Integrated Solar Water Heater

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ABSTRACT

Nowadays, water heating by using the solar energy has been spread all over the world. The studies on solar water heating system were stimulated the researchers due to the scarcity of natural energy resources, like fossil fuel and natural gas as well as the rising and rapidly fluctuating prices for these resources.

The purpose of this study is to design and manufacture a new storage domestic electric water heater with solar collector in North Cyprus. In this project, the normal cylindrical shape of the storage, which is available in North Cyprus, will be replaced by triangular shape to include the solar collector and the storage in a compact way (i.e., Integrated Solar Water Heater). Moreover, dual heaters will be used to improve the efficiency. Further investigation was done by adding extra dimensions to the solar absorber by extending it to 10cm from the two sides and the bottom.

The temperature profiles inside the new storage for two different flow rates were plotted, with and without the solar insolation. Additionally, the performance of the triangular Integrated Solar Water Heater (ISWH) was presented in terms of discharging efficiency and cumulative efficiency. The utilization of this system was studied by calculating the number of persons that can take a quick shower for electrical and solar water heating.

The obtained results show that, this system can receives approximately 893 W/m^2 of solar insolation with a maximum collection efficiency of 73%. In addition, the maximum discharging efficiency was 98% if amount of water withdrawn during the solar heating process at 12:00 and 14:00. This system would allow the user to get hot water as long as the ISWH can supply hot water above 40°C. If the ISWH is unable to supply hot water above 40°C, then the electric water heater turns on. The electric heater installed at a height of 47cm from the tank bottom will provide a 50L of warm water, which is the sufficient amount of water for one person to take a quick shower, with a discharging efficiency of 85.18%.

Keywords: Integrated solar water heater, Domestic hot water system, Thermal performance, Thermal stratification.

ÖZ

Günümüzde su ısıtma amaçlı güneş enerjisi kullanımı tüm dünyada yayıldı. Fosil yakıtlar ve doğal gaz gibi doğal enerji kaynaklarının kıtlığı yanı sıra bu kaynakların yükselen ve hızla değişen fiyatları nedeniyle, araştırmacılar güneş su ısıtma sistemlerindeki çalışmalarını hızlandırdı.

Bu çalışmadaki amaç Kuzey Kıbrıs'ta, yeni evsel güneş kolektörlü ve elektrikli su ısıtmalı bir depolama tasarımı ve imalatıdır. Bu çalışmada Kuzey Kıbrıs'ta kullanılan kesit alanı dairesel sıcak su deposu yerine daha kompakt olması için güneş kollektörünü de içeren (Entegre Güneş Su Isıtıcısı) kesit alanı üçgensel sıcak su deposu kullanılmıştır. Ayrıca, verimliliği artırmak için çift ısıtıcı kullanıldı. Güneş panelinin iki yan kenarı ve alt kenarı 10 cm uzatılarak etkisi araştırıldı.

Farklı iki akış hızında, yeni depo içindeki sıcaklık profillerinin grafikleri güneşli ve güneşsiz olarak çizildi. Ayrıca, üçgensel entegre güneş su ısıtıcısının termal performansı boşaltım verimliliği ve kümülativ verimliliği olarak sunuldu. Bu sistemin kullanımı elektrikli ve güneş su ısıtıcılı olarak kaç kişinin hızlı bir duş alabileceği hesaplanarak çalışıldı.

Elde edilen sonuçlara göre sistem yaklaşık 893 W/m^2 güneş ışınımı almakta ve azami toplama verimliliği %73'tür. Buna ilaveten suyun saat 12:00 ve 14:00'te çekilmesi halinde güneş ısıtma sisteminin boşaltım verimliliği %98'dir.

Entegre güneş su ısıtıcısındaki su sıcaklığı 40°C'ın üzerinde olması halinde kullanıcı sıcak suyu depodan alabilmektedir. Su sıcaklığı 40°C'ın altına düşmesi halinde elektrikli su ısıtıcaları devreye girmektedir. Su deposunun alt kısmından 47cm yüksekliğe yerleştirilen elektrikli su ısıtıcısı bir kişilik kısa bir duş için 50 litre ılık suyu %85.18 boşaltım verimliği ile sağlayabilmektedir.

Anahtar Kelimeler: Entegre güneş su ısıtıcısı, Evsel sıcak su sistemi, Termal performance, Termal tabakalaşma.

To my beloved family

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A	Collector area (m^2)
Cp	Specific heat of water (kJ/kg.K)
E_{incident}	Total energy incident on the system (kJ)
E_{out}	The energy stored in water withdrawn from the tank (kJ)
E_{st}	The energy initially stored in the tank (kJ)
H	Tank height (cm)
I	Solar intensity (W/m^2)
Q	Volumetric flow rate
T^*	Dimensionless temperature
t^*	Dimensionless time (t/t_{total})
T_{in}	Inlet water temperature (K)
T_j	Water temperature at layer j
T_{max}	Maximum water temperature within tank (K)
T_{out}	Outlet water temperature (K)
V_{st}	Total volume of water stored within tank (m^3)
z	Height of the heating element measured from tank bottom (cm)
z/H	Dimensionless height

Greek symbols

β	Optimal tilt angle
φ	Latitude angle
ρ	Water density (kg/m^3)
θ	Draw-off profile, $\theta = (T_{\mathrm{out}(t)} - T_{\mathrm{in}})/(T_{\mathrm{out}(t=0)} - T_{\mathrm{in}})$
η_{dis}	Discharging efficiency (%)
η_{cum}	Cumulative efficiency (%)

Abbreviations

CPC	Compound Parabolic Collector
EWH	Electric Water Heater
ICS	Integrated Collector Storage
ISWH	Integrated Solar Water Heater
PSP	Precision Spectral Pyranometer
SDHW	Solar Domestic Hot Water
SS	Stainless Steel
TIM	Transparent Insulating Material
wod	1st solar test, discharging the entire tank at 17:00.
w1d	2nd solar test, withdrawn amount of water at 12:00 then discharging the entire tank at 17:00.
w2d	3rd solar test, withdrawn amount of water at 12:00 and 14:00 then discharging the entire tank at 17:00.

Chapter 1

INTRODUCTION

The scarcity of natural energy resources, like fossil fuel and natural gas as well as the rising and rapidly fluctuating prices for these resources stimulated the researchers to use another form of energy (renewable energy) for example, the Sun, wind, tides, waves, biomass, and the Earth's heat (geothermal).

Cyprus does not have any fossil fuel resources (oil, coal, and etc.), and therefore, it is almost completely dependent on imported energy products, mainly crude oil and refined products to meet its energy demands [1]. At present, the only abundant natural energy resource available is solar energy.

Cyprus is located in the north-eastern part of the Mediterranean Sea, 33° east of Greenwich and 35° north of the Equator [2]. Due to its geographical position, the climatic conditions of it are often very sunny with daily average solar radiation of about 5.4 kWh/m^2 on a horizontal surface. Mean daily global solar radiation in the cloudiest months of the year varies from about 2.3 kWh/m^2, December and January, to about 7.2 kWh/m^2 in July [3]. Statistical analysis shows that all parts of Cyprus enjoy a very mild climate with a lot of sunny days. The amount of global radiation falling on a horizontal surface with average weather conditions is 1727 kWh/m^2 per year [4]. 69.4% of this amount reaches the surface as direct radiation (1199 kWh/m^2) and the rest 30.6% as diffuse radiation (528 kWh/m^2). Because of the large amount of sunshine received all year round, Cyprus is often called the "Sun Island".

Solar energy can be used as a form of heat, such as solar water heating, solar air heating, and desalination. Additionally, solar energy can be utilized to generate electricity, such as solar photovoltaic or solar thermal power.

Solar water heating systems are commonly referred to in industry as Solar Domestic Hot Water (SDHW) systems and it is a technology that is not entirely new. Cyprus started the manufacture of solar water heaters in the early sixties, at the beginning by importing the absorber plates and other accessories [5]. The thermosyphon solar water heating systems are the most common type of SDHW used in Cyprus which consists of two flat-plate solar collectors having $3m^2$ area in total, water storage tank with capacity between 150 to 180 L, and a cold water storage tank. An auxiliary electric immersion heater usually 3 kW is used in winter during periods of low or no solar insolation.

1.1 Solar Water Heaters and Collectors

SDHW systems usually consist of three main components: a solar collector, a water storage tank, and an energy transfer fluid, and some of them supplemented by pumps and a heat exchanger. The most important part of a SDHW system is the solar collector, which absorbs and converts the solar intensity to heat. After that, the heat is transferred to a fluid (water, non-freezing liquid) that flows through the solar collector. Then, this heat of fluid can be used directly or stored.

Two main types of SDHW systems are available: passive (or natural) systems and active (or forced circulation) systems. SDHW systems are also characterized as:

- Direct or open loop system, which heats the water directly in the collector.

- An indirect or closed loop system, which heats the water indirectly by heating a fluid which exists in the solar collector and then passes through a heat exchanger to transfer its heat to the domestic service water [6, 7].

A passive SDHW system is shown in Figure 1.1(a). The storage tank is situated above the solar collector, and the water circulates by natural convection (thermosiphoning) [7]. As water gets heated in the solar collector, it rises to the storage tank, due to the density difference created inside the solar collector, and cold water from the tank moves to the bottom of the solar collector. Since this water heating system does not use a pump, it is a passive water heater [8].

ISWH is categorized as passive solar system. This system incorporates thermal storage tank within the collector itself. The storage tank surface works as the absorber surface. Most ISWH systems use only one tank, but some use a number of tanks in series. As with flat-plate collectors, insulated boxes enclose the tanks with transparent coverings on the side facing the sun. While the simplicity of ISWH systems is attractive, they are generally suitable just for applications in mild climates with small thermal storage requirements.

Active solar water heater system (forced circulation) is shown in Figure 1.1(b). A pump is employed to circulate the fluid, it is usually controlled by a differential thermostat turning on the pump, when the water temperature at the top is higher than the temperature of the water in the bottom of the storage tank. A check valve is needed to prevent reverse circulation at nighttime thermal losses from the collector. An auxiliary heating element can be used to heat the water in the tank [8].

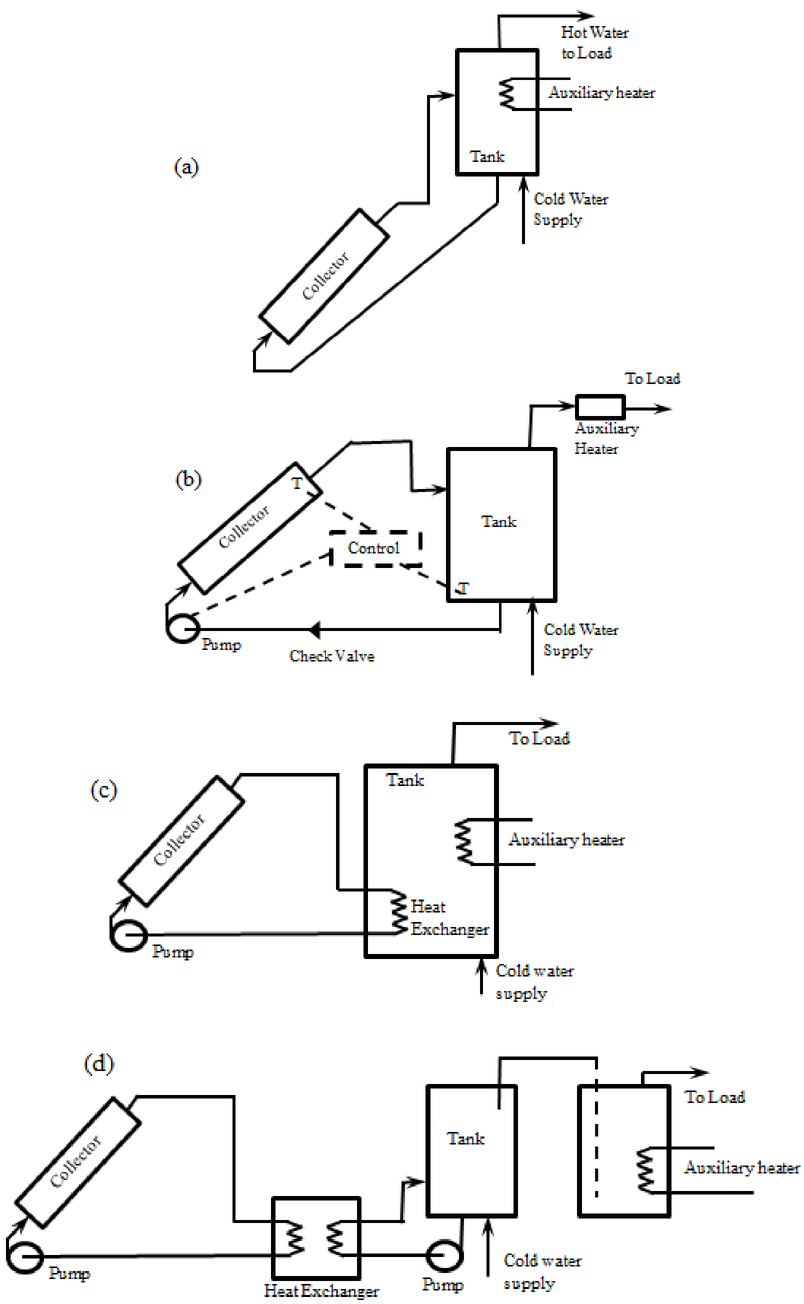


Figure 1.1. Schematic of Solar Domestic Hot Water types: (a) A passive solar water heater system. (b) One tank forced-circulation system. (c) System with internal heat exchanger and antifreeze loop. (d) System with external heat exchanger and antifreeze loop [6].

In cold climates where freezing conditions can occur, other systems with antifreeze fluids in the collector are used. Examples of systems are shown in Figure 1.1(c) and (d) [6].

The most important part of SDHW system is the solar collector. The flat plate, evacuated tube and concentrating collectors are the most common types of solar collectors. Flat plate collector is a metal box insulated and covered with plastic or glass, which is called “glazing”. The glazing is transparent to allow the light of the sun to hit the absorber plate and decreases the heat-losses to the ambient at the same time. Additionally, to minimize the heat-losses from the collector, the bottom and the sides of the box are insulated. The absorber plate is painted black to collect and absorb the solar insolation.

Evacuated tube collectors are made up of clear glass tubes containing a colored glass or metal tube in order to absorb the sun’s energy. The space between the outer glass tube and the inner absorber tube is evacuated. Conductive and convective heat losses are eliminated because there is no medium to conduct heat nor to circulate and cause convective losses.

Another type of collectors use surfaces of mirrors to collect the light of the sun on an absorber called receiver, this type is concentrating collectors. They can provide high temperatures when there is a direct sunlight exists. There are two ways can be used to design the concentrating collectors. One way is to concentrate the solar energy along a thin line called the “focal line”, while the second method is to concentrate the rays of the sun onto a “focal point”.

1.2 Literature review

As mentioned in the previous section, integrated solar water heater falls within the passive solar water heater types. This system has many advantages such as, it is simple, it use no pumps and no moving parts, requires no electricity for operation, and low maintenance. But it has disadvantages because it is bulky and inefficient in cold climates. The advantages of ISWH stimulated many authors to study different shapes of ISWH.

