Plate Heat Exchanger

GW   : Greywater

GWHR   : Greywater Heat Recovery

PART 1

INTRODUCTION

The increase in energy prices and environmental considerations require the improvement and development of energy consuming systems and equipment's. Today, in lots of countries about more than 25% of the total energy consumption is domestic. Unlike transportation or energy consumption in the industry, that is depend on the technological regulations, through a wide range of factors, that the residential energy consumption is determined [1]. Domestic water use leads to a large percentage of energy use, and also energy requirement to heat hot water that is determined about 22% of total household use [2]. The use of energy in the shower is estimated less than 5% from entire household energy which is used to heat water, where more than 85% of it flows as waste to drainage [3]. Electricity consumption used to heat water can be reduced by installing devices designed to recover excess energy from greywater that is drained into the bathtub [4]. Much energy has been achieved by reclaiming greywater [5]. The relationship between water use and energy consumption in buildings is strong. Where it was found that 84% of the energy related to water is used to heat water in buildings [6]. Hot water shower consumes about 40% of the total energy used in residential houses [7]. The city's fuel consumption will be reduced about 6.3% by greywater heat recovery. An integrated design that includes both a heat pump and greywater heat recovery for preheating hot water resulting in 28% to 41% in providing electricity for multifamily buildings and for separate homes for single beds, respectively [8]. Recovering heat from greywater is profitable in financial terms [9]. Studies indicated that system performances could be enhanced by water preheated loops [10]. Thermal energy recovery could be done by various methods to capture wasting energy. Recovery of waste heat load by direct or, more commonly, indirect methods. Two fluid body can be separated by a heat transfer surface in indirect heat recovery and categorized in two different subgroup as a passive or active heat exchangers [11]. In order to transfer the heat among two or more fluids body which

have temperature difference heat exchangers are used [12]. In use there are lots of heat exchanger types, a classification was defined due to their operation, construction, heat transfer, and flow types [13].

The domains of fluid stay separate in the indirect-contact heat exchangers. Heat transfer occurs in a separate wall in a transient manner. So, in reality there isn't any contact between two fluid body except thermal contact [14]. Geometrical construction type can be in the different forms such as tubes, plates, and extended surfaces [13]. The types due to the geometric construction could be grouped as below [15].

1. Shell & tube type
2. Double pipe type
3. Compact type
4. Air-cooled type

Figure 1.1 presents the shell and tube type of heat exchanger that is widely utilized in the industrial operations. Its general design is one shell-side passes and more than one side of tube pass [16].
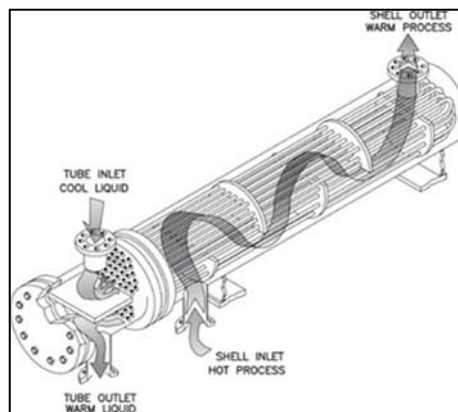
Figure 1.1. Exchanger of shell and tube [17].

The simplest form of heat exchanger between two fluid bodies is the double pipe heat exchanger. It consists of a tube inside a tube, with appropriate heat transfer relation of both fluids. Figure 2.1 shows the concentric tube heat exchanger [18].

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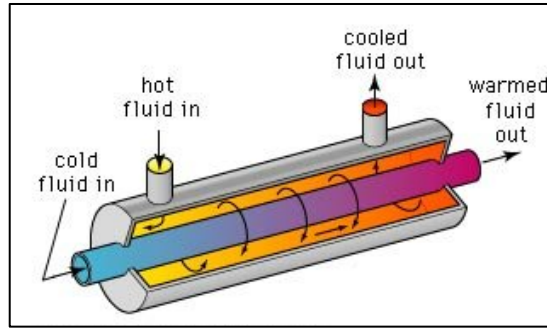
Figure 1.2. Concentric tube heat exchanger [19].

Compact heat exchangers could be described as a class of heat exchanger types and are exemplified in Figure 1.3. These heat exchangers could have multiple layers of serpentine plate fins and separated plates or tubes [20].
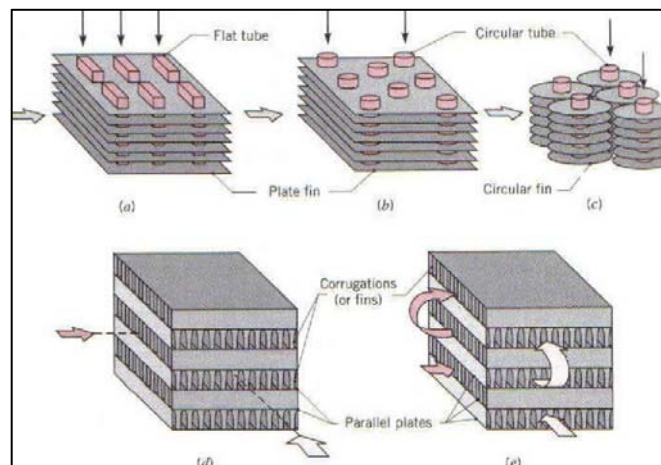
Figure 1.3. Compact type heat exchanger packets. (a) flat tubes, plate fins (b) circular tubes, plate fins (c) circular tubes, circular fins (d) single pass (e) multi-pass [21].

For single-phase heat exchange process, all fluids has a single stage, and the heat is moved between fluid domains through two different ways that are convection and/or conduction. The performance of thermal energy transfer is depend on the flow rate, specific heat capacity of fluid domains and heat exchange surface area. In two stage heat exchangers thermal energy change occurs during the phase change process in the device [22]. Heat exchangers could be arranged also in different flow arrangement these are exemplified as cross flow, counter flow or parallel flow [13]. In a counter flow heat exchanger that are shared in Figure 1.4, the two fluid bodies flow parallelly, but in reverse directions [23].

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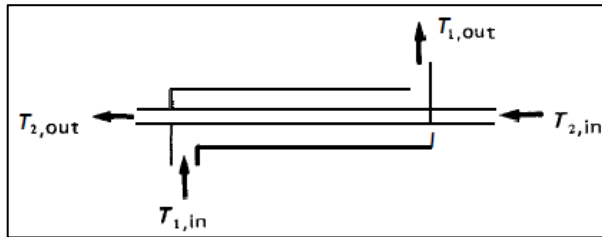
Figure 1.4. Counter-flow heat exchanger [23].

Through a parallel-flow heat exchanger, the two fluids flow parallelly, and in similar path as given in Figure 1.5 [23].
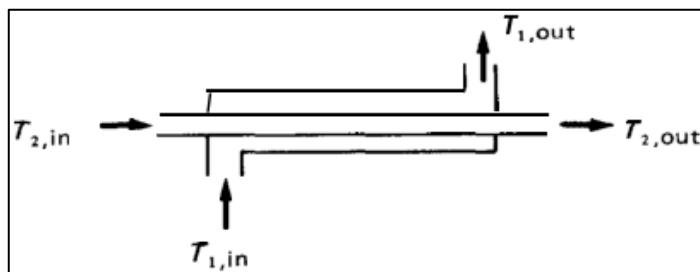
Figure 1.5. Parallel-flow heat exchanger [23].

In a cross flow heat exchanger, the two fluid body flow tangentially to each other as seen in Figure 1.6 [23].
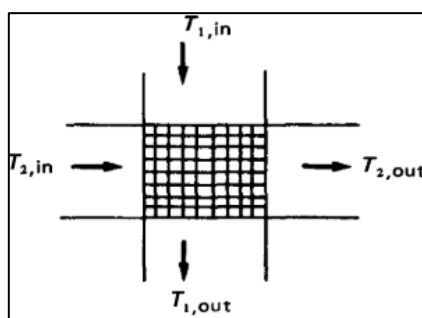
Figure 1.6. Cross-flow heat exchanger [23].

Configurations of numerous heat exchangers could conform the behavior of flow as shown in Figure 1.7 and are called cross counter flow exchangers [23].
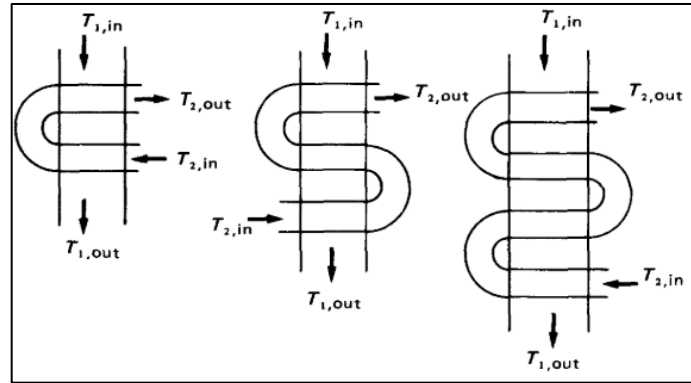
Figure 1.7. Cross-counter-flow heat exchangers [23].

Figure 1.8 shows multi-pass shell and tube heat exchangers, parallel flow and cross flow properties may be combined in the same heat exchanger, equally when pipes double back inside a singular shell. Also, the similar impact could be accomplished, with conventional pipes, by the delivery of appropriate subdivided headers [23].
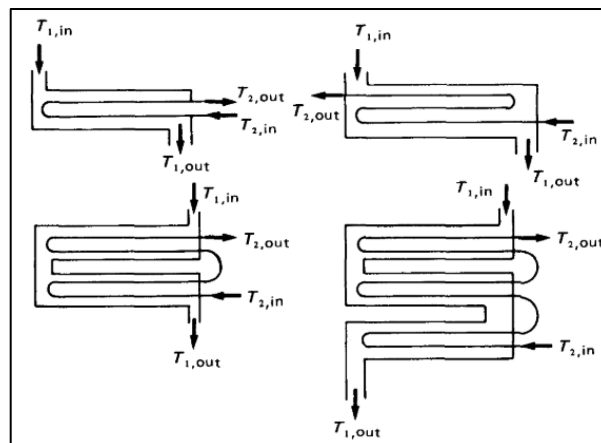
Figure 1.8. Flow arrangements of multipass shell-and-tube heat exchangers [23].

In this study three different type of heat exchanger attachment between the shower drain line and water heater feed water line to preheat the feed tap water before reaching water heater by exchanging heat from shower greywater was studied. In this context, the heat exchangers that are utilized in the study was introduced after this point. In our study, we have used three different types of heat exchangers that are helical coil, tube in tube and brazed plate heat exchangers. Figure 1.9 shows the tube in tube heat exchanger that produced with two concentric tubes.

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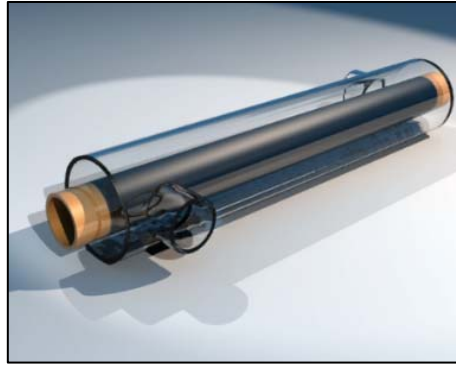
Figure 1.9. Tube in tube heat exchanger [24].

The literature discussed frequently that the heat transfer rate in helical coil heat exchangers are more than if compared with straight ones. Since the compactness and high heat transfer performance, helical coil heat exchangers are chosen where the high rate of heat exchange is needed with small occupants' area possible and it is visualized in Figure 1.10 [25].
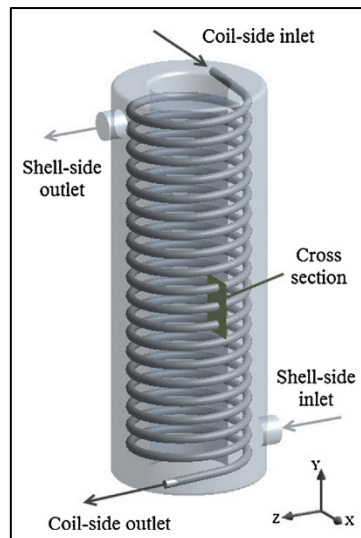
Figure 1.10. Helical coil heat exchanger [25].

Figure 1.11 shows the first example of plate heat exchanger which has been presented in 1930s. Their mostly using type is liquid/liquid heat exchanger configuration in the particulate industry due to its easy cleanability. The capabilities of temperature and pressure of them were increased to a great extent in recent times as a result of replacing their materials with new generation ones [26].
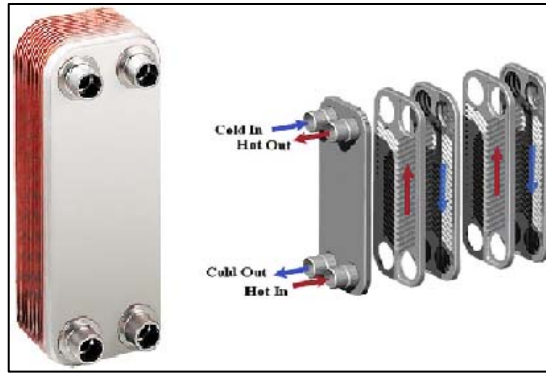
Figure 1.11. Brazed plate heat exchanger [27].

The shower greywater heat recovery could be visualized with the basic schema as in Figure 1.12 to realize how the heat recovery carried out.
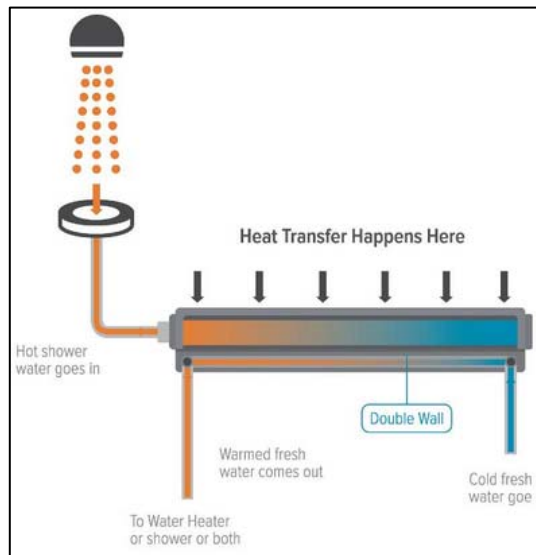
Figure 1.12. Basic scheme of heat recovery from shower greywater [28].

The select of the correct installation option for greywater heat recovery units, which are characterized by different configurations in the case of existing constructions, relies on numerous things including shower water heater location, availability of space of the system, and in addition to the ease in the implementation of installation work. Figure 1.13 shows the heat recovery unit mounting options [29].
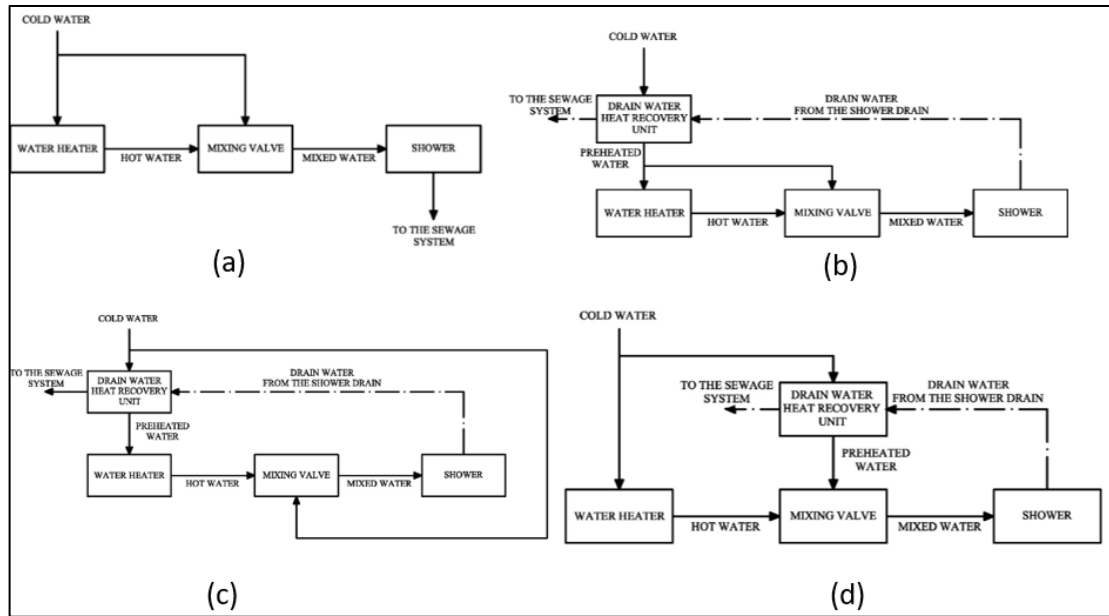
Figure 1.13. (a, b, c, d) Shower greywater heat recovery mounting options [29].

Increasing number of organizations and scientists are attempting to figure out how to recuperate waste heat from shower greywater because of expanding utilization of private high temperature water use, the potential of financial advantage in heat recovery. Some greywater heat recovery systems were constructed due to the work of various sorts or heat exchangers.

The aim of the experimental study is to search the performance of the heat recovery from the greywater of the shower. Saving energy to preheat the water used in the shower by connecting heat exchangers to the bath tray in two different placements that are the horizontal and vertical, and the preserving the environment through the possibility of reducing the amount of carbon emission and energy is used by the electric heater to heat the water during the shower.

Also, this study can have economic significance in the long term by the release of people about the importance of saving the consuming household-based energy by installing heat recovery units to the shower and its effect on environment. Additionally, there is scientific importance, to students, researchers and those are interested in studying in the related field.

PART 2
LITERATURE REVIEW

Manouchehri et al. discussed about the change in greywater heat recovery effectiveness by comparing heat exchangers that are positioned in different tilt angles from vertical orientation. Study showed that performance of the systems can goes worse by positioning them at an angle higher than 2° from vertical. Also, the efficiency of the mentioned angle has been regulated by ability at the vertical, delivering a suitable rate which refers the drop of performance because of the tilt angle [30].

Niewitecka studied on a heat recovery unit and assessed the quantity of the heat which may be gotten by the use of a greywater heat recovery system. It has been determined that by using a spiral type heat exchanger, approximately 50% efficient recovery of heat from the greywater is possible and it amounts approximately 1100 kWh. This gives a saving of cost amounted $ 145. It must be taken into consideration that the total cost of investment comprising the price of purchase and device installation in addition to a cost resulting from the system operation through the time of guarantee [31].

Shields and McNabola suggested the investigation and improvement of the horizontal drain wastewater heat recovery system for a residential shower. They showed that energy recovery at a satisfactory level from horizontal shower drains is possible by using heat recovery equipment's. However, the implementation of this technology nationally has been revealed to have possibility on bringing important decrease in the use of energy and emissions of CO_2 [32].

Wong et al. investigated the possibility of the heat recovery from shower greywater of bathrooms that are equipped with instantaneous water heaters. Results indicated that is between 4 to 15% of heat of shower water could be recovered through the heat exchanger. In addition, it is shown that the assumption has been made in the arrangement of the system, the experimental errors and simulations may pose

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suspicions to the estimations. In spite of the space limits for installation, good designs for the heat exchanger with modified payback time is necessary [33].

Frijns et al. commented about the water industry energy consumption global warming potential and they defined the equivalent amount is about 934,800 tons CO_2 per year. Energy use is also equivalent about 56% of the water sector carbon footprint. The rest of carbon contribution is from the process emission in addition to the indirect emissions. Altogether, the footprint of carbon for the public water sector of Dutch is approximated to be 1.67 million tons every year [34].