The first ISWH, was patented in 1891 by Clarence M. Kemp [9] under the name of ‘‘The Climax Solar-Water Heater’’. This system consists of four small 29 L oval-shaped cylindrical vessels manufactured from heavy galvanized iron, painted black and placed horizontally side by side in an insulated wooden box with a glazed cover in order to increase the surface area exposed to the sun. The system was installed on a roof with simple gravity feed forcing the hot water to the tap as the cold water from a reservoir entered the tank inlet. A 38°C maximum temperature was obtained by this system [10].

There are different factors affecting the ISWH efficiency. For example, storage tank size and shape, absorber plate type and its orientation, method of insulation, difference between inlet and outlet water temperature, etc. Therefore, numerous studies have been done to improve the performance of the ISWH.

The success of the Climax led Frank Walker (1898) to conduct his experiments on solar water heating system. A double glazing with 113 L tank was used in his system. The Walker tanks were directed vertically and connected in series. By setting the tanks on the roof the night-time heat loss would have been largely reduced and warmer water would have been available in the morning. The vertical orientation providing both aesthetic and would also have improved performance of the system by increasing thermal stratification in the tank. The Walker solar water heating system was patented with backup connections to a wet back wood stove [10]. Haskell in 1907 realized the importance of the ratio between the surface area to the tank volume. His patented work was on an ‘‘improved’’ ISWH design which is used a tank of rectangular shape having more surface area/volume ratio than the tank of cylindrical shape. He found that is less time is required for solar radiation to heat up the water stored if the exposed surface area to the volume ratio is large [11].

Brooks conducted a series of tests on two types of ISWH. The simplest heater, an exposed bare tank, was found to work better if sloped vertically. Then Brooks used several tanks enclosed in an insulated box covered with glass and he obtained much more satisfactory results. He found that a large amount of water supply above 49°C can be obtained in the afternoon [12].

Japanese researches concentrated on two solar water heater types; the first one is open-type collectors with rectangular tanks and cylindrical vessels. The second one is a long thin closed-pipe. Each of them had smaller surface area to volume ratios than USA designs ‘‘The Climax Solar-Water Heater’’ [13]. In 1985, Muneer [14] studied the effect of 2cm increase in the collector depth on performance. Results showed that this modification enhanced the storage volume which made the system operate at lower temperatures and so the heat losses are limited resulting in an increasing the system efficiency by 8%.

Many researchers have studied the performance of cylindrical storage integrated solar water heating system with different solar absorber types [15- 26]. Saroja et al. [15]

presented theoretical and experimental analysis of a cylindrical ISWH. Results showed a good agreement between them.

Kalogirou S.A. investigated a single and double cylindrical vessel ISWH utilizing a concentrating collector [16,17]. The single system has been implemented by considering a horizontal cylindrical tank with a total water storage volume of 65 L, Kalogirou preferred to use compound parabolic collectors (CPC) due to their ability to work without the need of tracking and to collect significant quantities of diffuse radiation. The main problem in this ISWH unit comes from the heat-losses during the night. This is due to the fact that there is a difficulty in insulating the collector absorber properly since it acts as a storage tank at the same time. This system had a disadvantage in the characteristics of the draw-off, very little water stratification in the cylinder, because the water cylinder tank/absorber is placed horizontally [16]. Kalogirou modified the initial system by introducing a primary cylinder with 110 mm diameter and 19 L water storage volume at the space between the glass and the main cylinder (at a symmetrical CPC reflector focal point), as shown in Figure 1.2. The cold water enters from the smaller upper cylinder and was withdrawn from the lower larger cylinder. There are many advantages obtained from the modified system such as, the capacity of the storage increased by 30%, the upper tank offers a kind of insulation as the lower tank unaffected by the solar radiations directly, the smaller upper tank reduced the night thermal losses since the flow of convection currents is restricted, and the primary tank works as a preheat tank thus the characteristics of the draw-off for the main cylinder tank should improve as the cold water will not in-flowing to the main tank directly. This modification increased the total cost of the system by 8% [17].

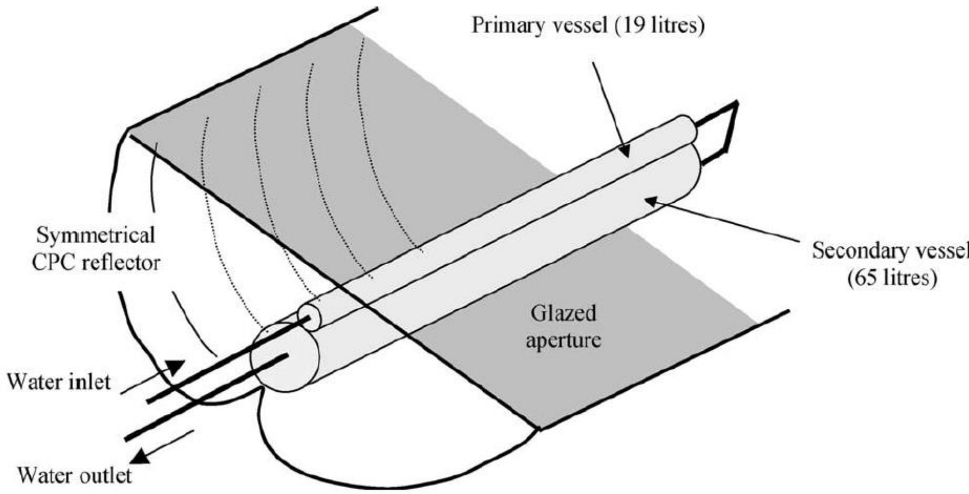


Figure 1.2. A double vessel concentrating ISWH [17].

Smyth et al. [18- 22], carried out a series of studies on a CPC ISWH in Northern Europe. At the beginning, they designed a cylindrical vessel with an inner sleeve arrangement to reduce heat conduction from the wall of the vessel and thus convective motion and water mixing. This decreased heat losses up to 20% as well as improving thermal stratification inside the inner store [18]. Two years later, they used this arrangement in two different systems as illustrated in Figure 1.3. System A designed as partially enclosed within the reflector sections with a storage capacity of 85 L, while system B was fully enclosed within the reflector sections and had 57 L storage volume. A comparison on these units showed that system A performs better than system B in terms of the solar energy collection. The average collection efficiency of system A was 45.4% whilst 43.7% for system B. The two systems could supply hot water continuously at temperatures of 50°C for system A and 40°C for system B [19]. A modification to improve both systems to operate during winter period was made by heavily insulating all the pipes to and from the device with a hose made of rubber. This gave a possibility to system for movement, reduced the conduction heat-losses along the pipes from the ISWH, and gave the system the ability to resist the possibility of freezing the water in the pipes [20]. After that, Smyth et al. developed these systems in order to reduce the heat losses during periods when there is no solar energy collection [21]. Additionally, they presented cost analysis of these systems in detail [22].

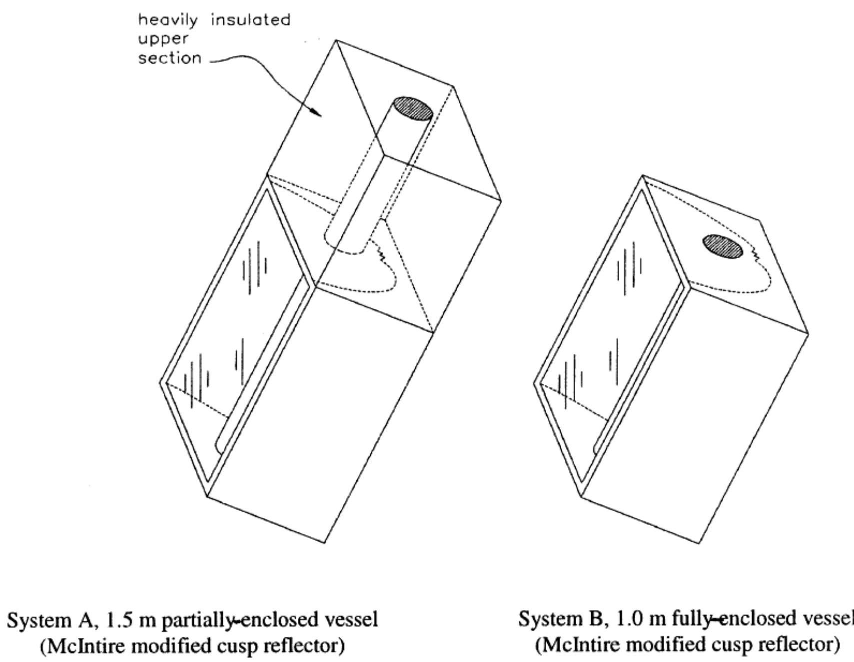


Figure 1.3. Partially enclosed and fully exposed ICS vessels [19].

More recent studies on cylindrical storage ISWH carried out by Tripanagnostopoulos Y. and Souliotis M. [23], Hussain Al-Madani [24], Khalifa and Abdul Jabbar [25], and Borello D. et al [26].

Other authors examined the performance of a rectangular storage tank in their researches [27- 33]. They concluded that rectangular storage tank can serve and perform as well as the storage tank of cylindrical shape.

Mousa S.M. and Bilal A.A. [27] built and study experimentally the performance of two identical ISWH systems with rectangular tank, except one with fins and the other without fins. The authors concluded that these systems can achieve a temperature rise of more than 30°C with cumulative efficiency of 50% to 59% for the system without and with extended fins, respectively. The use of fins in this study was to increase the heat absorbing while other studies used different methods to reduce the heat losses and increase heat retaining.

Reddy K.S. and Kaushika N.D. [28] showed that the use of transparent insulating material (TIM) has led to effective suppression of heat loss. TIM used as the cover located between the absorber plate and the top glazing of ISWH. A comparison between different configurations was done and concluded that a sheet of 10 cm structured TIM is effectively improved the collection performances. Based on this study, Reddy K.S. and Sridhar A. [29] modified a cuboid ISWH and developed a TIM to minimize the heat losses at night. They reported that thermal stratification increases with increasing the depth of the system.

Another design, built and performance results of the test of an ISWH was presented by Dharuman et al. [30]. The collector has a double-glazing of toughened glass plate mounted in an aluminum frame. Reflector mirrors were placed on the sidewalls in-between the glass cover and the absorber plate. Figure 1.4 illustrates the main components of the ISWH. In order to reduce the heat-losses during the nighttime, a screen manufactured from very thin material used to cover this system. The average temperature and overall efficiency obtained were 55°C and 40%, respectively.

Extensive experimental studies on ISWHs were done by Mousa S.M. et al. [31] to estimate the collector performance and examine the optimal depth of the water storage

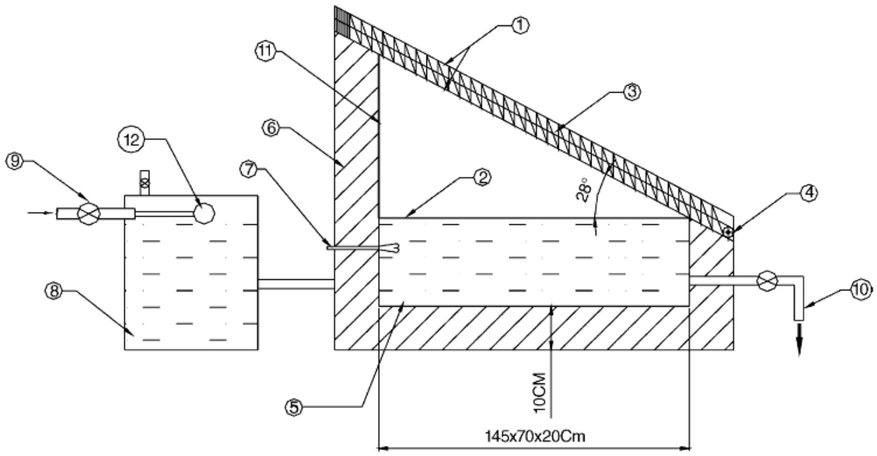


Figure 1.4. Integrated solar water heater configurations investigated by Dharuman et al. [30]. (1) Glass cover, (2) absorber plate, (3) screen insulation, (4) motor with pulley, (5) SS tank, (6) side insulation, (7) heater, (8) feed water tank, (9) inlet valve, (10) outlet, (11) mirror and (12) float.

tank. These systems equipped with single and double glazing cover. They concluded that 10cm depth of storage tank gave an optimum system performance with maximum temperature of 68°C for single glazing, while the system of double glazing is more effective in retaining of heat during nighttime.

Kumar R. and Rosen M.A. [32] considered a rectangular storage tank with a corrugated absorber surface instead of plane. This shape of absorber having more surface area exposed to solar radiation resulting in more useful energy converted into useful heat. The maximum water temperature was 64°C with 1cm depth of the corrugated surface, whereas the efficiency decreased marginally due to the increased losses from the system. After a year [33], they proposed to extend the ISWH with extra storage tank in order to improve the efficiency of the system. The first water tank is exposed to incoming solar intensity, whereas the second storage unit is connected to the first water tank and is insulated on all the sides.

On the other hand, many researchers investigated the thermal performance of a triangular storage ISWH system. Ecevit A. et al. [34], Prakash J. et al. [35], and Kaushik S. C. et al. [36] suggested that a triangular storage tank can perform better than the rectangular tank due to increased natural convection. Ecevit A. et al. [34] examined the impact of different volumes in triangular ISWH showing good overall performance in all designs. Kaushik S.C. et al. [36] studied the thermal performance of a triangular built-in-storage solar water heater under different orientations during winter months (Figure 1.5). The triangular cross-section of the system leading to higher solar gain and enhances the natural convection results in a higher water temperature. A side by side comparative experimental study of a triangular and rectangular shaped ISWH was carried out by Soponronnarit et al. [37] under same conditions. The efficiencies of the triangular and rectangular systems were found to be 63% and 59%, respectively. Sokolov M. and Vaxman M. [38] used a baffle plate for separation of the absorbing plate from the water storage volume. Kaushik S.C. et al. [39] studied the baffle plate effect on the triangular ISWH performance. Mohamad A. A. [40] introduced a thermal diode fixed to a Plexiglas sheet allowing one-way flow only to prevent opposite circulation at nighttime as well as reduces heat losses as shown in Figure 1.6. Mohamad presented a maximum average water temperature of 42°C and 34°C at 17:00 and 05:00, respectively. He found that the efficiency of the storage tank with a thermal diode is 68.6% and 53.3% for the system without thermal diode. As a result, he concluded that the system thermal efficiency is comparable with other conventional systems.

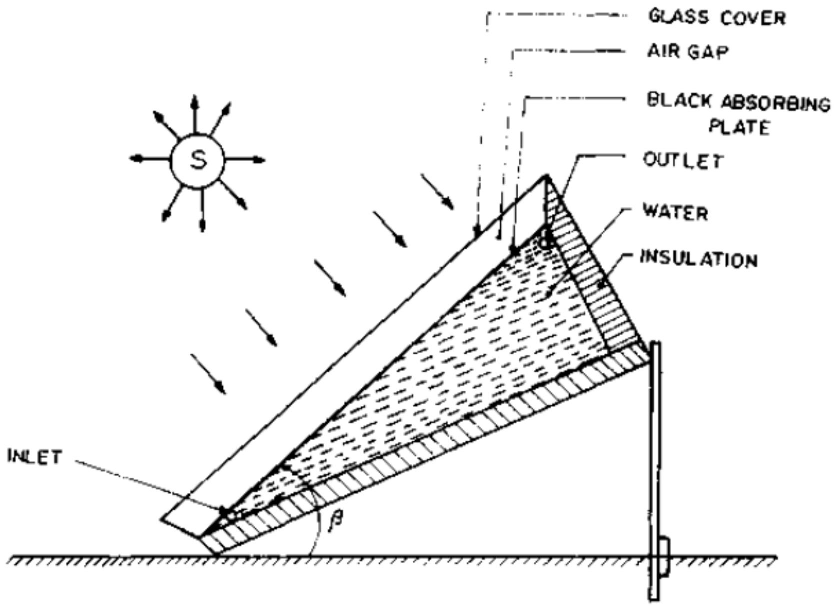


Figure 1.5. Schematic diagram of ISWH of triangular storage tank [36].