Chae and Kang discussed that the heat recovery from the greywater appeared to be the most effective factor on the energy independence, which depends directly the number of operation period of the heating and cooling devices. Change of climate increased worries about the water sector and the importance to find ways to enhance energy independence and in the same time, enhancing the quality [35].

Meggers and Leibundgut clarified the recovery of heat loss from the greywater in residential scale. They concluded that for four bedrooms resident the bathroom hot water heating need approximates 2400 kWh and supported with only 400 kWh for input of energy by greywater heat recovery [36].

Cipolla and Maglionico searched the usability of sewer water heat as a source. They argued that the amount of gainable energy from greywater depends on the ideal heat recovery systems design and the parameters that are the temperature and flow rate [37].

Oesterholt and Hofman discussed about the installation of the heat exchangers for a student housing complex in Amstelveen. They assessed that 100 showers sink heat exchanger installation theoretically makes possible approximately 50% of heat recovery from shower greywater. Due to the obtained results they guessed that € 100 of annual saving for a one family size house could be possible. Additionally, the payback period of the investment estimated about 6 years for a single shower unit [38].

Liu and Jiang studied the usage of exhaust heat of a public shower facility to increase the heat pump unit performance. They argued that by the heat recovery, water heater power requirement decreased [39].

Zaloum and Lafrance compared different heat recovery unit's performance. They tried to optimize the performance and size. They concluded that the longer pipe arrangement tends only increase cost; shorter pipes have better performance on a per foot basis [40].

Stec and Kordana evaluated the cost effectiveness of the usage of heat recovery units at a shower. They determined that about 29% of the wasted heat recovery is possible. The results reached by this study is characterized by practical aspects and may offer direction for probable stockholders of similar facilities. The income of the application of examined installation modify in these countries may be even greater [41].

Ramadan et al. studied experimentally heat recovery from shower greywater. The study suggested heat recovery by a system to recover the wasted energy from the hot drainage wastewaters by coupling with heat pump by the use of three dissimilar circumstances. They reached maximum \$ 47 saving and and 259 kg of CO_2 emission could be declined by heat recovery [42].

Tanha et al. experimentally studied on a greywater heat recovery unit effectiveness. They found that annual heat recovery capacity of the unit is 789 kWh and an overall performance of it is approximately 50% [43].

Liu et al. compared two dissimilar types of thermal energy recovery units for public showers. The greywater of shower system has been strained and directed to the heat exchanger unit to preheat the main water. The preheated temperature of water was increased from 12 °C to 25 °C and the temperature of greywater dropped from 30 °C to 17 °C, correspondingly [44].

Wallin et al. targeted to study the greywater heat recovery performance in the arrangement of vertical inline heat exchanger. The investigation showed that large portion of heat recovery can be available by vertical arrangement [45].

Guo et al. designed a greywater heat recovery unit for shower. They got heat recovery performance more than 50%. Results also indicated that by using heat recovery equipment's to the shower systems a good economic property could be reachable. Nevertheless, many waste heats is available and we may enhance the device performance by designing new types of these devices in near future. Moreover, it is important to develop new techniques in the device to decrease the drop of water pressure pass through the exchanger [46].

Smith studied experimentally on a heat recovery unit that is connected in a house. The results of the study showed that comparative amount is highly depending on the social class and the occupants' lifestyle. Many studies performed on heat recovery system which were installed in the house has revealed that about 10% of energy saving and payback about three years [47].

Parker and Tucker studied on a residential water heating system. The study described the building and testing the houses hot water system. They tried to recover heat by employing greywater heat recovery unit. They succeeded maximum of 32% of recovery [48].

Ni et al. studied on a greywater heat recovery unit to increase residential efficiency. They concluded the possibility of decrease in energy consumption that is about 33.9% by the heat recovery [49].

Bartkowiak et al. introduced the design of a greywater heat recovery unit to reduce the energy requirement of a residential shower. They concluded that greywater heat recovery unit could makes possible an average of $ 160 saving from an electric water heater consumption. The finding of the study compiled to software in order to guess the cost of individual household and saving of energy hoping that real computations make the technology of GWHR more ordinary. In addition, this experiment presented that GWHR is the most practicable to household with recurrent shower use in cold weathers [50].

Torras et al. analyzed the capability of a greywater heat recovery unit at different rates of flow and temperatures. They concluded availability of heat recovery from 34% to 60% [51].

Lee et al. installed a heat exchanger in the shower, it is a plate consisting of three heat exchanger devices, they assumed that a family occurs with 4 people and the total shower duration is 60 minutes with 40 ℃ hot water after conducting the experiment they found its possible provide about 1.937 kWh [52].

Ramadan et al. were discussed about the recovery from hot greywater in their study. They assessed that is the effectiveness of heat recovery through a heat exchanger depends on the rate of mass flow in addition to the fluid domain temperature difference [53].

Lee and Bedrossian studied the effect of counter-flow heat exchanger application on a thermosiphon system experimentally. They constructed a numerical model to evaluate its performance [54].

Farr et al. discussed in their studies about the recovery of heat load from the mine discharge water. They concluded the heating energy gain approximately 72 MW [55].

Zarea et al. studied on the design enhancement of a crossflow arrangement plate-fin type heat exchanger, numerically. They succeed about the usage of the Bees Algorithm numeric model for the design process of the heat exchanger [56].

Collins et al. discussed about the retrieval of heat from greywater by a falling film heat recovery unit and evaluated the cost effectiveness of it. They suggested the requirements of studies that are domestic scale and low flow rate cases in the future [57].

Beentjes et al. discussed about the falling film greywater recovery unit. It is concluded that by increasing flow rate, the performance of unit decrease [58].

Alobaid et al. studied the heat recovery from steam generator during its startup period. They generated a numerical model and compared with experimental studies. They concluded about the good agreement of numerical and experimental results [59].

Manouchehri and Collins discussed about greywater heat recovery unit performance to preheating of tap water. They related the unit performance with the flow rate, and heat transfer surface area. They discussed the coincidence of numeric and experimental results [60].

Ruiz et al. studied the drain water heat recovery unit phase change material application. They concluded that phase change material plate application could be a good alternative to save more energy in the residential size greywater heat recovery units [61].

Dong et al. studied experimentally on a shower greywater unit. They assert that about 70% of greywater energy could be recovered from a single family shower unit [62].

Akbarzadeh et al. numerically investigated the thermal performance of a greywater heat recovery unit. They concluded that by the increase of flow rate decrease in the performance [63].

Stewart et al. discussed about the finned tube heat exchanger optimization methodology. They discussed 23% performance enhancement possibility by the optimal design of a finned tube heat exchanger [64].

Yousefi et al. examined the design optimization process of a heat exchanger. They assert the generation of a new design algorithm that is simple, accurate and applicable [65].

Raja et al. exemplified a new methodology to optimize the crossflow plate heat exchanger. Their algorithm is directly related with the flow parameters that are flow length, fin sizes, and configuration [66].

Li et al. tried to reduce energy consumption and carbon emissions, they studied three heat recovery plans. And compare them in a plant for processing aquatic products. According to the results, the different heat recovery modes have a different energy efficiency, and the energy recovery efficiency can reach approximately 40%. This depends on the temperature of the inlet and outlet of the recovered water [67].

Paduchowska et al. installed the GWHR unit in two student dormitories in Poland and after measurements and analysis they concluded that about 53% of greywater energy could be saved by using heat exchangers [68].

Cooperman et al. used a copper heat exchanger immersed in a freshwater tank. Warm wastewater flows through the heat exchanger and provides a preheated water inlet for the water heater.

.

When placing the heat exchanger between drainage and incoming freshwater they concluded that it could save up to 40% of this wasted energy and reduce energy that is used to heat the required water is between 49% to 54% [69].

Nolde and Partne launched a program for recycling heat from greywater by a heat exchanger. Based on this result after 1.5 years of research and monitoring, it is possible to save 40 kWh of thermal energy through this system [70].

Picard et al. focused on the two systems to reduce domestic consumption of energy. They tried to recovery of energy from greywater for bathing by the heat exchanger. They concluded from their study that it can save between 36% to 49% annually of the energy used to heat the water, i.e. saving between 691-934 kWh/year [71].

Nobile created a heat exchanger to recover the heat from the grey shower water, by a device that has two channels connected to each other, one for the cold water coming to the shower and the other for the wastewater coming out of the shower. After installing it to the shower, the device was able to save approximately $ 50 annually in the energy costs used to heat the water with the electric heater, in a house of four people they showering daily [72].

Ted Collins et al. tested a heat exchanger in a residential building to recover heat from greywater for a shower and after study and they found that there is a possibility of saving equivalent between 30% to 50% of the energy requirement to heat the shower water [73].

Takla et al. presented a practical study of two types of heat casing. After converting the results into readings and comparing them, it was concluded that the sheet heat exchanger has a higher efficiency than the tubular heat exchanger with the cover in terms of heat transfer coefficient the economic cost and the financial returns also [74].

Eslami et al tested a device relate with GWHE to reduce the electricity consumption used in a number of electric water heaters, they concluded that the energy required for heating water annual is 5299 kWh, and 4501 kWh without and with a GWHE, respectively [75].

Springer et al. studied heat exchangers for energy recovery from wastewater were incorporated into a sports facility that contains 8 showers, and the results of the study indicated that the heat capacity that can be provided reaches about 50% annually [76].

Brunn installed two types of heat exchangers: Shell and tube and helical coil in a gym that contained 10 showers and was able to raise the cold water temperature from 26.3 °C to 34.3 °C and the annual average energy saving was around $ 1400 [77].

Culha et al. compared several studies that were conducted to recover heat from wastewater in various fields. Based on the results of experiments conducted on heat exchangers to recover heat from wastewater, it appeared that they could achieve a reduction in the cost of energy up to 40% and that without using these technology about 90% of energy is wasted in the channel sewage , and using these systems reduces carbon and heat emissions to the environment [78].

Gavilán et al. implemented a system of heat exchanger at a building, which consists of 23 apartments and it is estimated that 60% of the total water used in the building is hot

water. After study and research, they found that 23% of the energy used to heat the building water can be saved [79].

Vaičiūnas et al. installed a system of heat exchanger in sport and wellness center in Lithuania to recover heat from greywater. The center contains 20 shower and they tested the exchanger for a week daily from 8 in the morning 9 in the evening. They concluded that this heat exchanger system could provide approximately 53% of the energy needed to heat water in this center [80].

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PART 3

THEORETICAL BACKGROUND

In this study, it is aimed to search experimentally the recoverability of shower greywater waste heat with a heat exchanger in two different position: horizontal and vertical that can be connectable to the residential shower cabin. There are three types of heat exchangers that are helical coil, brazed plate and tube in tube were used during the experimentations. At this section, we will summarize the theoretical base of heat transfer which is occurred in heat exchangers. The rate of heat exchange between two fluids could be equated as in eq. (3.1).

$$\dot{Q} = \dot{m}\, c_p\, \Delta T = A\, U\, \Delta T_{LMTD} \tag{3.1}$$

In eq. (1), $\dot{Q}$ designates the heat exchange rate, $\dot{m}$ presents the mass flow rate, c_p designates the specific heat transfer coefficient, ΔT symbolize the difference of temperature, A represents the surface area of heat exchange, U represents the overall heat transfer coefficient, ΔT_{LMTD} represents the difference of logarithmic mean temperature. The average heat exchange between cold preheating water and the shower greywater could be determined by the eq. (3.2).

$$\dot{Q} = \frac{\dot{Q}_{pw} + \dot{Q}_{gw}}{2} \tag{3.2}$$

where $\dot{Q}_{pw}$ is the heat exchange rate to preheating water, $\dot{Q}_{gw}$ is the heat exchange rate from greywater. The logarithmic temperature differences could be equated as in eq. (3.3).

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\frac{\Delta T_1}{\Delta T_2}} = \frac{\left(T_{gw,in} - T_{pw,out}\right) - \left(T_{gw,out} - T_{pw,in}\right)}{\ln\frac{\left(T_{gw,in} - T_{pw,out}\right)}{\left(T_{gw,out} - T_{pw,in}\right)}} \tag{3.3}$$

In eq. (3), $T_{gw,out}$ and $T_{gw,in}$ represent the greywater heat exchanger inlet and exit temperatures. $T_{pw,in}$ and $T_{pw,out}$ are the preheating water heat exchanger inlet and exit temperatures. Eq. (3.4) defines the overall heat transfer for tube in tube and helical coil heat exchangers.

$$\frac{1}{U} = \frac{A_o}{h_i A_i} + \frac{A_o \ln{^{d_o}/_{d_i}}}{2\pi k L} + \frac{1}{h_o} \qquad (3.4)$$

Overall heat transfer coefficient could be defined as in eq. (3.5) for brazed plate heat exchanger.

$$\frac{1}{U} = \frac{1}{h_i} + \frac{t}{k} + \frac{1}{h_o} \qquad (3.5)$$

The symbols are d_i and d_o designates the inner and outer diameter of tubes. A_i and A_o represent the internal and external surface areas. h_i and h_o are internal and external side convection factor. k represents the thermal conductivity. L represents the length of tube.

PART 4
METHODOLOGY

In this study, three different types of heat exchangers that are tube in tube, helical coil, and brazed plate are connected to a residential scale shower unit with two different positioning, and the saving that can be achievable in water heater energy consumption were experimentally studied by using the shower greywater heat to preheat the shower water fed from the network to the water heater. The brazed plate and helical coil heat exchangers heat transfer surface areas are equal and 0.06 m². Tube in tube heat exchanger heat transfer surface area is about 0.03 m². Figure 4.1 shows the heat exchangers which are used in the experiments.
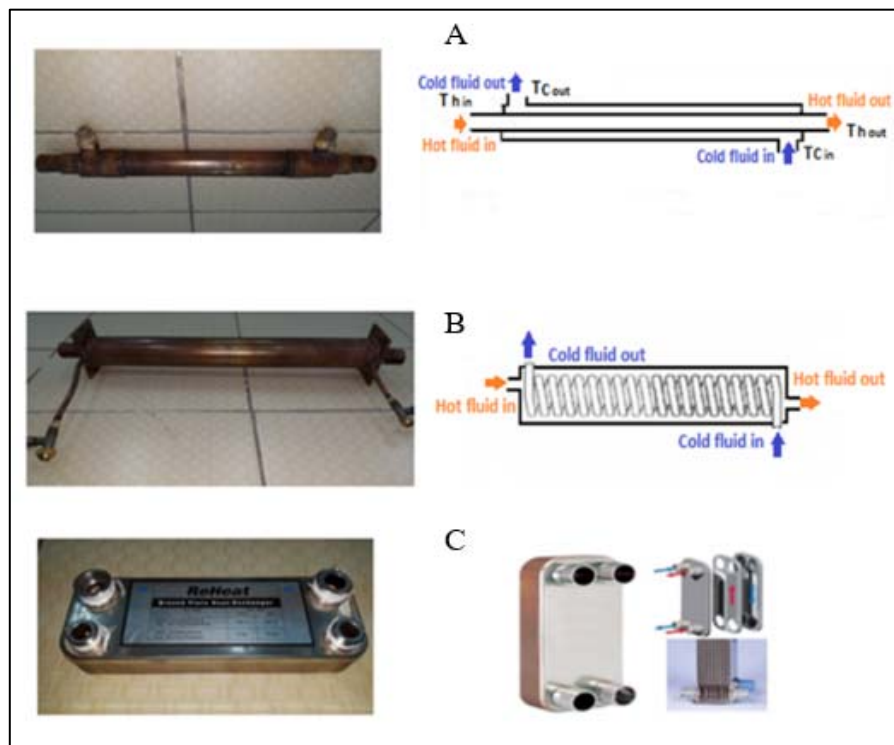

Figure 4.1. Experimented heat exchangers: (A) tube in tube, (B) helical coil, (C) brazed plate

Heat exchangers which were connected to the shower with a mounting configuration as seen in Figure 4.2.
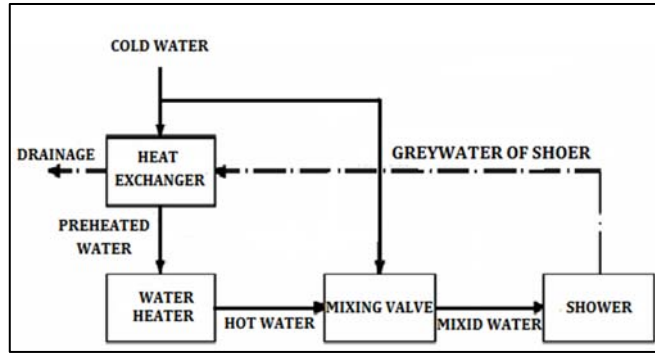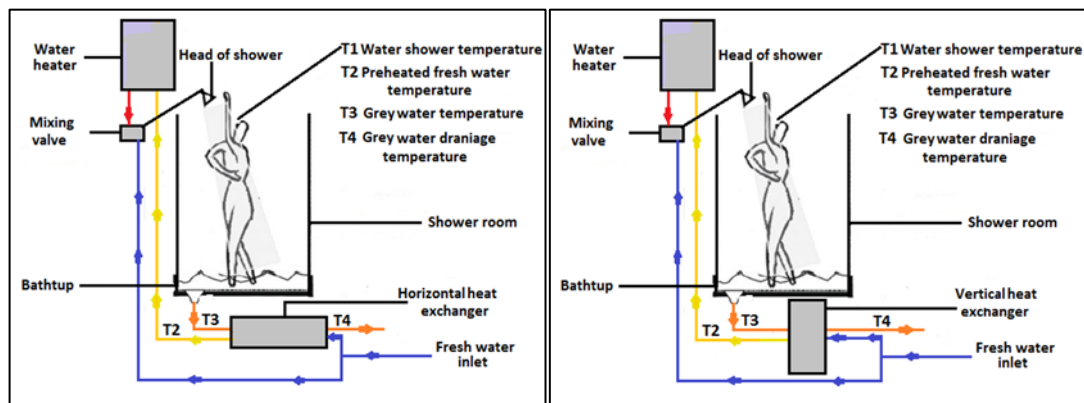
Figure 4.2. Heat exchanger mountining configuration to shower.

Experimentations were done on two different configurations, the first one is the horizontal and the second one is the vertical attachment of heat exchangers to the shower unit. The horizontal and vertical positioned heat exchanger attachment to the shower were schematized as seen in Figure 4.3.

(a)   (b)

Figure 4.3. Heat exchanger attachment to shower a) horizontal, b) vertical

Experimentation unit was built with plexiglass panels, a shower tray, rain shower headset, shower faucet, fixing equipment's and pipes. K-type thermocouple and CEM DT-3891G datalogger couple were utilized to measure the temperature data. The shower rate of water flow was measured by Arduino Uno by taking signal from YF-S201 sensor of water flow. Water heater energy consumption has been measured by T-Technic PM6907C digital wattmeter. The constructed experimentation setup and its' equipment's were given in Figure 4.4.
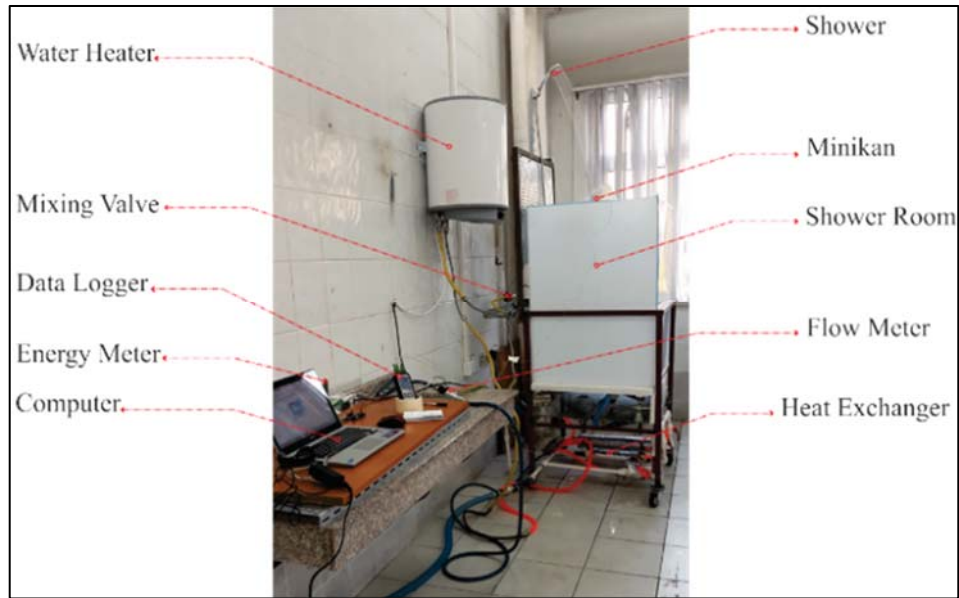
Figure 4.4. Picture of experimentation setup.