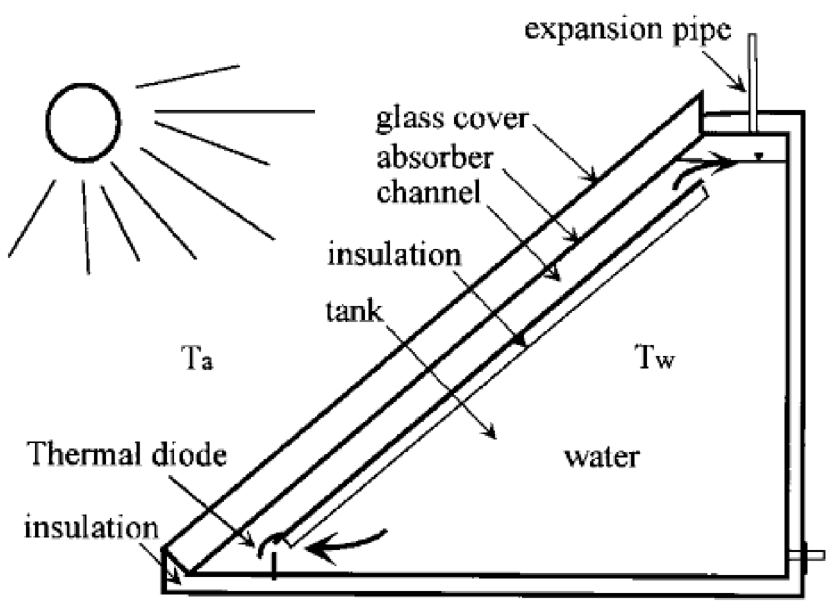


Figure 1.6. Schematic diagram of ISWH investigated by Mohamad A. A. [40].

Al-Talib et al. [41] examined a stratified ISWH with a triangular shape and get very successful results in solving the problem of night cooling faced by the other ISWH types. Numerous shapes of ISWH have been reviewed by Smyth M. et al. [42]. Solar water heating systems are normally designed to supply hot water load between (50-80)%. This is due to the fact that solar energy is variable and intermittent. Therefore, an auxiliary electric heater is often used to provide the remaining energy requirements [43].

Sharian A.M. and Löf G.O.G. used an electric heater controlled thermostatically for water heating when the energy gain from the solar collector is insufficient to meet the requirements of the hot water [43].

In recent studies, Hegazy and Diab [44], and Hegazy [45] presented a new design of inlet port, this was done by placing diffuser (a perforated, wedged, and slotted pipe-inlets) horizontally near to the bottom of the storage tank in order to direct the flow of cold water entering the storage tank. This design improved the thermal stratification of the water inside the storage tank which resulted in an improvement in the discharging efficiencies. Additionally, this design enhanced the thermal performance as tank aspect-ratio increased with decreasing flow-rate.

The performance of the electric water-heaters (EWHs) also effected by electrical heating element location. This was studied by Sezai et al. [46] by using an EWH having 120 L cylindrical storage tank, which is used in North Cyprus. In most of these systems, the electric heaters are installed at the bottom tank. They conclude that the efficiencies of energy-utilization was low for such systems since the whole water storage tank would be heated even for taking a one shower quickly, whereas the amount of the hot water required is just a little amount of the whole storage capacity. Therefore, they experimentally investigated the secondary heater performance installed close to the upper side of a storage tank for the conservation of energy. They concluded that, with the electric heater mounted horizontally on the tank side, only the water stored above the heating element would be affected by the process of heating, while the cold water below the heating element remained almost not affected by the heating process with a thin thermocline region in between.

J. Fernandez-Seara et al. [47, 48] analyzed experimentally the storage tank of EWH and studied it in static and dynamic mode of operation. The static mode of operation of an EWH considers the thermal behavior of water in the storage tank when it's not being used, when there is no discharging/charging process of hot water. While the dynamic mode of operation of an EWH refers to the operation of the system when thermal energy from the storage tank is being used, when the charging/discharging process of hot water is taking place.

1.3 Objectives

The purpose of this study is to design and manufacture a new storage domestic electric water heater with solar collector. In this project, the normal circular shape of the storage will be replaced by triangular shape to include the solar collector and the storage in a compact way. Moreover, dual heaters will be used to improve the efficiency. Temperature profile inside the new storage will be plotted with/without the solar insolation, for 2 different flow rates. Additionally, thermal performance of the triangular integrated solar water heater will be presented in terms of discharging efficiency and cumulative efficiency. The utilization of this system was studied by calculating the number of persons can take a quick shower for electrical and solar water heating. The chapters of this thesis are organized as follow:

Chapter 2, presents the configuration of the new solar water heating design from integrated type and the components and configurations used to model the system are documented as well as the experimental procedure are listed.

Chapter 3, results and discussion for heating the water by using immersed electric-resistance type heating element are included in this chapter.

Chapter 4, results and discussion for solar water heating are examined in this chapter. Conclusions and recommendations are presented in chapter 5.

Chapter 2

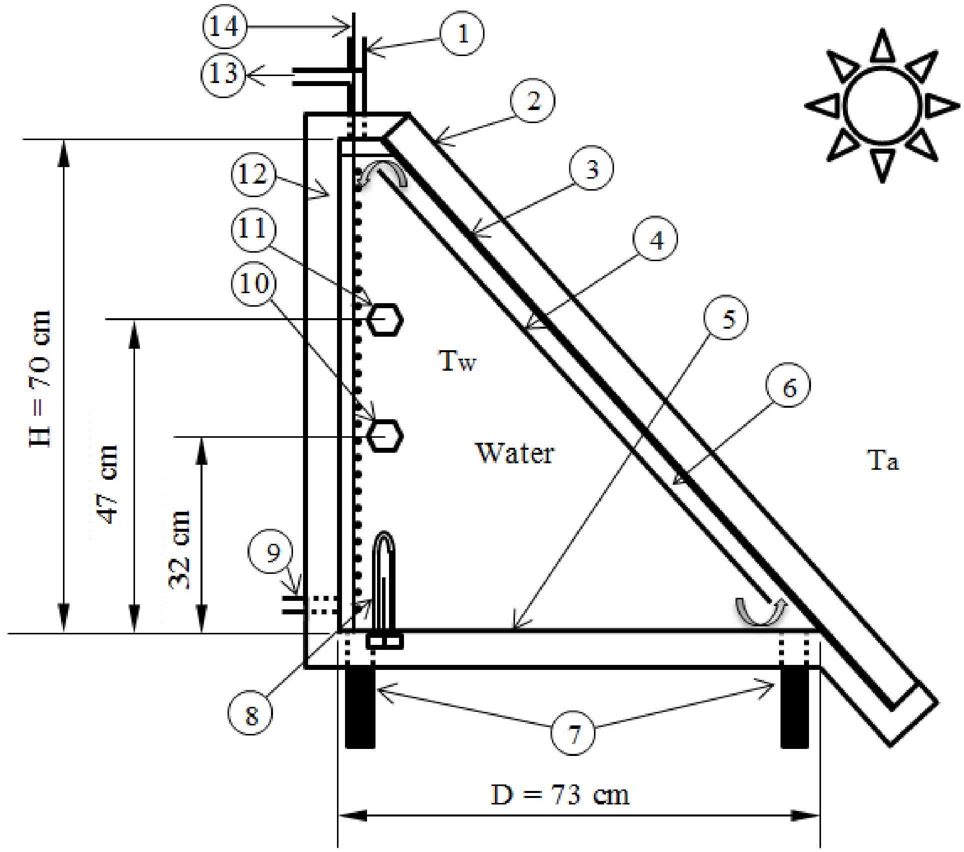
EXPERIMENTAL SET UP

As discussed in the previous chapter, integrated solar water heater includes the water storage tank with a flat plate collector in a compact way. In this chapter, the construction of a new ISWH will be explained in detail. The details of the equipment and their accuracy used for this study will be presented in this chapter. In addition, all the experimental equipment used and experimental procedure are listed and explained.

2.1 The apparatus

2.1.1 Storage tank

The water storage tank was made of 0.2cm galvanized steel sheet. It was well-insulated with 3.5cm thick glass wool from the sides and bottom. The tank has a triangular shape front side with rectangular shape rear side shape connected together as shown in Figure 2.1. A 70cm equal side triangle, 45° angle, with 50cm in width was used. Whereas the rectangular shape has a dimensions of 70cm × 50cm × 3cm in height, width and depth respectively. The capacity of the tank is 130 L. A sheet of baffle plate was fixed inside the tank parallel to the absorber plate. Mohamad A.A. [40] used an insulated baffle plate of a Plexiglas sheet. The purpose was to reduce the heat losses by conduction at night-time and enhancing the buoyancy force. Moreover, a study by Kaushik et al. [39] showed that the material and thickness of the baffle plate had a little effect on the performance of the ISWH. The space between the baffle plate and the absorber plate



(1) Expansion pipe	(2) Glass cover
(3) Absorber plate	(4) Baffle plate
(5) Tank	(6) Channel
(7) Holders	(8) Heater A
(9) Inlet water	(10) Heater B
(11) Heater C	(12) Fiberglass insulation
(13) Outlet water	(14) Thermocouples

Figure 2.1. Schematic diagram of the integrated solar water heater.

forms a channel 2.5cm in depth. The baffle plate is fixed at a distance of 2cm from the bottom and top of the tank in order to enhance the buoyancy force. The storage tank equipped with the cold water from the rear surface, 2cm above the tank bottom. The outlet pipe of the hot water is placed at the top surface. Standard steel coupling of 1/2 inch, flush welded to the tank surface, was used for both the inlet and outlet pipes. A vent pipe is located on the top surface 5cm from the side in order to prevent pressure build-up in the tank. In order to have a hot water during the night or on a fully cloudy day, a three 3kW immersed electric-resistance type heating element is installed to the tank to heat the water [46] as shown in Figure 2.1. This heating element manufactured with a thermostat as one unit to regulate the water temperature, so that it can be easily fixed on flanges welded on the surface of the tank. Performance tests were carried out for three different locations of the immersed heating element. At location A, the heater is located vertically at the bottom surface of the storage tank, whereas at locations B and C, it is placed horizontally on the side of the tank, at heights of 32cm and 47cm, respectively.

2.1.2 Solar absorber

A flat plate collector was used in this design. Stainless steel used to manufacture the absorber plate. It has dimensions of 109cm × 70cm with a surface area of 0.763m^2 (see Figure 2.2). The solar collector was oriented according to the location of Famagusta city in North Cyprus (Latitude 35.125°N, Longitude 33.95°E) with an optimal angle 45° facing to south to make sure that the solar intensities at most times are normal to the absorber surface. The tilted angle is fixed according to the study of Reiss and Bainbridge [49], Chiou and El-Naggar [50], they conclude that the optimal tilt angle is latitude + 10° ($\beta_{opt} = \varphi + 10°$).

Figure 2.2. Picture of the absorber plate.

The absorber plate was fixed on the front face of the storage tank. For increasing of the surface area of the absorber plate, a 10cm sheet metal was added to the absorber plate from the two sides and the bottom. An additional insulation is used to insulate the extra extension of the absorber plate to prevent the heat losses from it. Black matte paint used to paint the front face of the collector and covered with a 0.3cm sheet of glass. The glass cover was fixed at a distance of 2.5cm from the absorber plate to reduce heat losses from it. Figure 2.3 shows a picture of the new ISWH.

2.2 Experimental Equipment

2.2.1 Temperature Measurements

The distributions of the temperature in the water storage tank were measured by using thirty three T-type thermocouples placed at 2cm intervals from the tank bottom. These thermocouples, fixed on an acrylic bar, were placed at the mid cross section of the tank (see Figure 2.1). Seven thermocouples inserted inside the tank in a horizontal cross section to measure the horizontal temperature profile. The distance between the junctions was fixed to be 4cm. The horizontal thermocouples were installed at a distance of 47cm from the tank bottom. Additionally, three thermocouples were used for each of the inlet and outlet water temperature measurement. A calibration test for the thermocouple readings were examined and showed that the accuracies were within ±0.15°C. The thermocouples were connected to data-acquisition system to read water temperatures.

2.2.2 Data-acquisition system

OMEGA’s OMB-Multiscan-1200 data-acquisition system was used in this study. Figure 2.4 shows the data-acquisition system. It is simply the gathering of data or

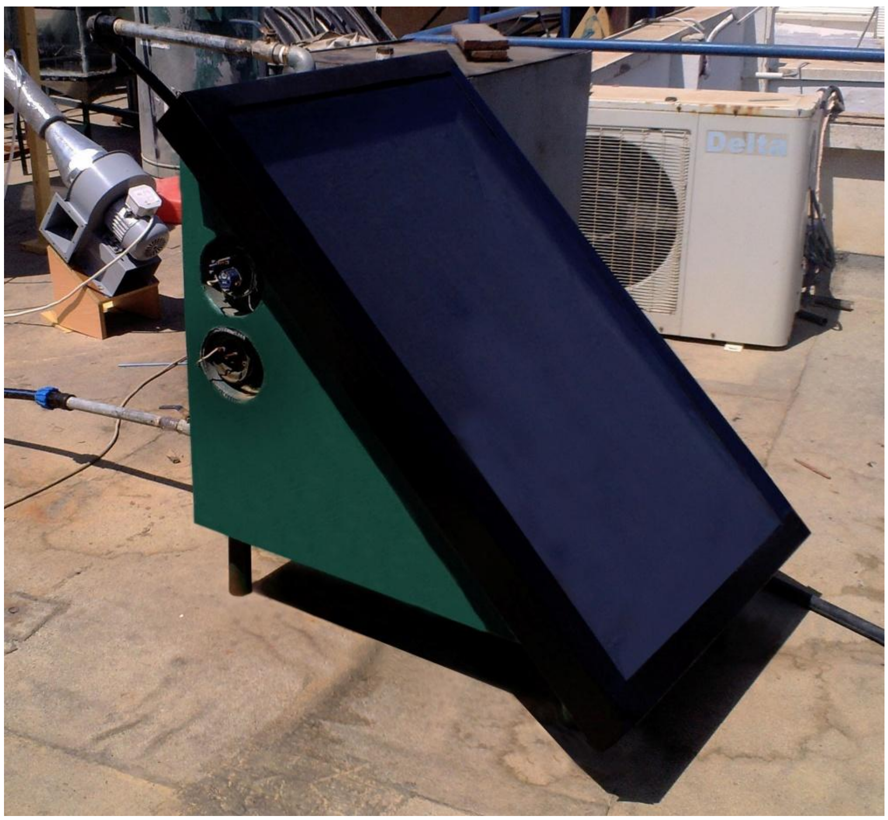


Figure 2.3. The new integrated solar water heater.