The horizontal and vertical heat exchanger attached shower experimentation setup data taking points were given in Figure 4.5.
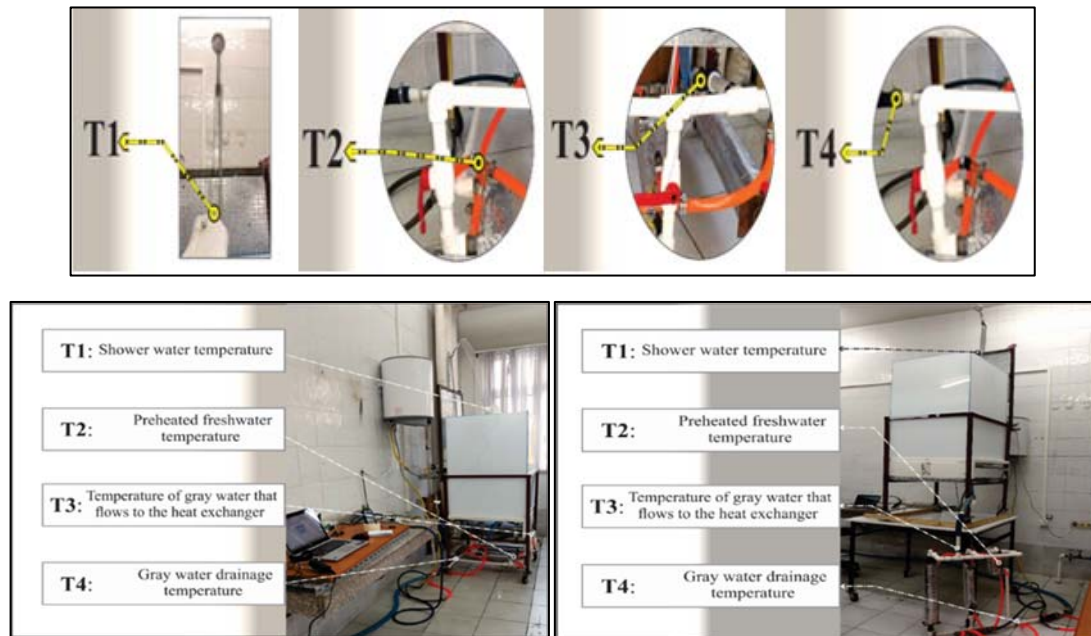
Figure 4.5. Shower experimentation setup with horizontally and vertically attached heat exchangers and data taking points.

Water temperature of the shower has been set to 40 ºC and the shower period have been chosen 30 min to the experiments. The water flow rate of shower has been regulated to 2 L/min because of the laboratory tap water flow capacity. Each experiment was started with the water heater fully filled and the water warmed up. After 30 minutes of experimentation, the shower water was turned off, the energy consumption of the heater was measured until water heater full filling and heating the water completely.

PART 5

RESULTS AND DISCUSSION

In this part the collected data by the measurements through the experimentations, which were explained in the previous chapter were assessed to evaluate the heat recovery potential of tube in tube heat exchanger, brazed plate and helical coil heat exchangers from shower greywater for two different positioned attachment of them. In this respect, the shower setup was experimented without heat exchanger attachment to reach the regular energy consumption of water heater for a half an hour shower period. The average set shower water temperature and temperatures of drainage and tap water were presented in Figure 5.1.
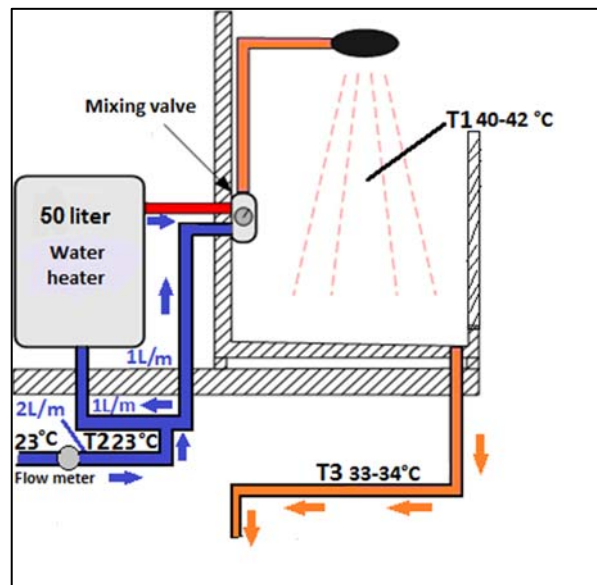

Figure 5.1. Shower water temperatures.

The measured temperature of shower and drainage water that flows from shower tray to drainage were given in Figure 5.2.
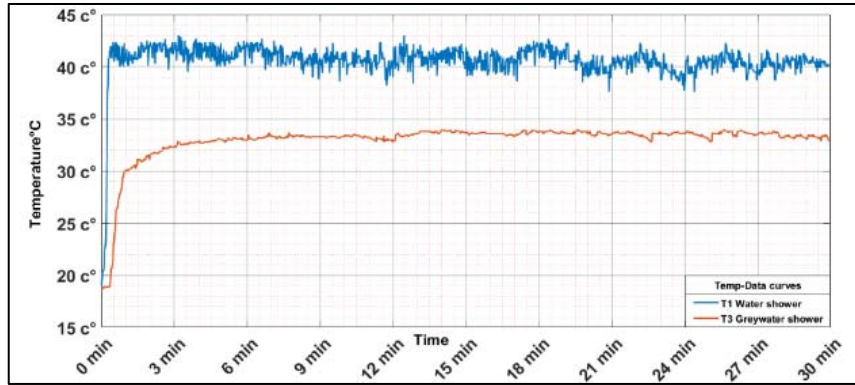
Figure 5.2. The measured shower and greywater temperature data.

As seen in Figure 5.2, temperature data are fluctuating in wide range and to eliminate this unwanted case, the curves were fitted due to the 6th order polynomial equation that is given in fitted curve figures. Figure 5.3 presents the fitted curves of Figure 5.2.
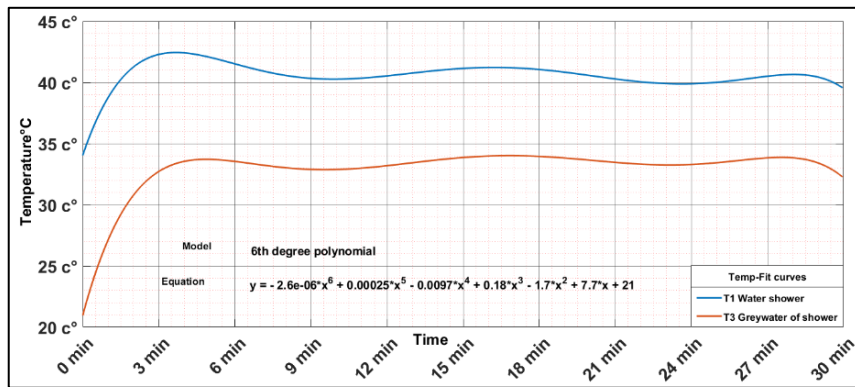
Figure 5.3. Fitted shower and greywater temperure data.

As clarified in the Figure 5.3, the water temperature of shower was kept in an average temperature of 41 ºC during the half hour shower period. The water lost an amount of energy until it is reaching from shower tray to the drain line, and its temperature decreases to an average of 33 ºC. It seems possible to the preheating of the tap water that is supplied to the heater at 23 ºC in a heat exchanger by using the shower greywater. The average value of the water temperatures measured by the performed experiments at the tube in tube heat exchanger horizontally and vertically connected shower units are given in the Figure 5.4.

(a)   (b)

Figure 5.4. Average water temperatures by the attachment of tube in tube heat exchanger a) horizontally, b) vertically

Figure 5.5 shows the measured water temperature data of the tube in tube heat exchanger that is attached to the shower system.

(a)

(b)
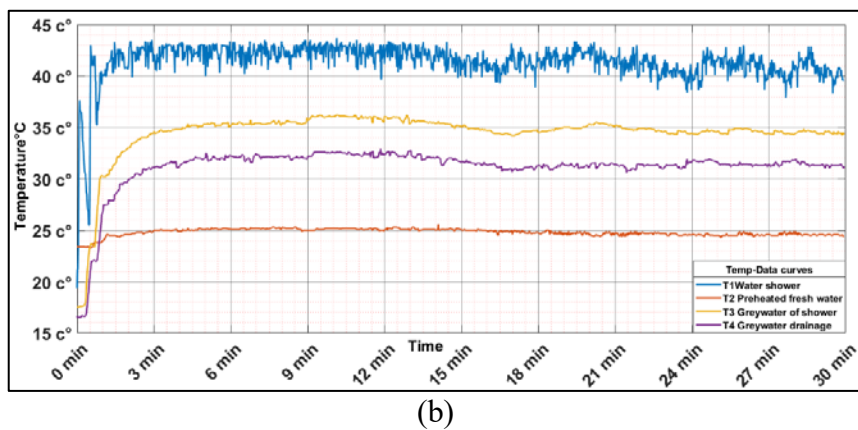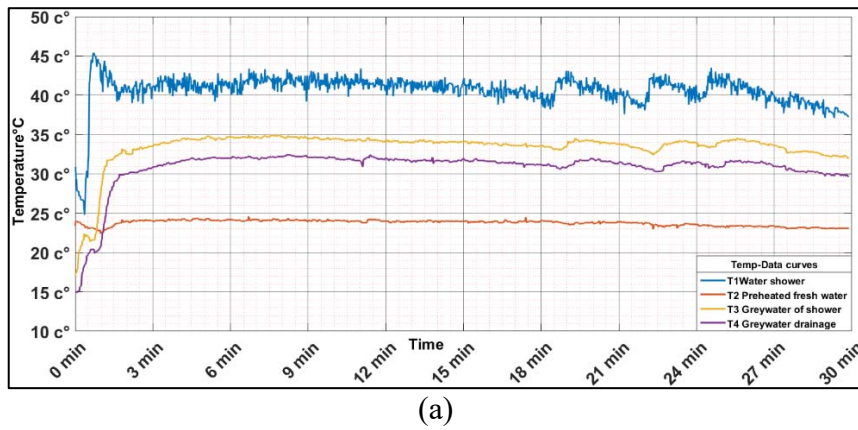
Figure 5.5. Water temperatures by the attachment of tube in tube heat exchanger a) horizontally, b) vertically

The noisy data in Figure 5.5 that were fitted due to the 6th order polynomial equation is seen as in Figure 5.6.
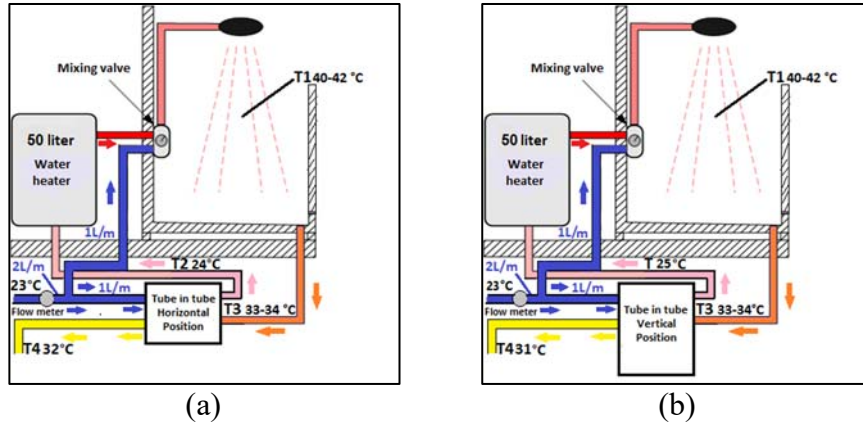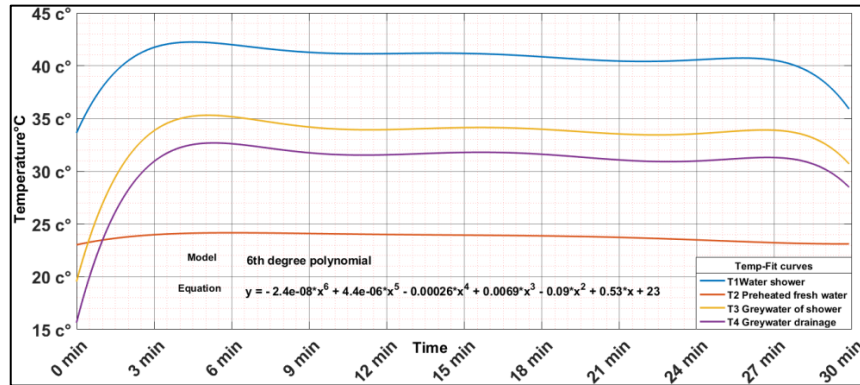

(a)
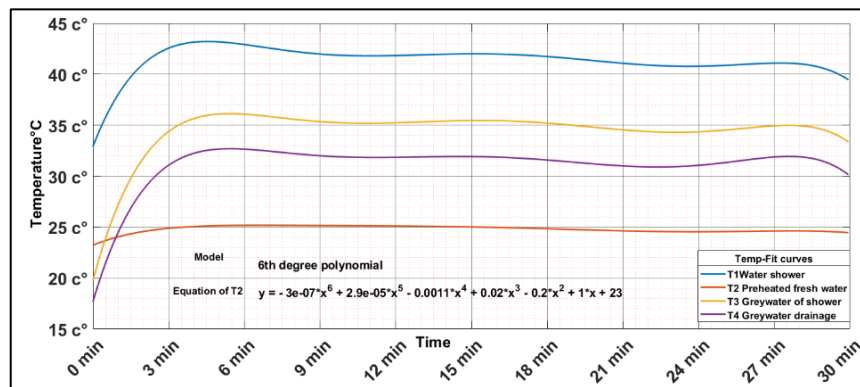
(b)

Figure 5.6. Curve fitted water temperatures by the attachment of tube in tube heat exchanger a) horizontally, b) vertically

It is observed that the fed tap water to the heater undergoes 1 $^\circ$C temperature increase in the horizontally positioned tube in tube heat exchanger. By vertical heat exchanger positioning, approximately 2 $^\circ$C temperature increase in the preheated water was measured. The theoretical amount of energy gain of fed tap water to heater by preheating is approximately 0.139 kWh by the state of horizontal position of the heat exchanger and approximately 0.279 kWh for the vertical positioning of the heat exchanger. The heat exchanger of helical coil was attached to the shower unit was also experimented and measured average values of the water temperatures that are shower water, preheated water, greywater, and the drain water temperatures were presented in Figure 5.7.

(a) (b)

Figure 5.7. Average water temperatures by the attachment of helical coil heat exchanger a) horizontally, b) vertically

The measured water temperature data were given in Figure 5.8.

(a)

(b)

Figure 5.8. Measured water temperatures by the attachment of helical coil heat exchanger a) horizontally, b) vertically

The noisy data set were curve fitted and shared in Figure 5.9.

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(a)

(b)

Figure 5.9. Curve fitted water temperatures by the attachment of helical coil exchanger
a) horizontally, b) vertically

In Figure 5.9, it is presented that the measured water temperatures that are shower water, preheated water, greywater from shower and greywater from the heat exchanger to drain in case of the attachment of helical coil heat exchanger to the shower unit, horizontally and also vertically. It was noted that the heat exchanger of helical coil was able to raise the temperature of the water entering the electric heater from 23 °C to 26 °C in the horizontal case and add about 3 °C to tap water, but in the vertical case, the tap water temperature in the electric heater increased by 6 °C, that is from 23 °C to 29 °C, and the greywater temperature for the shower decreased about 5 °C for the horizontal positioning and 8 °C for the vertical positioning. Heat exchanger of brazed plate attachment to the shower unit in horizontal and vertical positioning were experimented and water temperatures that are shower water, preheated water, greywater, and drain water from heat exchanger to drain were measured and the average values were shared in Figure 5.10.
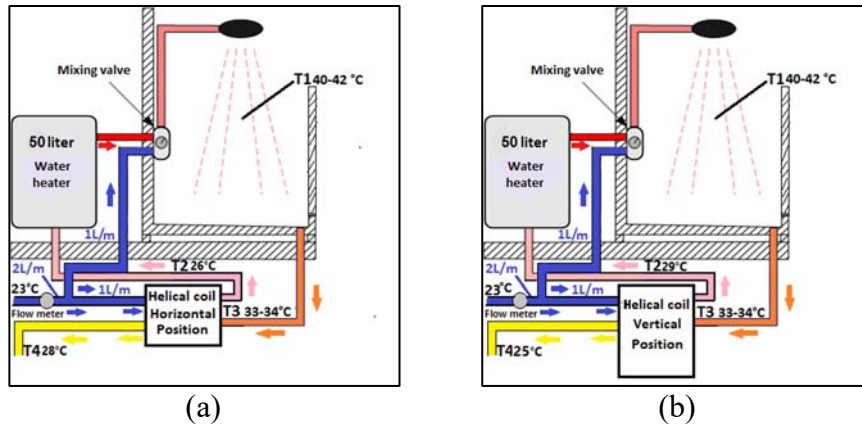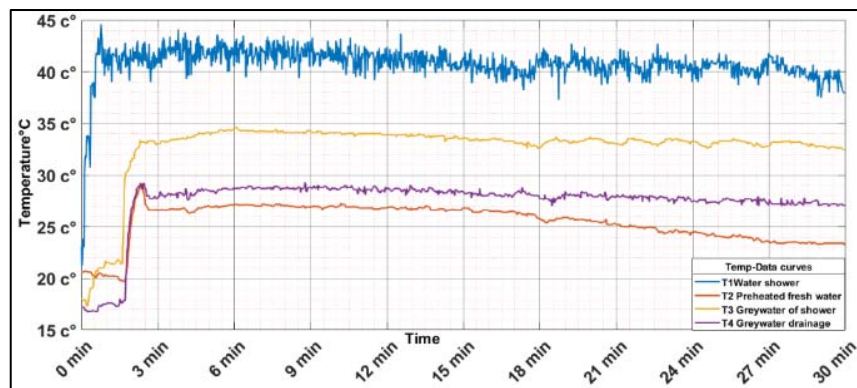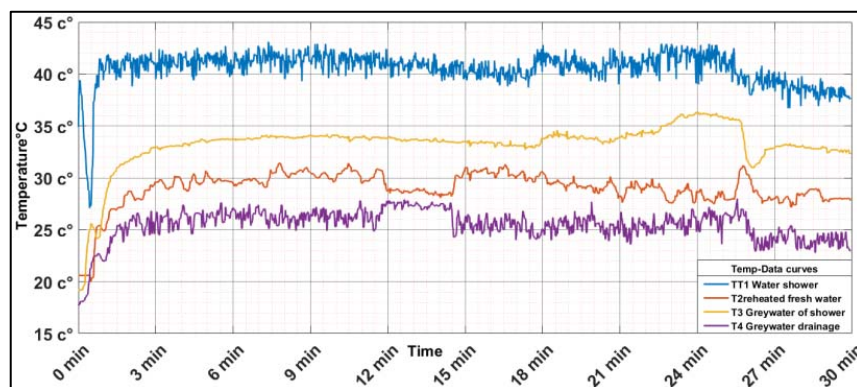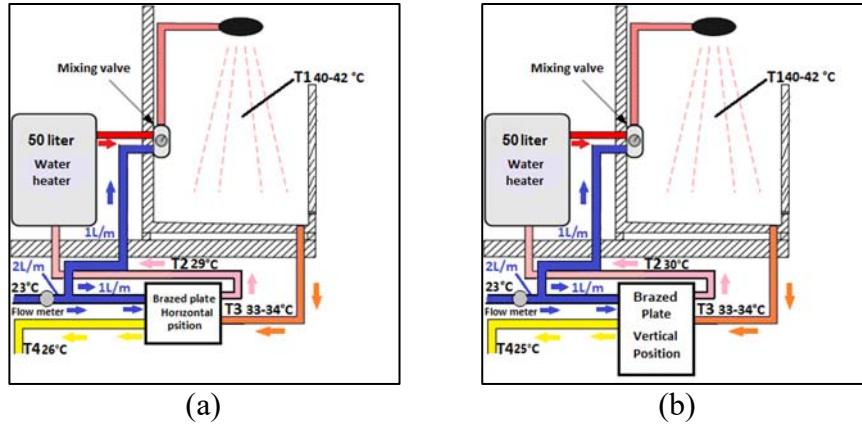
Figure 5.10. Average water temperatures by the attachment of brazed plate heat exchanger a) horizontally, b) vertically