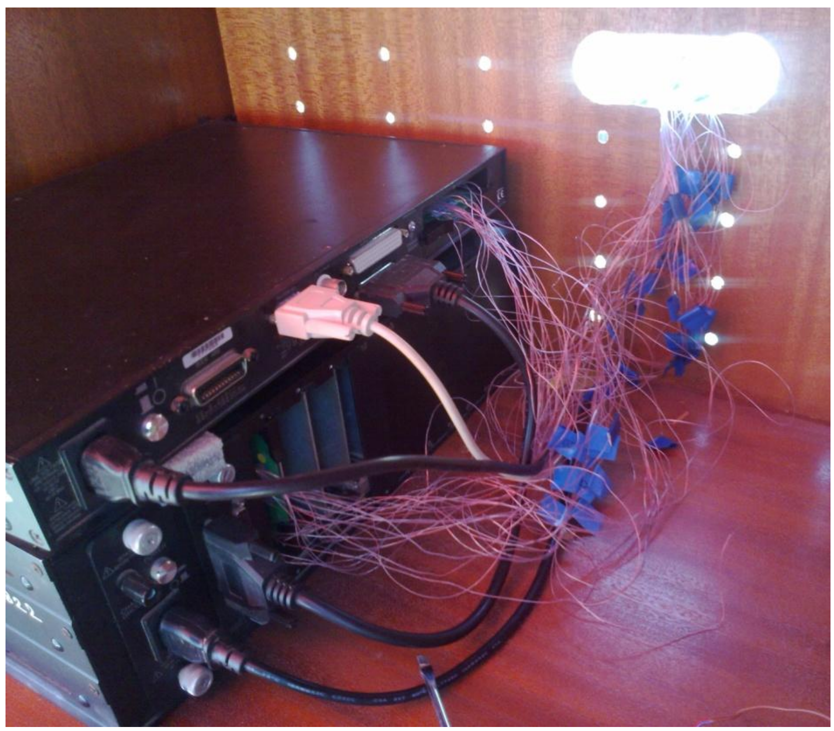


Figure 2.4. Data-acquisition system.

information about a process or system.

Data-acquisition system is a core tool to the control, management, and understanding of such processes or systems. Parameters information such as pressure, temperature or flow is gathered by sensors which are converting the information into electrical signals. The electrical signals from the sensors are transferred by optical fibre, wire or wireless link to an instrument which conditions, measures, amplifies, processes, scales, displays and stores the sensor signals. Accordingly, after connecting the thermocouples to data-acquisition system, it is connected to a personal computer and programmed to record the temperature readings for each different test.

2.2.3 Pyranometer

The Eppley Radiometer Pyranometer (PSP) type was fixed beside the glass cover of the ISWH to measure the global solar radiation incident on an inclined surface. The surface is tilted facing south at an angle of 45° with respect to the horizontal to obtain maximum solar radiation incident on the glass cover. It was coupled directly to a voltmeter model EX410 digital, basic DC accuracy of ±0.5% over range from 0 to 2800 W/m^2. Figure 2.5 shows the PSP and EX410 digital voltmeter.

2.3 Experimental Procedure

The experimental work was performed at the outdoor of the roof of the Mechanical Engineering Department, Eastern Mediterranean University under Famagusta prevailing weather conditions during the summer months, 21.06.2011- 17.07.2011.

Water flow rate was set to the desired value by using the adjusting valve attached after the inlet valve, while keeping the inlet and outlet valves fully open during testing. The draw-off rate was measured using a scale cylinder and a stopwatch. Tests were

Figure 2.5. The Eppley Radiometer Pyranometer (PSP) type and digital voltmeter.

carried out for two draw-off rates of 5 and 10L/min for each of the three heater locations A, B, and C as well as for solar heating.

All the water in tank was emptied before the beginning of a new test. Then, the inlet valve was opened to fill the tank with cold water and the outlet valve was closed when the storage tank was full with cold water at a uniform temperature.

2.3.1 Electrical heating tests

The heating element was switched on to heat the water till the temperature of the water at the top section of the tank reaches 70°C. During heating process, the temperatures inside the tank were recorded each 3min intervals. Then, the heater is switched off and data recording is started after the water is stabilized. At the same time, the outlet valve is opened to start the discharging process, at the same time the tank is charged at the same rate with cold water. During the discharging/charging process, all the thermocouples readings are recorded 5sec intervals to obtain the necessary data in order to study the temperature distributions in the storage tank. The test ends when inlet water temperature becomes equal to the outlet water temperature. Six experiments were done by using heating elements A, B, and C for 5 and 10L/min flow-rates for each heating element. All these tests were done at night when there is no solar radiation.

2.3.1 Solar heating tests

In case of solar heating, the tests have been done from 08:00 to 17:00 for all the tests. Before 08:00, the water in the tank was re-circulated for 15min before we started taking the data as a result the water temperature at the beginning of the experiment was uniform. Then heating process by using the solar radiation started at 08:00 until 17:00 for the first test (wod) with 5L/min draw-off rates. At 17:00, the discharging process started as the outlet valve opens, while same rate of the cold water charging the storage tank. During the heating process, all the thermocouples readings and solar intensity radiation were recorded hourly, whereas for discharging/charging process, the thermocouples readings were recorded for 5sec intervals.

The second test (w1d) has been done with two discharging periods and 5L/min draw-off rates. Solar heating process started at 08:00 till 17:00. Data (water temperatures and solar intensity radiation) were taken hourly. By checking the maximum water temperature and according to minimum inlet water temperature, an amount of water, which is the amount for a person for taking a quick shower, would be discharged. During discharging process, solar heating process was ongoing. At 17:00 all the hot-water in-tank was discharged until the inlet and outlet water temperature became equal. All thermocouples readings were recorded for 5sec intervals.

Another test was investigated for three discharging periods (w2d) with 5L/min draw-off rates. Two discharging processes were carried out at 12:00 and 14:00 in case of two persons taking a quick shower at each time. Data (water temperatures and solar intensity radiation) were taken hourly. Then, the heating process was continued until 17:00 where the entire tank was discharged. All data recorded for the discharging process every 5sec intervals.

All the tests mentioned above have been repeated for 10L/min draw-off rates.

2.4 Thermal analysis

The initial temperature profile of the water in the storage tank was recorded directly before discharging the hot water and the initial energy stored (E_{st})in the storage tank, relative to the temperature of the inlet water (T_{in}), is calculated by

$$E_{\mathrm{st}} = \sum_{j=1}^{33} (\rho V C_p)_j (T_j - T_{\mathrm{in}}), \tag{2.1}$$

Where,

ρ water density (kg/m^3)

V control volume (m^3)

C_p specific heat of water (kJ/kg.K)

All of these parameters are corresponding to the thermocouple at layer *j*. The temperature T_j is assumed as the temperature prevails over the layer *j* which is measured by thermocouple *j*.

The water stored energy that drawn out from the storage tank up to time *t* is calculated from

$$E_{\mathrm{out}} = \int_0^t \rho V C_p (T_{\mathrm{out}}(t) - T_{\mathrm{in}}) dt, \tag{2.2}$$

Where E_{out} is the energy withdrawn, $T_{out}(t)$ is the water temperature measured in the pipe near the outlet port at time *t*. The energy calculated in this way is relative to the temperature of inlet water.

The performance of the storage tank for all cases, where the heating element is installed at positions A, B, and C, and for solar heating tests, is evaluated by determining the discharging efficiency, η_{dis}. It is defined as the fraction of the energy extracted by the time the temperature of the discharged water drops to a specified temperature. In the present study, this temperature is taken to be 40°C. Hence, the discharging efficiency is calculated from

$$\eta_{\mathrm{dis}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{st}}} \tag{2.3}$$

The discharging efficiency indicates the energy that can be utilized when the water temperature is more than 40°C. When the heating element is positioned at location B or C, the withdrawn water (above 40°C) is the amount of the capacity of the whole storage tank. Therefore, the performance assessment based on one tank volume of discharged water is inappropriate.

Chapter 3

ELECTRICAL HEATING

In this chapter, the results obtained from the first part of this experimental study, heating water in the storage tank by using electric-resistance heating element, are presented and discussed. All the experiments were carried out on the roof of Mechanical Engineering Department at night-time to ensure there is no solar intensity. The experiments have been conducted for different discharging rates of 5 and 10L/min. The performance of the storage tank was determined for the two flow rates for each electrical heating element installed at three positions, A, B or C shown in Figure 2.1.

The temperature profile in the water storage tank is presented in terms of the dimensionless temperature T^* and height z/H, where z is the position of the heater measured from the bottom of the tank and H is tank height. Equation 3.1 defines the dimensionless temperature taking the maximum water temperature (T_{max}) and the inlet water temperature (T_{in}) as reference.

$$T^* = \frac{T_{(z,t)} - T_{in}}{T_{max} - T_{in}} \tag{3.1}$$

where $T(z, t)$ is the temperature of the water in the storage tank at height z, at time t. The maximum temperature of the water (T_{max}) is also equal to the draw-off temperature, water temperature leaving the tank, measured immediately when the discharging process started; that is $T_{max} = T_{out}(t = 0)$

Figure 3.1 shows the initial temperature distributions in the water inside the storage

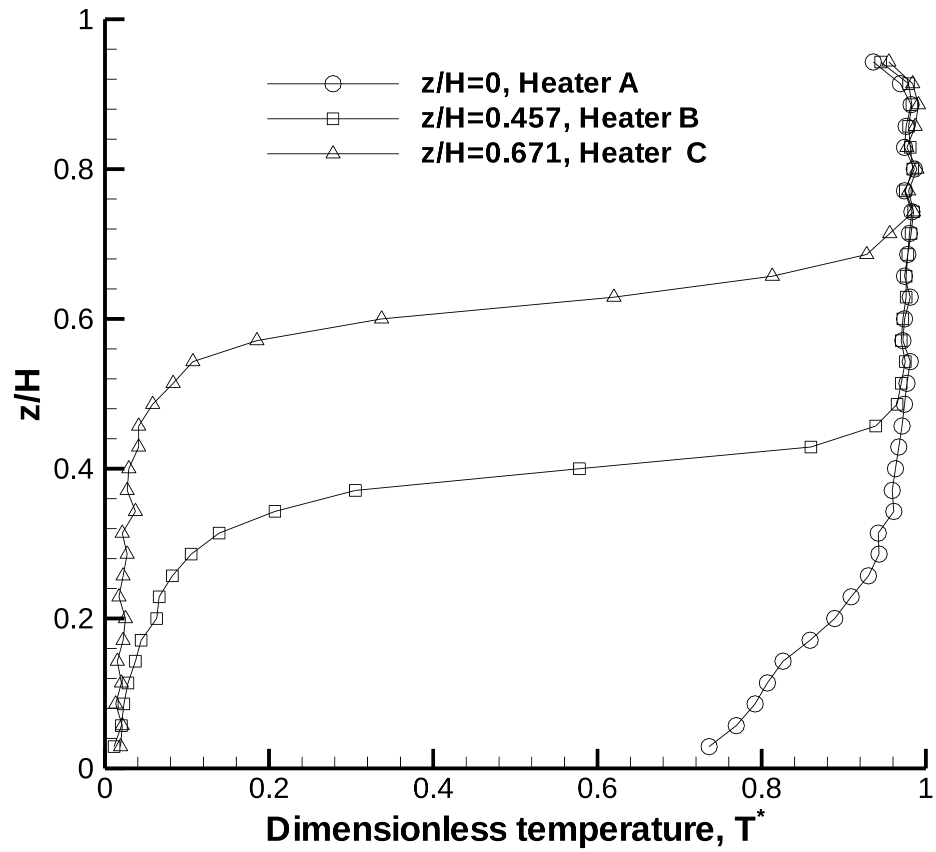


Figure 3.1. The distributions of the temperature in the water within storage tank before discharging process, for heating element locations A, B, and C.

tank after the heating process, $t = 0$, for different heating element locations A, B, and C. For heating element at position A, where it's mounted vertically at the bottom of the storage tank, all the water in the storage tank is approximately heated to a uniform temperature except the region near to the bottom of the tank, where the temperature drops slowly. The small variation in water temperature in this region is partly due to the deficiency of the vertical heater in heating the bottom layers and partly attributed to the conduction heat-losses through the metal of the inlet port, the absorber plate, the baffle plate inside the tank, and the supporting rods of the apparatus since all of them serve as cooling fins. On the other hand, when the heating element is located horizontally at the lateral wall, position B or C, two different temperature regions form in the water storage tank after heating were observed. It can see from Figure 3.1, when the heating process is completed, the water above the electric heating element is heated to a rather uniform temperature whereas the bottom layers of water remain almost unaffected by the heating process. A thin layer separated these two regions, cold and hot water masses, in which the temperature drops sharply. Such stratification could be useful if a small volume of hot water is required since otherwise the energy stored in the lower unused part of the water storage tank would be eventually lost to the ambient. However, there are temperature drops at the end of the three curves, the region near to the top of the tank, due to the conduction heat-losses through the absorber plate, baffle plate and the outlet pipe.

The distributions of the temperature in the water within tank during the heating process were recorded along the horizontal direction. Figures 3.2 and 3.3 show the temperature distributions for heaters installed at A and B respectively. These figures shows that there is no circulation inside the storage tank, i.e. the heat transferred inside

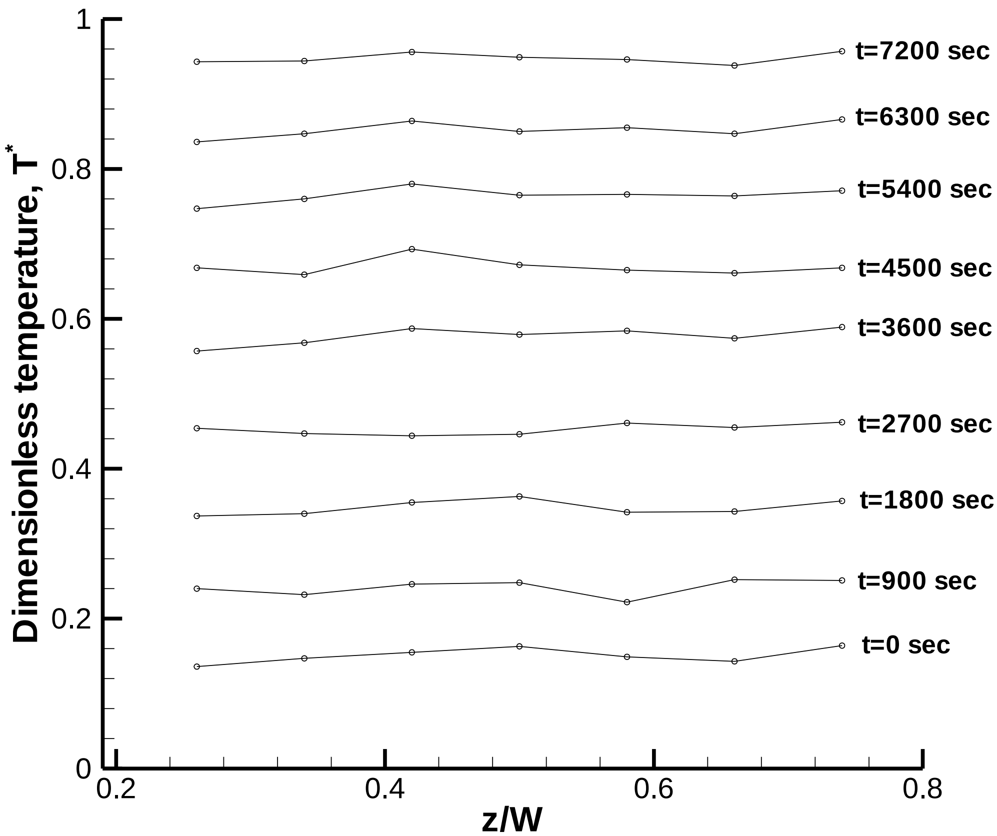


Figure 3.2. The distributions of the temperature in the water within storage tank along the horizontal direction prior to discharging, heater at A.