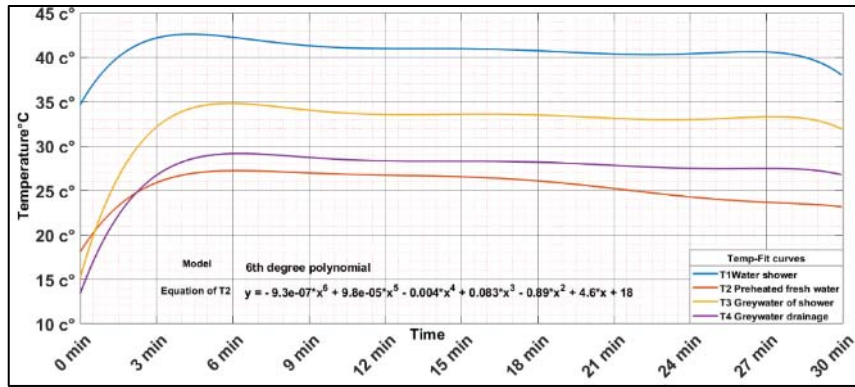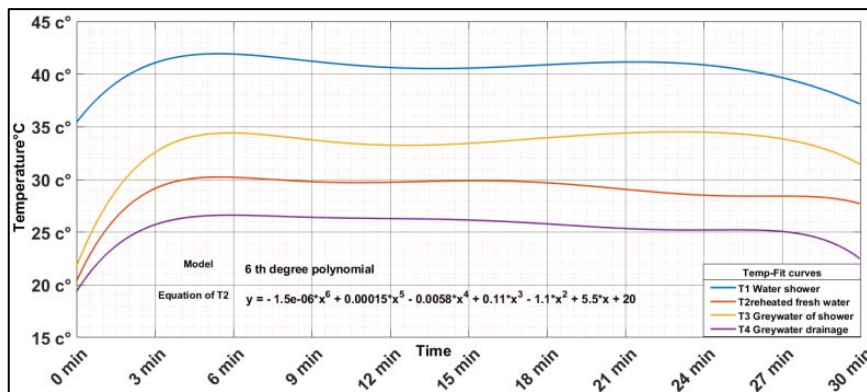The measured water temperatures were visualized in Figure 5.11.
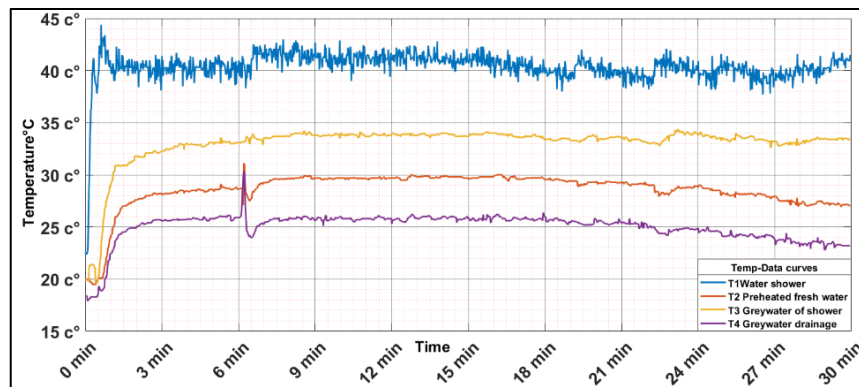
(a)
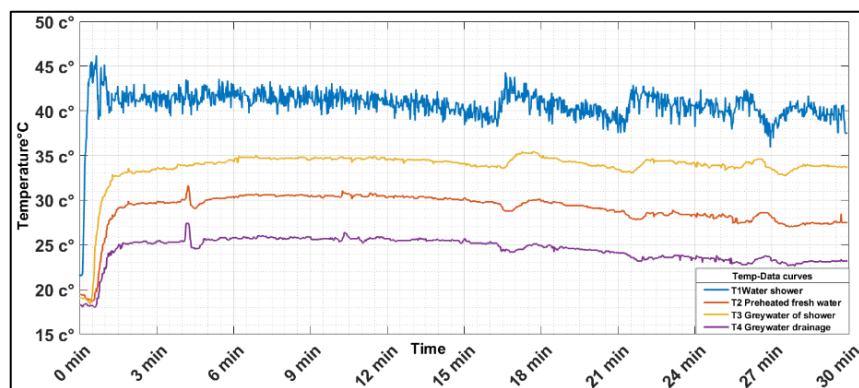
(b)

Figure 5.11. Measured water temperatures by the attachment of brazed plate heat exchanger a) horizontally, b) vertically.

The fluctuated data set is seen in Figure 5.11 that was curve fitted and were given in Figure 5.12.
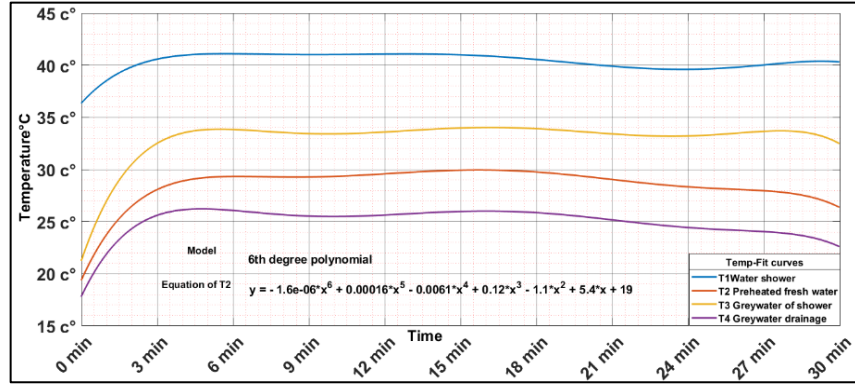
(a)
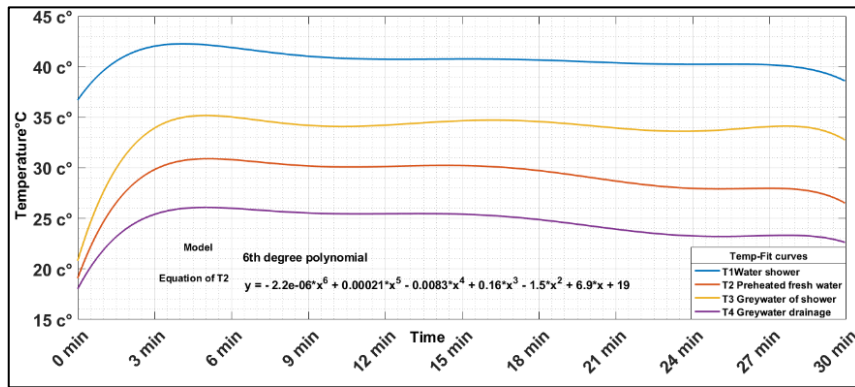
(b)

Figure 5.12. Curve fitted water temperatures by the attachment of brazed plate heat exchanger a) horizontally, b) vertically

Measured data of the shower system that is connected to the brazed plate heat exchanger is seen in the Figure 5.12. It was observed that the tap water which is flowing through the heat exchanger had been heated to 29 °C in horizontally positioned heat exchanger and 30 °C in the vertical positioned of the heat exchanger, too. The temperature of tap water is raised almost 6 °C degrees for the horizontal positioning and 7 °C for the vertical positioning. The temperature of the greywater of shower is lowered by about 7 °C for the horizontal positioning and 8 °C in the vertical positioning. The energy gain theoretical value of the tap water fed to the heater by preheating is determined as approximately 0.836 kWh for the horizontal position state of the heat exchanger and approximately 0.975 kWh for the vertical position. Table 5.1 and Table 5.2 summarize the results for the horizontal and vertical attachment of

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heat exchangers to the shower system. The theoretical amount of saving was compared with the measured amount of saving due to the data that were given in Table 5.1 and Table 5.2 and it was recognized that data sets coincident with each other. In real case, we saved less energy than the theoretical amount by the heat exchanger attachments. The rate of energy saving for per half an hour showering period is approximately about 2.56%, 16.13% and 20.62% for the horizontal attachment of the heat exchangers that are tube in tube, helical coil and brazed plate in the order. The saving rate for the vertically attached case of the heat exchangers to the shower gives better saving opportunity than the horizontal one. The rate of saving was calculated about 7.09%, 24.69% and 27.34% for the vertical connection of tube in tube, helical coil and brazed plate heat exchangers as seen in Figure 5. 13.
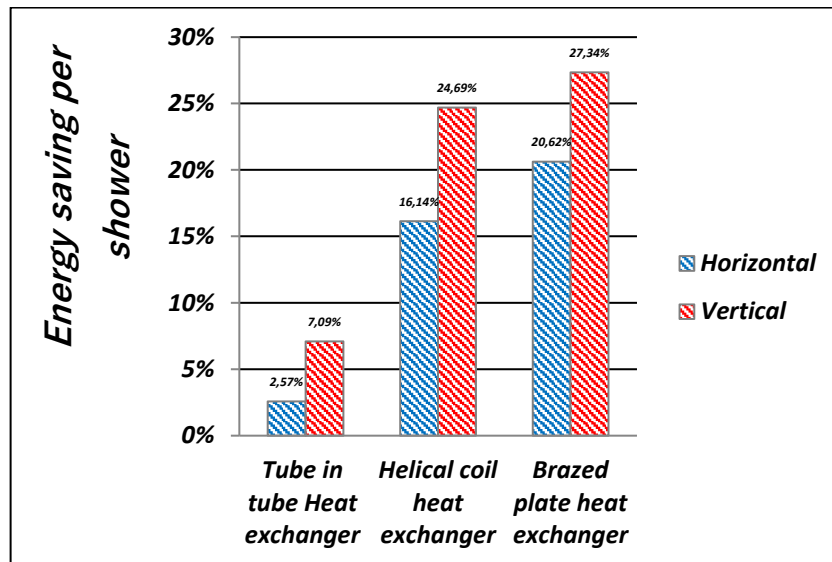
Figure 5. 13. Rate of energy saving per shower by heat exchanger

As seen in Table 5.1, the water heater energy consumption is about 2.454 kWh for half an hour shower at 40 °C and 60 L of shower water usage. In the reality, by the attachment of tube in tube, helical coil and brazed plate heat exchangers to the shower drain line in horizontal positioning the energy recovered from the shower greywater at an amount of 0.063 kWh, 0.396 kWh and 0.506 kWh. 0.174 kWh, 0.606 kWh and 0.671 kWh of energy recovered to preheat the refill water of the water heater in case of vertical attachment of heat exchangers as shared in Table 5.1 and Table 5.2. and as shown in Figure 5.13.

Table 5.1. Energy consumption analyses for horizontal positioning of heat exchangers

Type of heat exchanger	Shower water flow rate (L/m)	Tap water temperature (°C)	Preheated water temperature (°C)	Theoretical amount of saved energy (kWh)	Measured value of energy consumption of water heater (kWh)	Percentage reduction in energy for per shower (%)
without	2	23	-		2.454	-
Tube in tube			24	0.139	2.391	2.567
Helical coil			26	0.418	2.058	16.136
Brazed plate			29	0.836	1.948	20.619

Table 5.2. Energy consumption analyses for vertical positioning of heat exchangers

Type of heat exchanger	Shower water flow rate (L/min)	Tap water temperature (°C)	Preheated water temperature (°C)	Theoretical amount of saved energy (kWh)	Measured value of energy consumption of water heater (kWh)	Percentage reduction in energy for per shower (%)
without	2	23	-		2.454	-
Tube in tube			25	0.278	2.280	7.09
Helical coil			29	0.836	1.848	24.69
Brazed plate			30	0.975	1.783	27.34

The result from Table 5.1 and Table 5.2 was used to find the amount of total savings in one year. A typical family involves of four individuals in Turkey. By assuming each individual take shower three times in a week. For a year total amount of 624 times of shower can be taken and the amount of saving of energy is equivalent to 39.31 kWh and 108.57 kWh by the attachment of tube in tube heat exchanger in vertical and horizontal positions. By attachment of helical coil heat exchanger, the saving amount can be determined approximately 247.1 kWh and 378.14 kWh in the same order for horizontal and vertical attachments. Lastly, by the application of brazed plate heat exchanger about 315.74 kWh and 418.7 kWh of electricity to heat the shower water can be saved by the recovery of heat from greywater as presented in Figure 5.14.
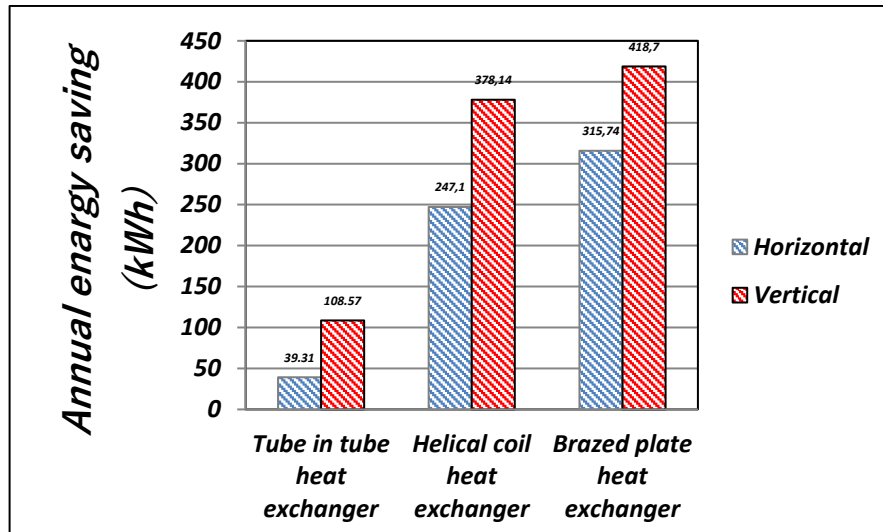
Figure 5. 14. Annual energy saving

The cost of attachment of a heat exchanger for the shower unit is approximately estimated about minimum $ 87 with its hoses and fixing equipment's. The minimum annual saving could be reached about 39.31 kWh by tube in tube heat exchanger horizontal attachment and the price of this annual saving is approximately $ 4 due to the current electricity unit price is $ 0.102/kWh. The payback period can reach 20 years. Tube in tube heat exchanger attachment is not seeing suitable to the investment. The minimum payback period can be approached by the maximum amount of saving. Approached in this respect, about 418.7 kWh of electricity can be saved by the attachment of brazed plate heat exchanger to the shower system. The economical size of the saving is approximately $ 42.7, and the minimum 2 years of payback is seeing possible. The heat exchanger type and the positioning directly affect the amount of saving rate and payback period. In this study, we determined about minimum $ 4 and maximum $ 42.7 of annual saving. The production of electricity from natural gas or coal is equivalent to the 0.825 kg/kWh carbon emission [81], by the possible saving, minimum 32.43 kg and maximum 345.42 kg of carbon emission load could be eliminated annually.

PART 6

CONCLUSION

In this study, we searched and investigated the possibility of heat energy recovery from greywater of a domestic scale shower by the usage of heat exchangers. They were attached to the shower basin of the experimentation setup that were designed for the study and detailed in the methodology section. Heat exchangers that were connected to the shower, are three different types such as tube in tube, helical coil, and brazed plate. Additionally, they were installed to the setup in two different cases that are horizontal and vertical. Each experimentation period was occurred in 30 minutes of shower time. The results showed that the heat recovery potential is equivalent to the 2.56%, 16.13% and 20.61% in the horizontal position and 7.09%, 24.69% and 27.34% in the vertical position of the tube in tube , helical coil, and the brazed plate heat exchangers. By assuming the usage of the shower by a four-person average family and they take approximately about 624 times of shower annually. We concluded that it may be saved about 39.31 kWh minimum and 418.7 kWh maximum electricity from water heater o heat water for per year. Also, the amount of saving economical size is minimum $ 4, and maximum $ 42.7 dependently type and positioning of the attached heat exchanger to the shower system. By this saving, the emission of carbon dioxide can be reduced by 32.43 kg as a minimum and 345.42 kg as a maximum, annually. The price of the equipping per shower system is approximately $ 87 currently in Turkey. The minimum payback period of a shower system equipping could be estimated minimum 2 years.

PART 7

SUMMARY

In this experimental study, the possible maximum amount of heat recovery by a heat exchanger attachment to an individual household system was investigated. Three different type of heat exchangers that are tube in tube, helical coil and brazed plate and were attached to a constructed household size shower experimentation setup in two different positioning. In the first configuration, all three different type of heat exchangers that are connected to the shower system horizontally. In the second case, they were attached vertically. The water heater energy consumption decreased approximately 2.56%, 16.13% and 20.62% to heat the shower water for half an hour shower time by horizontally connected tube in tube, helical coil and brazed plate heat exchangers. The rate of saving also was reached by the attachment of them vertically to 7.09%, 24.69% and 27.34%. For a four-people average family, the reachable annual saving was determined minimum 39.31 kWh and maximum 418.7 kWh. Economical size of the saving is also calculated minimum $ 4/year and maximum $ 42.7/year. The average cost of the heat exchanger application to a per shower is approximately $ 87 with its hoses and fixing equipment's due to the market prices in Turkey. By the possible saving, minimum 32.43 kg, and maximum 345.42 kg of carbon release to the environment could be eliminated, annually.

RECOMMENDATIONS

It is recommended that future researches to develop heat exchangers to use in the field should focus on the following areas:

1-Size of the heat exchanger; a further study on the size of the heat exchanger could be make it a better performance of the heat exchanger, compact and could be in the form of user-friendly installation design.

2- Research and improvement in the ability of the heat exchanger to resist the negative effects that can occur as a result of materials accompanying greywater such as soap, hair and other chemicals, which can reduce the efficiency of the heat exchanger as a result of accumulation on the heat transfer surfaces of the heat exchanger after a period of time.

3-Finally the costing of heat exchanger, it should be produced in low prices to optimize its economic feasibility.

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RESUME

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