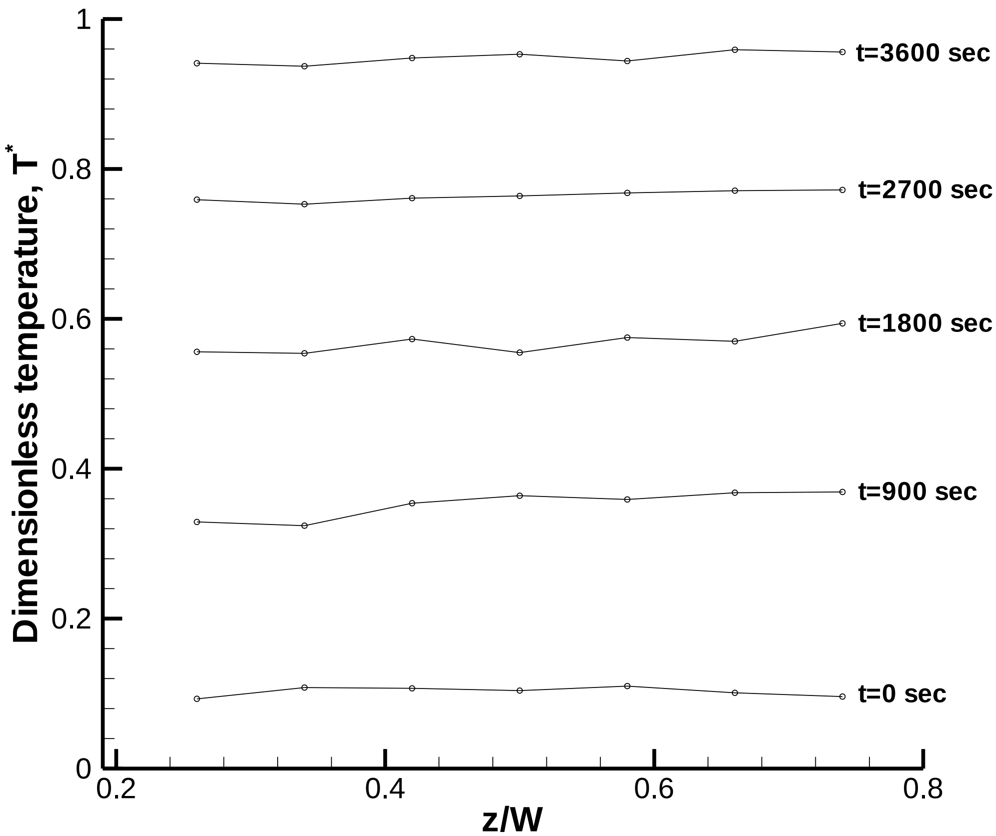


Figure 3.3. The distributions of the temperature in the water within storage tank along the horizontal direction prior to discharging, heater at B.

the triangular storage tank is by conduction and convection along tank walls, absorber plate and baffle plate.

The distributions of the water temperature within tank at each 40sec periods of time during the charging/discharging process, $t > 0$, for the vertical heating element (position A) and a 5L/min draw-off rate, is shown in Figure 3.4. During the discharging/charging process, thermal stratification of the water inside the storage tank is built up as cold water enters from the bottom port of the storage tank while hot water is discharged from the top port of the tank. The stratification separates the hot water that moves to the upper part of the storage tank, due to its lower density, from the cold water that moves to the tank bottom, due to its higher density, with a mixing region between them which is called thermocline. At the beginning of discharging/charging process, the temperature distribution is uniform except at the tank bottom where the temperature gradient was negative. The negative temperature gradient of the hot water at the bottom is attributed to the mixing between the cold water inlet and the hot water within the tank. At this point, the thermocline layer formation began inside the storage tank as the temperature gradient maintained during the drawn-off process and forms the upper portion of the rising thermocline. Consequently, it can be concluded that the greatest changes in the temperature of the water occurs in the thermocline layer. As a result, there are three different zones were distinguished inside the storage, warm water zone with higher temperature in the top partition, cold water zone with lower temperature in the lower partition, and high temperature and density difference zone, thermocline region, between the two zones. As observed in Figure 3.4, the thermocline layer started to vanish as time passes, this was due to increasing in cold and hot water mixing, heat-losses from the absorber plate and baffle plate by conduction, and attributed to the water storage tank

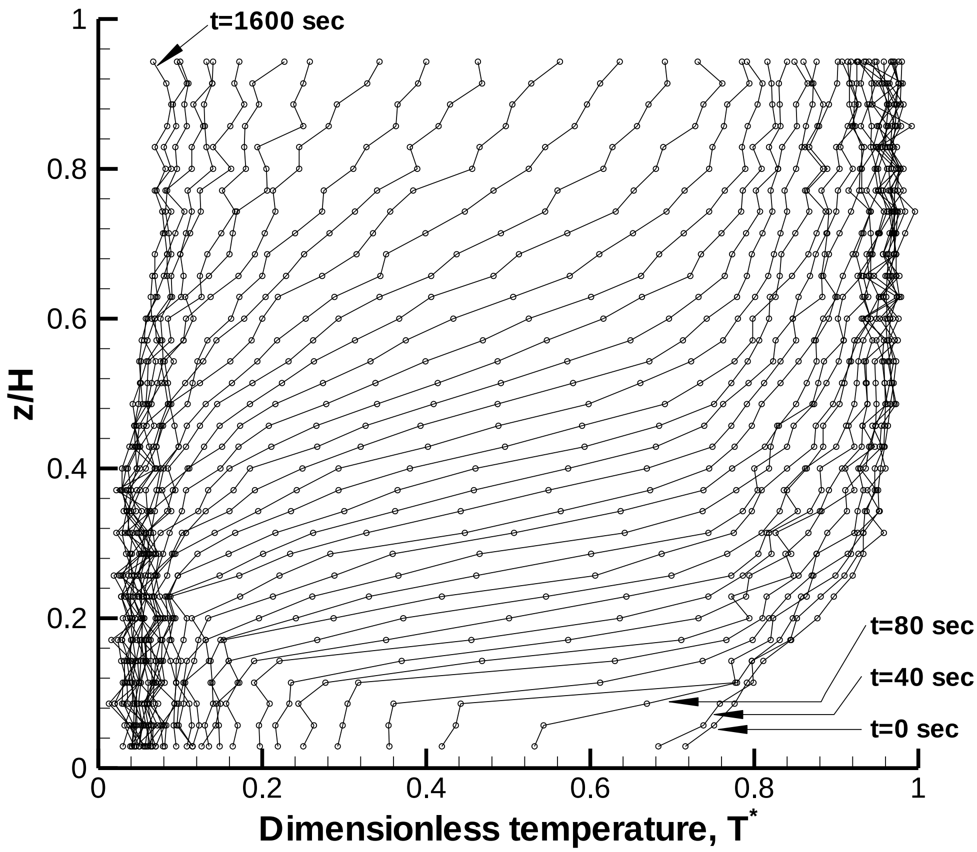


Figure 3.4. The distributions of the temperature in the water within the storage tank for the heating element located at A, Q = 5L/min.

geometry since the distributions of the temperature inside the triangular storage tank different from the cylindrical storage tank [44- 46, 48]. That is, the cylindrical tank is more stratified than triangular tank which is used in this study. This is because of the triangular tank has an absorber plate for solar heating purpose, which affected the heat retaining inside the tank since there is a heat-losses to the surrounding from it.

On the other hand, because of the horizontal positioning of the heating elements that were mounted at positions B or C, the thermocline layer has a higher initial temperature gradient in this case (see Figures 3.5, 3.6). Therefore, the thermocline layer was thicker for the case of heating from below compared to this case. However, the temperature gradient is maintained until the discharging process ends for all tests after half of the heated water was discharged.

For flow rate of 10L/min, the distributions of the water temperature within tank are shown in Figures 3.7- 3.9 at each 40sec interval, for different heater positions. For the case where the heating element installed at position A (Figure 3.7), there is a distortion in the temperature profiles at the thermocline layer bottom at the beginning of the charging/discharging process, this was due to the cold and hot water mixing in the tank. These temperature oscillations resulted from the convective motion resulting from the in-flowing cold water and it is maintained until the discharging process finish. The thermocline layer was vanished when about more than half of the storage is filled with low water temperature. This was due to increasing in water layers mixing and storage tank shape because of the dimensions at the upper part of the tank was decreased since it has a triangular cross section. For the cases where heating element installed at position B or C (Figures 3.8, 3.9), the effects of the cold water inlet is less since the jet caused by the incoming water is far away from the thermocline layer formation. Therefore, there

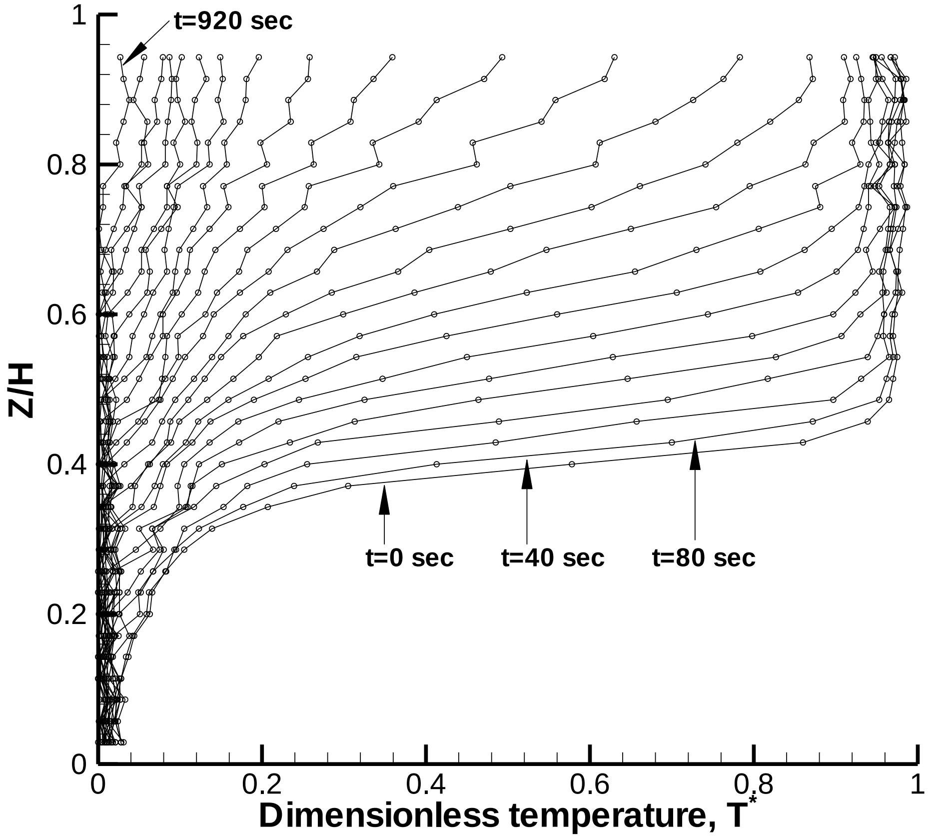


Figure 3.5. The distributions of the temperature in the water within the storage tank for the heating element located at B, Q = 5L/min.

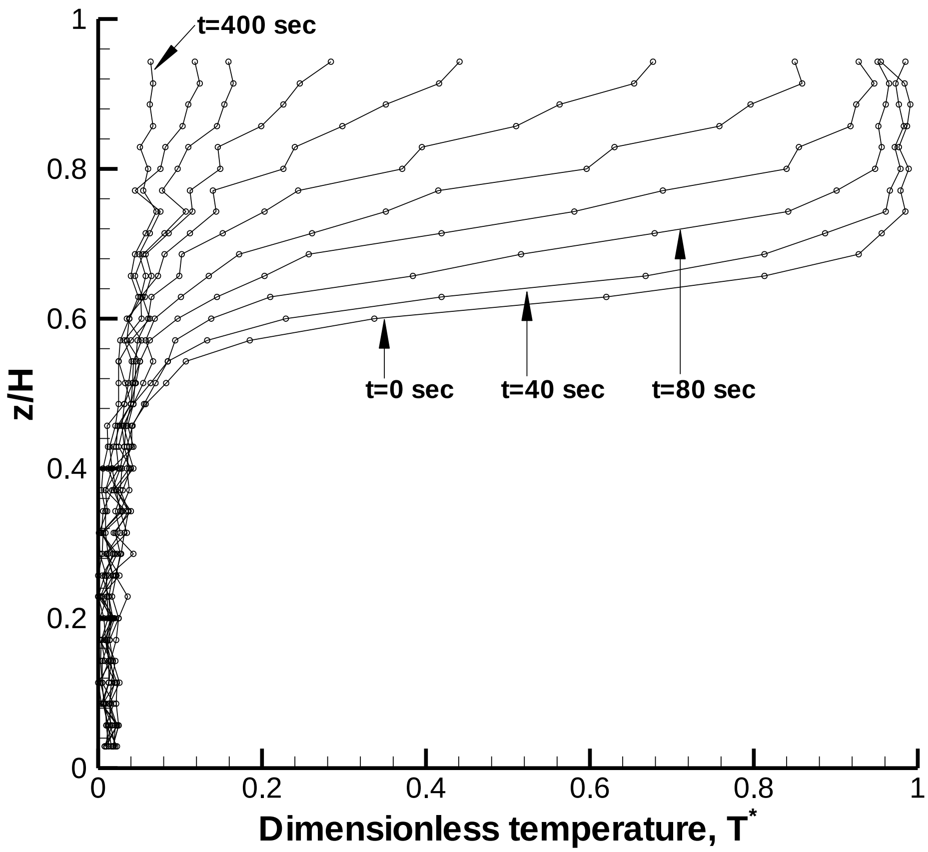


Figure 3.6. The distributions of the temperature in the water within the storage tank for the heating element located at C, Q = 5L/min.

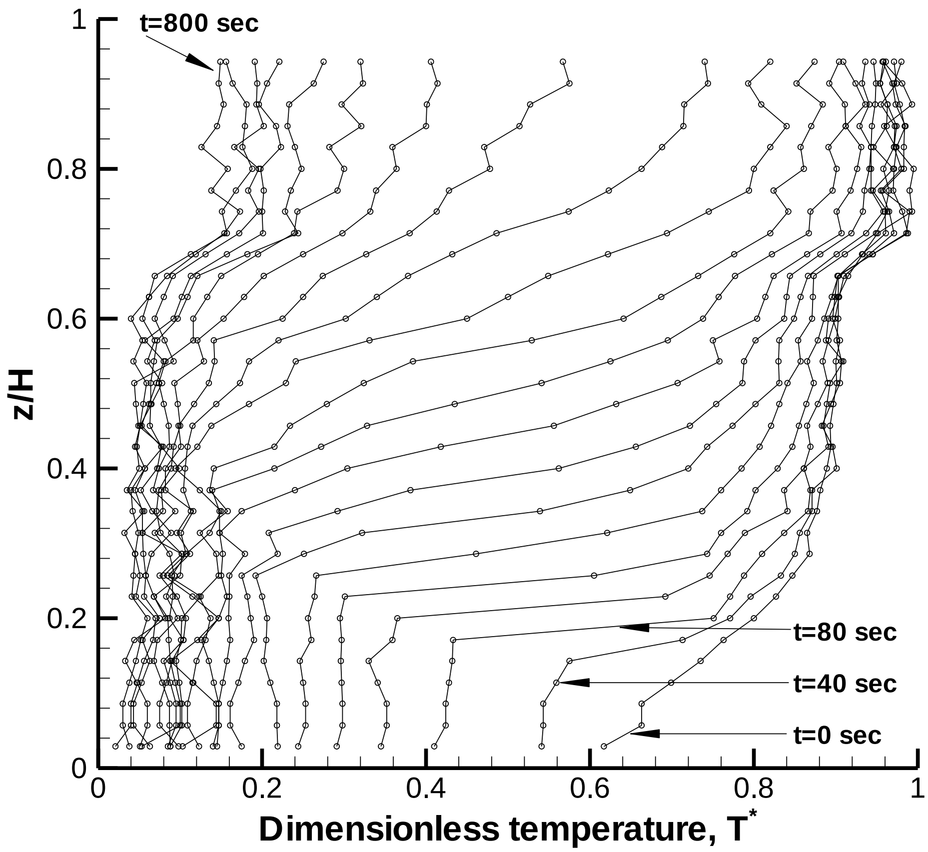


Figure 3.7. The distributions of the temperature in the water within the storage tank for the heating element located at A, Q = 10L/min.

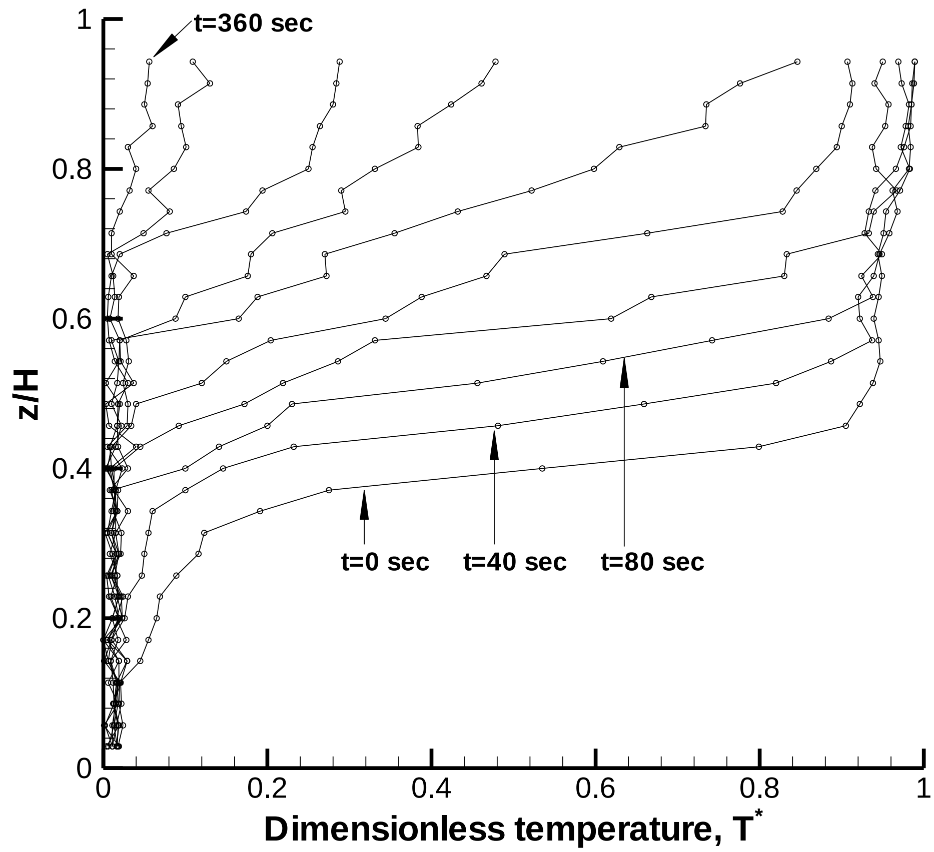


Figure 3.8. The distributions of the temperature in the water within the storage tank for the heating element located at B, *Q* = 10L/min.

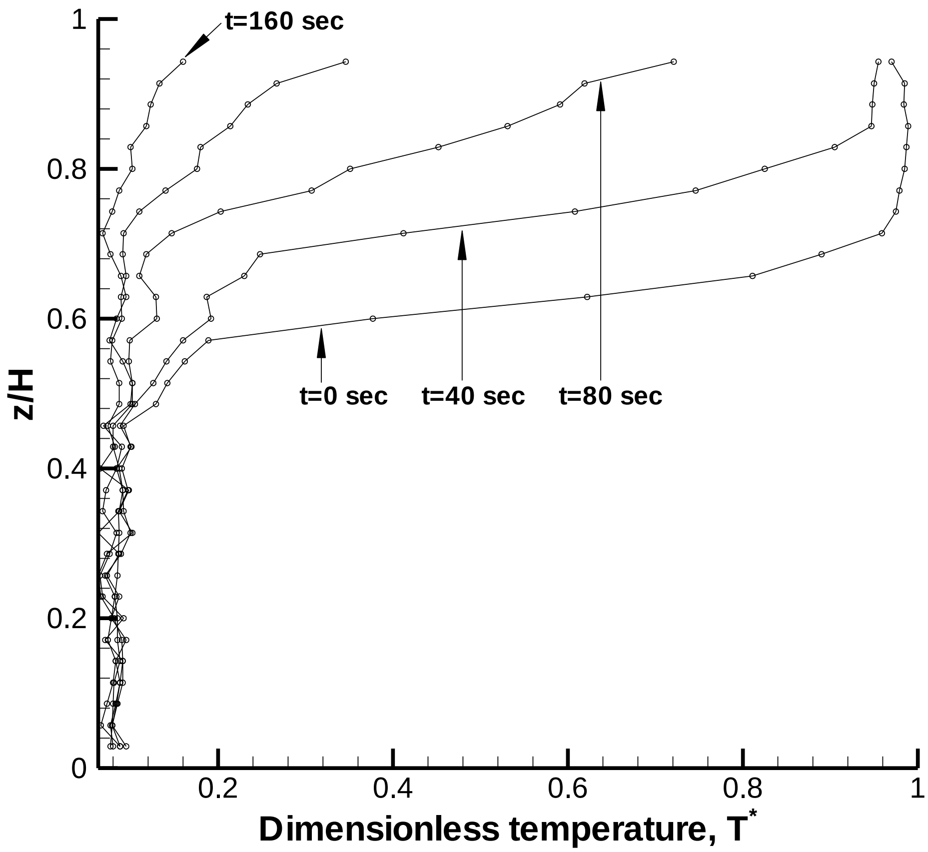


Figure 3.9. The distributions of the temperature in the water within the storage tank for the heating element located at C, Q = 10L/min.

were no distortions in the temperature as in case where the heater is at A, as well as the thermocline region is thinner and it is vanished when half of the hot water volume is discharged.

The history of the water temperature $T_{out}(t)$ withdrawn from the water tank is expressed in form of dimensionless as:

$$\theta = \frac{T_{out}(t) - T_{in}}{T_{out|t=0} - T_{in}}, \tag{3.2}$$

where θ is the drawn-off temperature profiles of the water and $T_{out|t=0}$ is the highest water temperature initially exist in the storage tank. The water draw-off temperature profiles is plotted as a function of the dimensionless time, t^*, which is defined

$$t^* = {}^{t}/_{t_{total}}, \tag{3.3}$$

where, t_{total} is defined as the total time necessary for fully charging/discharging the whole water tank volume at constant volumetric draw-off rate and it also represents the fraction of the storage water withdrawn from the tank. The total time can be calculated from

$$t_{total} = {}^{V_{st}}/_{Q}, \tag{3.4}$$

where V_{st} and Q is the total water volume stored in the storage and the water volumetric draw-off rate during the process of charging and discharging, respectively. Figure 3.10 illustrates the draw-off temperature profiles as a function of the dimensionless time for the three heating element locations, A, B, and C, and for 5 and 10L/min draw-off rates. The experimental curves are discontinued when the temperature of the discharged water drops below 40°C. For the case where the electric-resistance heating element installed at

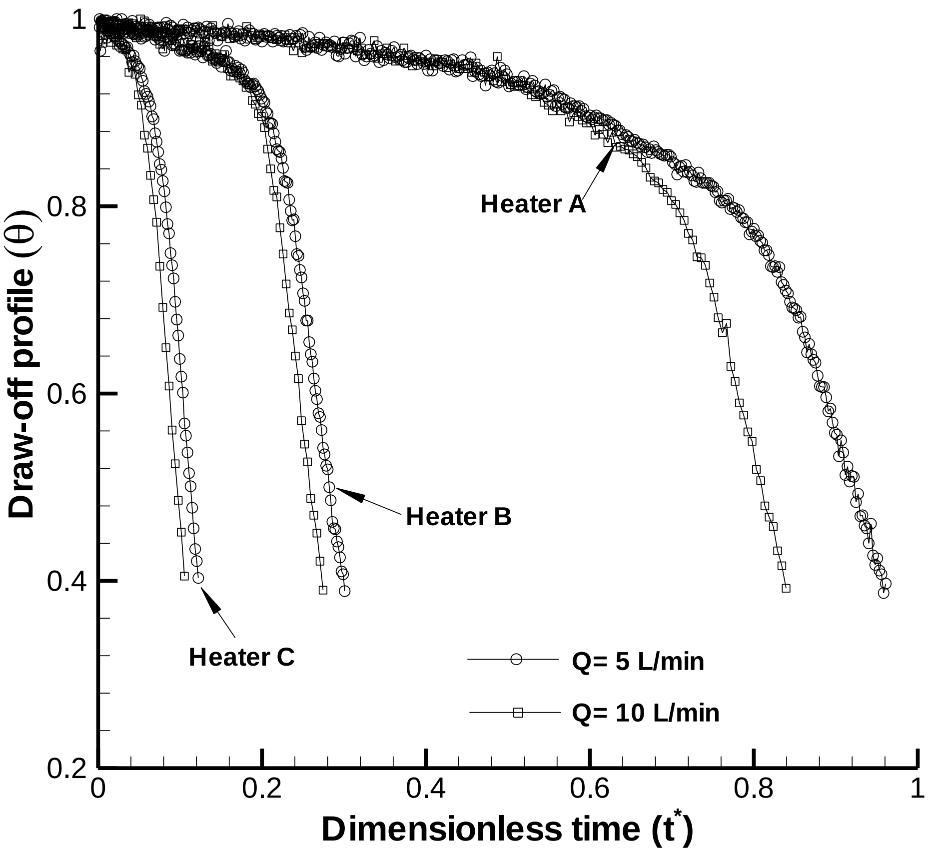


Figure 3.10. Draw-off temperature profiles as a function of the dimensionless time for different heater positions and flow rates.

position A, the draw-off water temperature decreases continuously. This decreasing is attributed to the increasing of the cold water in the storage tank, which leads to increase the heat transferred between the cold and hot water. Moreover, the draw-off temperature decreasing also attributed to the heat-losses from the front side of the storage tank since this side is without insulation. From these results, it is found that the draw-off temperature profiles for 5 and 10 L/min flow-rates remains almost constant during the hot water discharging process till $t^*< 0.7$. At this time, the draw-off temperature profiles for flow-rate of 10 L/min dropped sharply whereas, for flow-rate of 5 L/min, the temperature profiles curve is continuous approximately till $t^*= 1$. That means the volume of the hot water withdrawn is only slightly less than the total volume of the tank, since t^* represents the fraction of the storage water withdrawn from the tank. However, as shown from Figure 3.10, the dimensionless time, t^*, elapsed for the water temperature withdrawn from the tank to drop to 40°C is larger for flow-rate of 5 L/min compared with that of 10 L/min, indicating that a higher fraction of the total stored hot water volume can be discharged at lower flow-rates. On the other hand, for heating element at B or C, the fraction of the storage water withdrawn is approximately equal to the total water volume stored above the heater with a small difference of the draw-off temperature profiles between the two flow rates tested.

The fraction of the storage water, which resides above the heating element, is equal to the water volume stored above the heating element divided by the total volume of the tank. The fraction of the storage water residing above the heating-element and the fraction of the hot water that can be discharged above 40°C after the heating process are listed in Table 3.1. It is observed that, for heating element installed at position A and flow rates of 5 and 10L/min and heating element at B with 10L/min, the fraction of the water that is stored above the heating element is less than the fraction of the storage water that can be discharged above 40°C. This is due to the heat-losses from the front face of the storage as well as due to the heat exchanged between the cold and hot water in the tank. Moreover, for the other cases, the fraction of the water that is stored above the heating element is approximately equal to the fraction of the storage water that can be discharged above 40°C. However, according to these results, the heating element position for a certain amount of hot-water requirement can be calculated easily.

Table 3.1. Fraction of the storage water heated and discharged.

Heater position	Fraction of the storage water above the heating element	Fraction of the storage water discharged above 40°C	
		5 L/min	10 L/min
A	1.00	0.96	0.84
B	0.31	0.30	0.27
C	0.13	0.12	0.11

The thermal performance of the triangular water tank, by using electric-resistance heating element installed at different positions, is determined in terms of the efficiency of the discharging process, by using Eq. 2.3. The discharging efficiency of the triangular storage tank is compared with the cylindrical storage tank that was studied by Sezai et al. [46] and presented in Figure 3.11. It was noted that there is decreases in the discharging efficiency as the draw-off rate increasing irrespective of the heating-element location. For the case where heating element is located at A, the discharging efficiency decreasing with the discharging flow-rate increasing is in line with the past works on storage tanks thermal-energy [44- 46, 48]. The discharging efficiency decreasing in case of discharging draw-off rate increasing is attributed to increase the hot and cold water

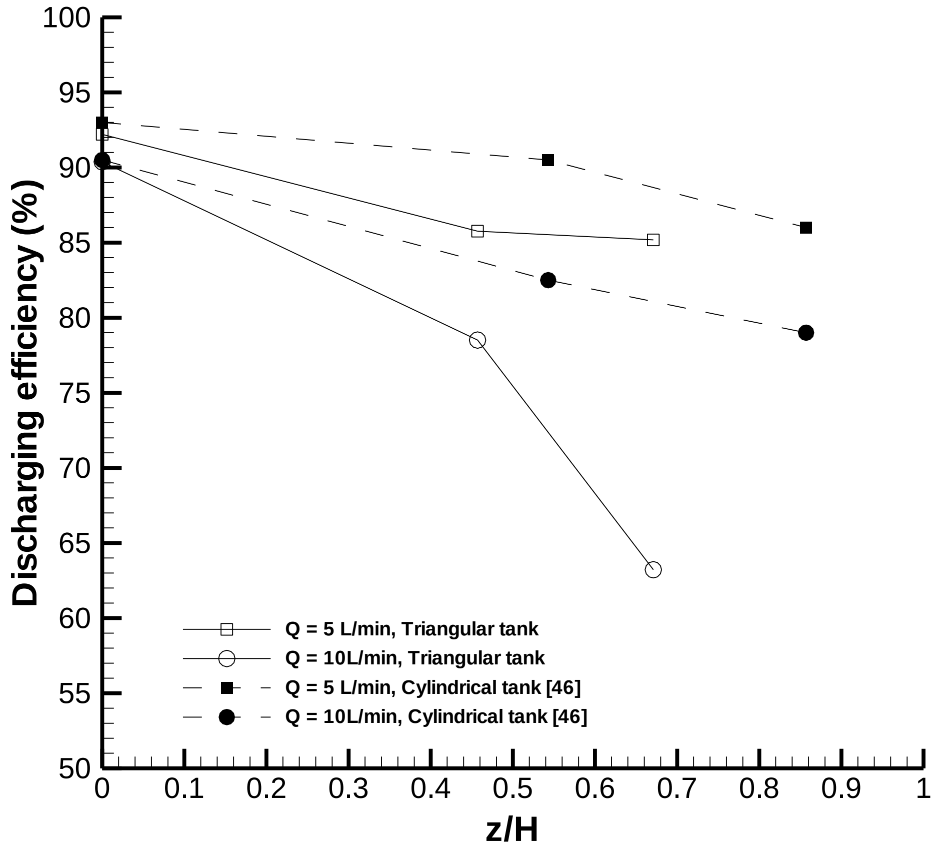


Figure 3.11. The discharging efficiency comparison between triangular and cylindrical storage tanks with different heating-element positions and flow-rates.

mixing, indicating a decrease in the useful energy drawn.

When the electric heater fixed at the upper part of the tank, small quantities of hot water will be discharged indicating a drop in the discharging efficiency. However, this drop in the discharging efficiency is acceptable. For instance, the discharging efficiency was about 85.18% for a flow rate of 5L/min where the heating element fixed at position C. These results are approximately same to the results obtained by Sezai et al. [46] who concluded that mounting a secondary heating element at location C would enable to heat and discharge a small fraction of the water at a high discharging efficiency. Figure 3.11 shows a same approach for the cylindrical and triangular storage tank for decreasing of discharging efficiency when the heater is fixed at the upper part of the tank, but the discharging efficiency is higher for cylindrical than triangular storage tank. This was due to the heat-losses from the triangular tank are more than cylindrical tank as there are a high-losses from the absorber plate.

The warm water amount, that is comfortable for a person to take a quick shower, was taken by Sezai et al. as 50L at 40°C according to the Turkish Standards [46, 51]. The amount of hot water that should be extracted is depends on the cold water temperature entering in the storage tank. Table 3.2 shows the number of persons who can take a quick shower for different heating cases, when the heater is at different places A, B and C. For example, when the heater placed at C, 15.9L of hot water at 70°C can be used for the preparation of 50L of warm water at 40°C if it is mixed with cold water around 27°C. These results would be different in winter period since the tests were done during summer time and on the roof. Table 3.3 shows the winter calculations for number of persons that can take a shower if the cold water temperature was assumed to be 10°C.

Table 3.2. No. of persons can take a shower for different heater positions.

Heater position	No. of persons can take a shower
A	8
B	3
C	1

Table 3.3. No. of persons can take a shower for different heater positions in winter.

Heater position	No. of persons can take a shower
A	5
B	2
C	1

Chapter 4

SOLAR HEATING

The obtained results for solar part will be analyzed and presented in this chapter. As explained in chapter two, six different tests were performed for two different flow-rates (i.e., 5 and 10L/min). All the tests were carried out from 08:00 to 17:00 at time intervals of one hour for every day. For these tests, the performance of the integrated solar water heater was examined.

Figure 4.1 shows the solar intensity versus time for all the days when the experiments were done. The solar intensity was increasing from the early hours to a peak value at noon, and then it was decreasing in the afternoon until sunsets. The highest daily solar radiation measured was 893W/m^2 while the mean average values of solar radiation for all the days of the experiment was 641W/m^2. The amount of solar radiation measured for each day during the experiments was stable.

The distributions of the temperature in the water within storage tank along the vertical direction during the solar heating process for each 1hr intervals are shown in Figure 4.2. As it was mentioned in chapter 2, the water in the tank was re-circulated for 15min before taking the data as a result the water temperature in the tank at the beginning of the day was uniform (08:00). It is observed that, the water temperature inside the storage tank was increased and the temperature difference between the upper layer and lower layer increased too. The increasing in the water temperature was due to

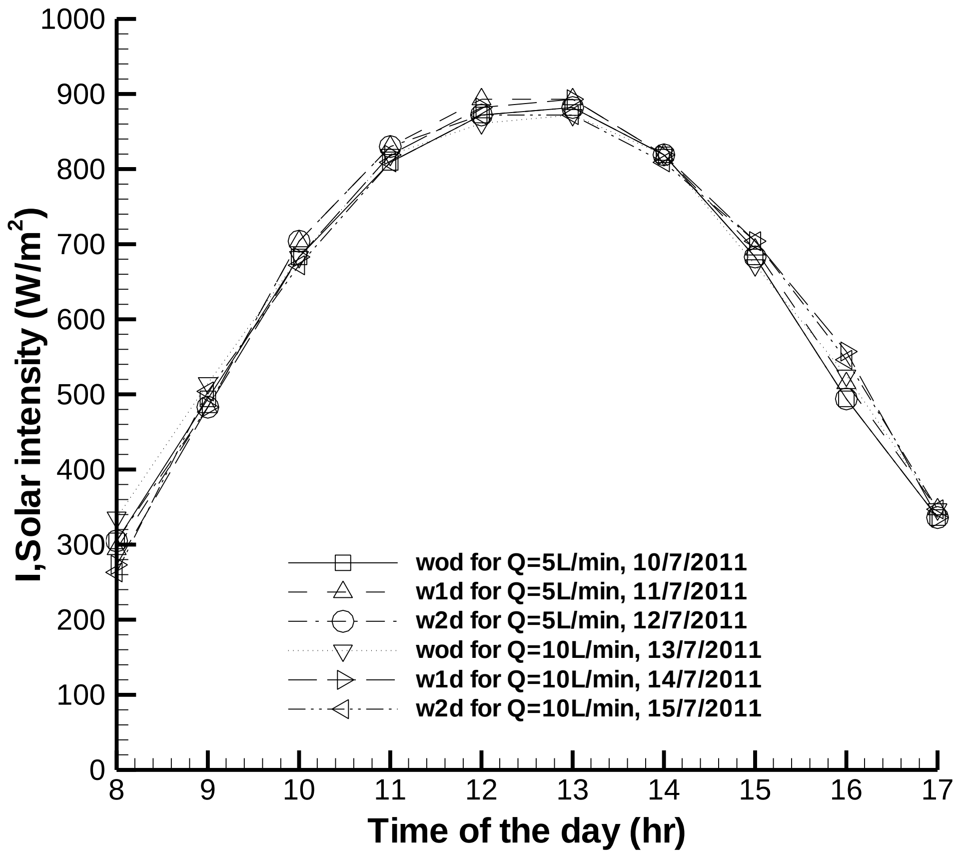


Figure 4.1. Solar intensity versus time for all the days when the experiments were done.

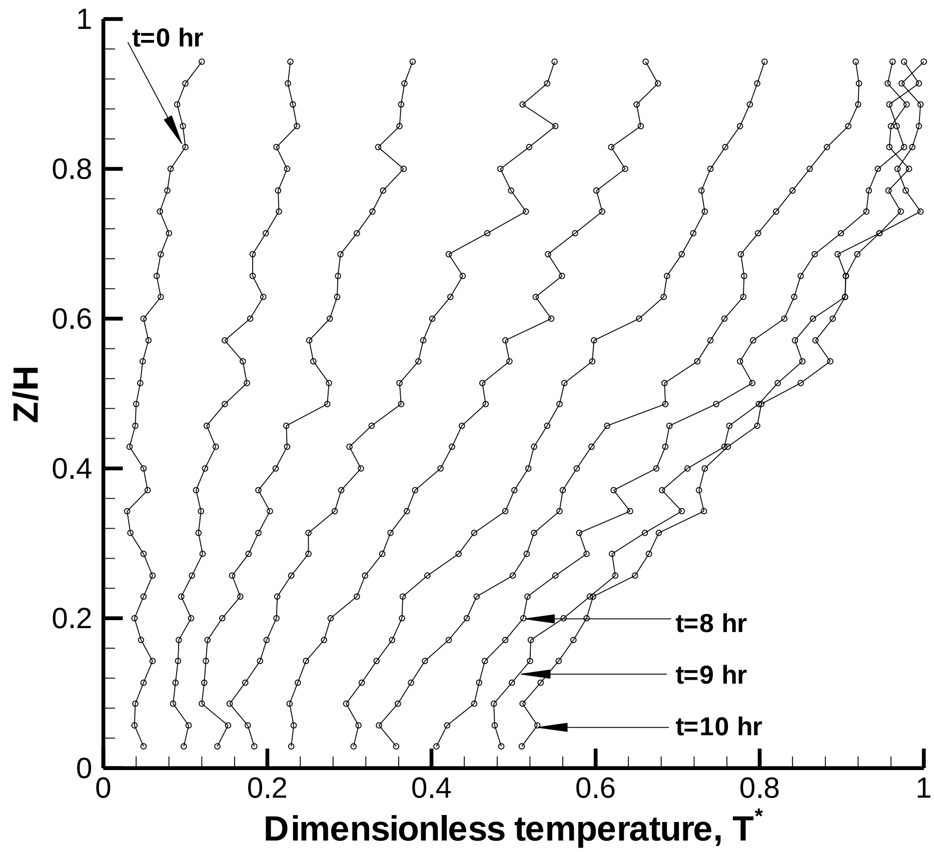


Figure 4.2. The distributions of the temperature in the water within storage tank along the vertical direction during the solar heating process.

the increasing the solar intensity (Figure 4.1). Moreover, the increasing in the water temperature inside the tank will be not sensitive with time for the last two hours (i.e., at 16:00 and 17:00).

It can be mentioned that no circulation was observed inside the ISWH (Figure 4.3). Figure 4.3 illustrates the temperature distributions in the ISWH tank along the lateral horizontal direction during the solar water heating process. The heat transfer from the absorber plate to the water layer inside the tank was by conduction and convection. The water temperature inside the tank increased rapidly with time up to 15:00 due to the increasing in the solar intensity and the ambient temperature. The water temperature inside the tank between 16:00 to 17:00 (Figure 4.2) was almost same since the solar intensity was reduced sharply at that time of the day (Figure 4.1). Similar behavior was also obtained by Al-Talib et al. [41] who experimentally investigated the triangular ISWH.

Figure 4.4 shows the temperature profile inside the tank before discharging process began (17:00). The temperature profile for the three different cases studied in this work is almost same. This means that the amount of water drawn for one person to take a shower at 12:00 or 14:00 will not change the temperature profile inside the tank at discharging time. The temperature profile for solar heating process is not uniform process as the case of heating by using an electric heating element. That is, when the solar intensity incident on the absorber plate, the absorber plate will be heated to a desired temperature uniformly, the amount of water in the lower side of the tank is more than the amount of water at the upper side, as a result, the water temperature at the upper side increases faster than the lower side.

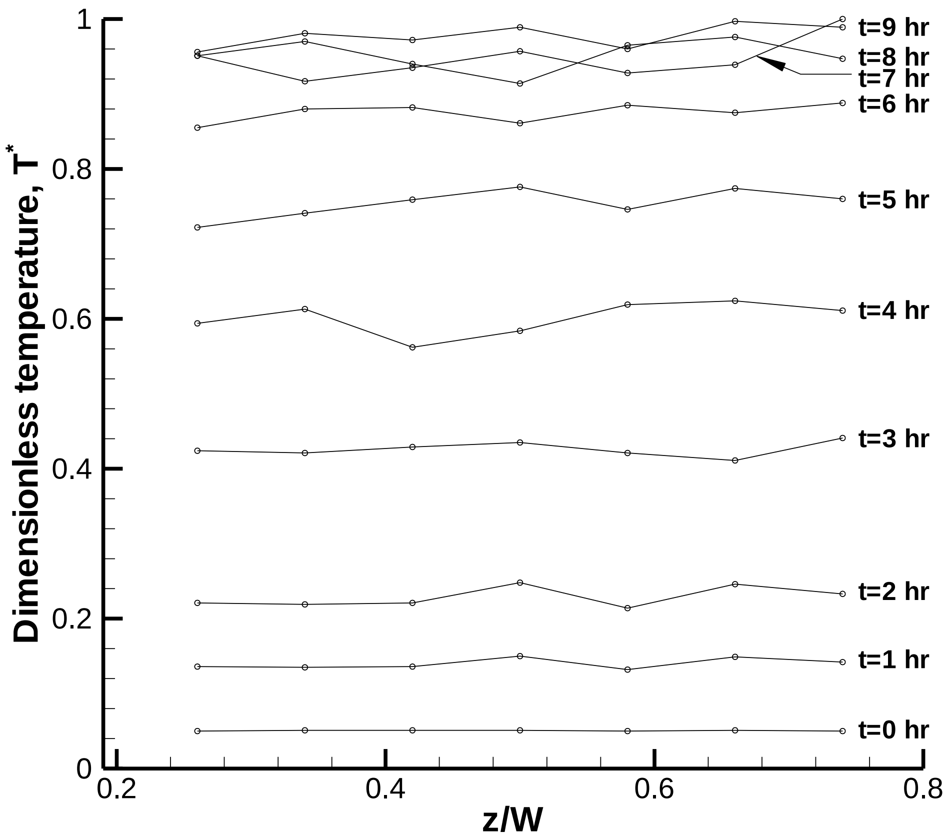


Figure 4.3. The distributions of the temperature in the water within storage tank along the horizontal direction during the solar heating process.

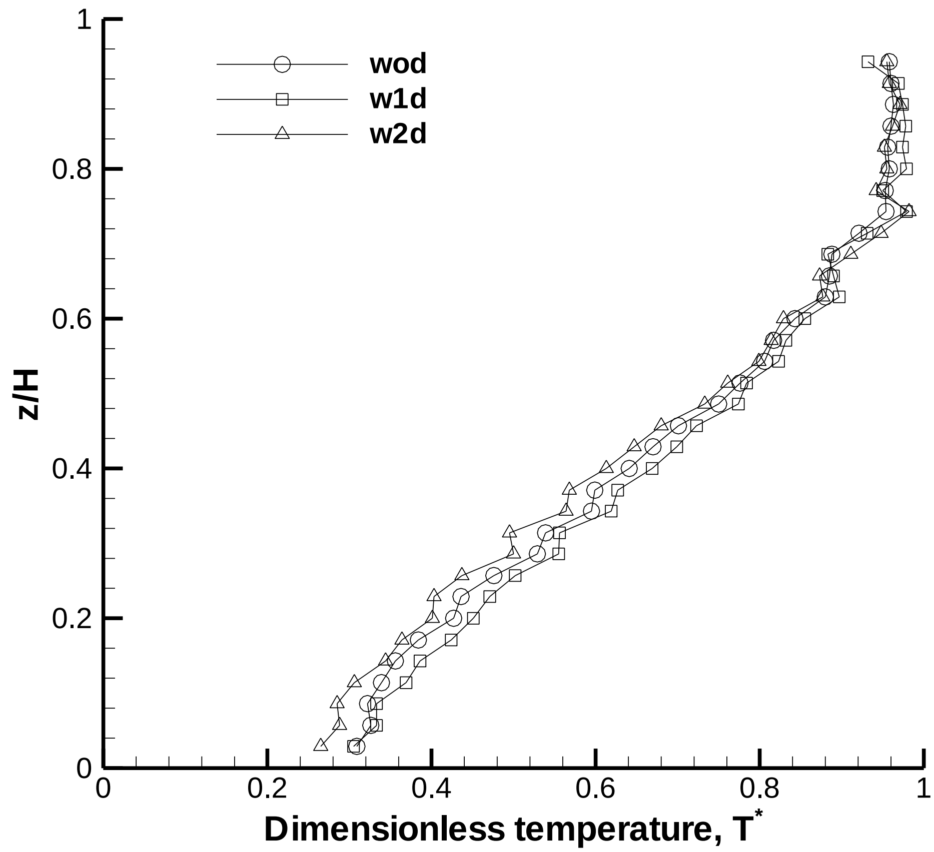


Figure 4.4. The distributions of the temperature in the water within storage tank before discharging process, for different experiments of solar water heating.

The transient temperature distributions of the water in the ISWH tank at each 40sec intervals during the discharging/charging process, $t > 0$, were presented in Figure 4.5(a-c), for each of the three solar water heating, wod, w1d, and w2d, and for flow-rate of 5L/min. For all cases, during the charging/discharging process, the thermocline layer inside the ISWH tank is built up after 120sec as cold water enters from the bottom port of the storage tank while hot water is discharged from the top port of the tank. On the other hand, the thermocline layer inside ISWH tank is built up after 40sec for the case of 10L/min flow-rate (Figure 4.6).

As shown in Figure 4.5, the thermocline layer was rather thin at the first time of the formation. Then, it is started to vanish after half of hot water volume discharged with a temperature gradient until the end of the discharging/charging process. In addition, the time required to discharge the hot water from the tank is reduced gradually depending on the number of withdrawn process and by increasing the discharging flow-rate (Figure 4.6). The time required for discharging the tank for the first case (wod) was 1280sec whereas it was 1200, 880sec for the other two cases, w1d, w2d respectively. On the other hand, the required time to discharging the hot water was decreasing as the flow-rate increased (Figure 4.6 (a-c)). The temperature at the lower part for the three cases is different due to the mixing layer between the cold and the hot water depending on the number of withdrawn processes.

Figure 4.7 displays the draw-off temperature profiles as a function of the dimensionless time for three different solar water heating tests, wod, w1d, and w2d, and for 5L/min flow-rate. All the curves are cut off when the discharged water temperature drops to less than 40°C. The drawn-off profiles of the temperature for the three tests showed moderately stratified tank. The draw-off water temperature decreases continuou-

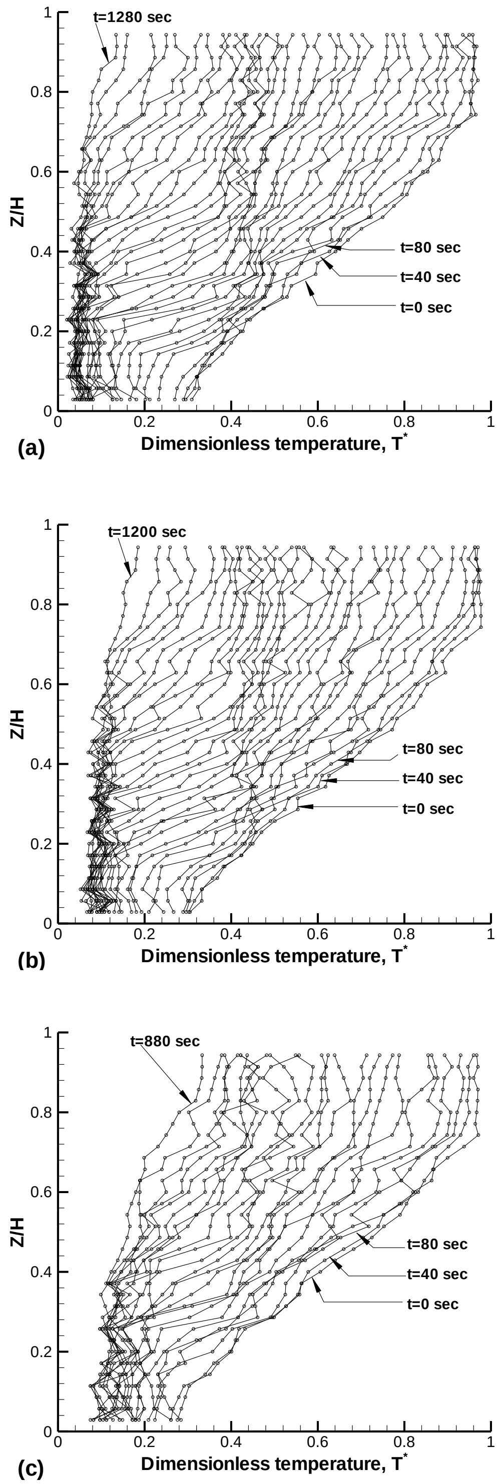


Figure 4.5. The distributions of the temperature in the water within storage tank for the solar water heating (a) wod, (b) w1d and (c) w2d. at flow-rate of 5L/min.

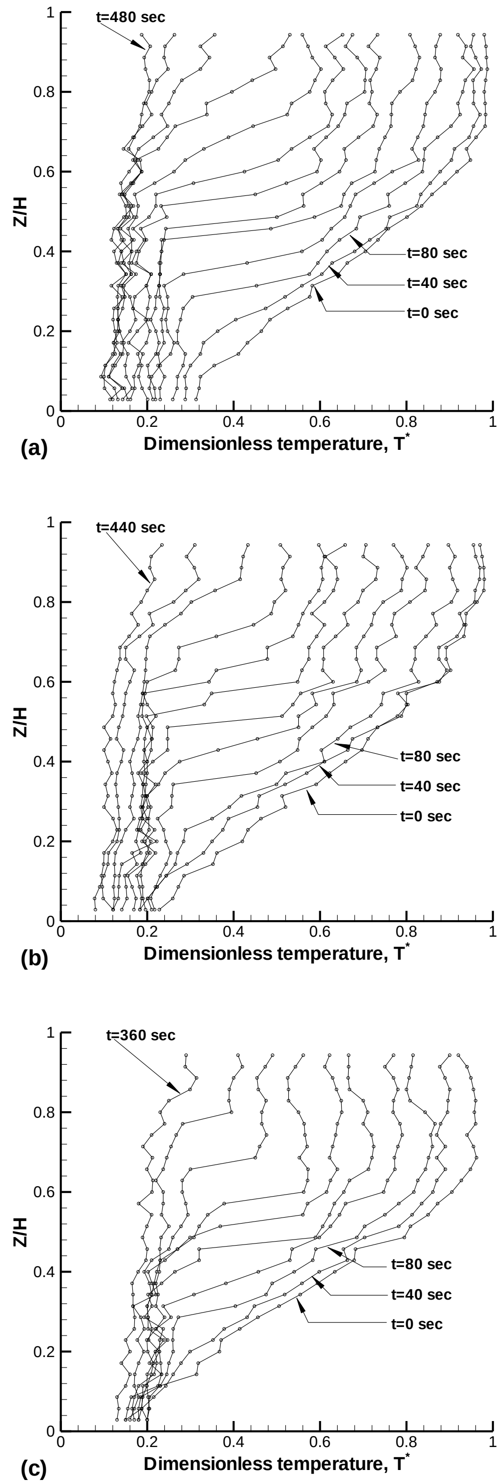


Figure 4.6. The distributions of the temperature in the water within storage tank for the solar water heating (a) wod, (b) w1d and (c) w2d. at flow-rate of 10L/min.

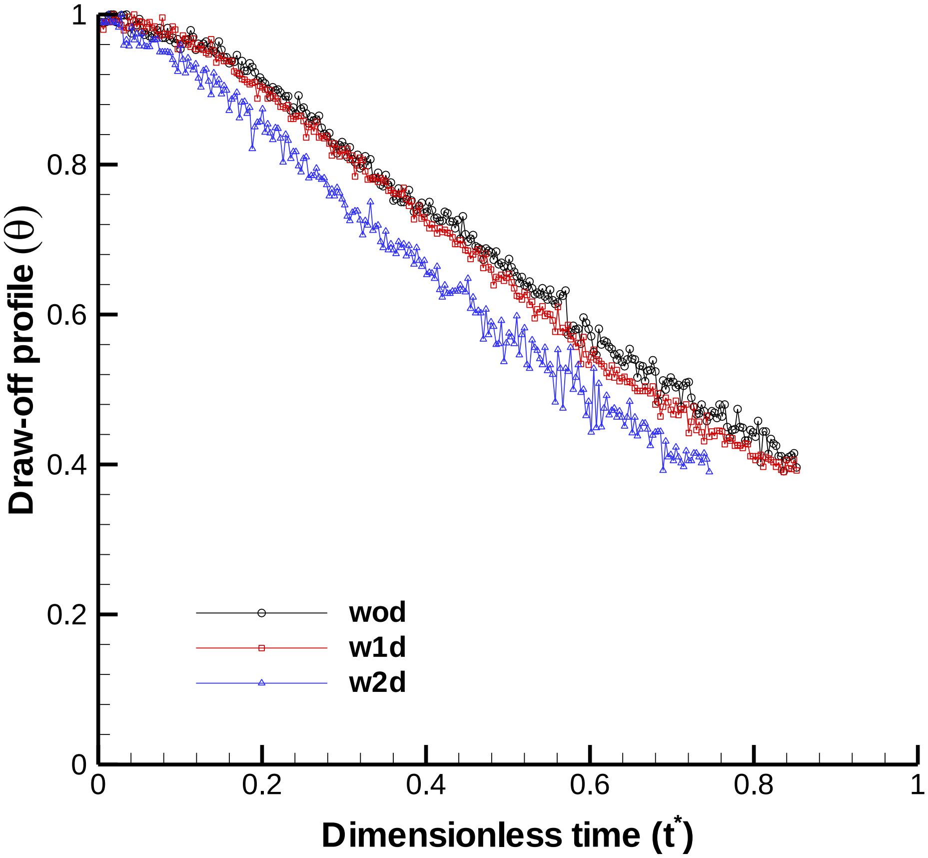


Figure 4.7. Draw-off temperature profiles as a function of the dimensionless time for different solar water heating tests and flow rate of 5L/min.

sly. This decreasing in the draw-off temperature profile is because of the temperature difference between the top and the bottom of the tank where the temperature decreased from the upper side to the lower side of the tank. The time required to discharging the hot water was decreasing as the flow-rate increased. As is appears from the curves, the hot water volume that extracted from the tank is lower than the whole storage tank volume for all cases and it is higher for the first experiment compared with others. However, the volume of the hot water withdrawn for the second and third experiments was higher if the hot water volume withdrawn at 12:00 and 14:00 would be added to these volumes. This reflects that the system can provide more hot water volume if the device used to supply an amount of water during the heating process, at 12:00 and 14:00. The draw-off temperature profiles for the same three tests with 10L/min flow-rate were presented in Figure 4.8. When the process of the discharging started, the draw-off temperature profiles decreased continuously until all the hot water within the tank emptied. The comparison between the two flow-rates of 5 and 10L/min are shown in Figure 4.9. The draw-off rate of 5L/min performs better than 10L/min as the fraction of the hot water withdrawn and water temperatures within the tank is greater for 5 than 10L/min. Comparing the results for 5L/min with those of electric heating element-resistance at position A, shows a difference between electric and solar water heating due to the high temperatures difference between the incoming cold water and the hot water in the tank for the electrical heating case which gave a more stratification case and less mixing in the water layers, whereas for solar water heating case the temperature difference was less. Therefore, there is a less stratified tank during solar heating.

The fraction of the hot water that can be discharged above 40°C after the heating process is 0.88, 0.85, and 0.75 for wod, w1d, and, w2d tests if the flow-rate is 5L/min

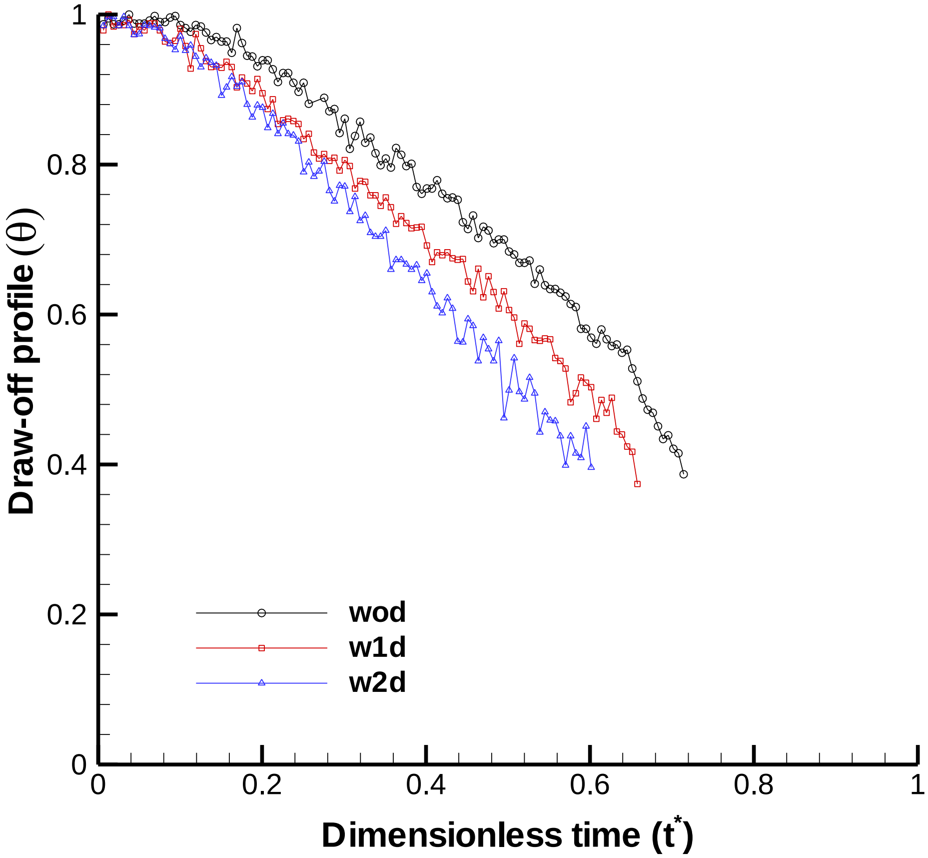


Figure 4.8. Draw-off temperature profiles as a function of the dimensionless time for different solar water heating tests and flow rate of 10L/min.

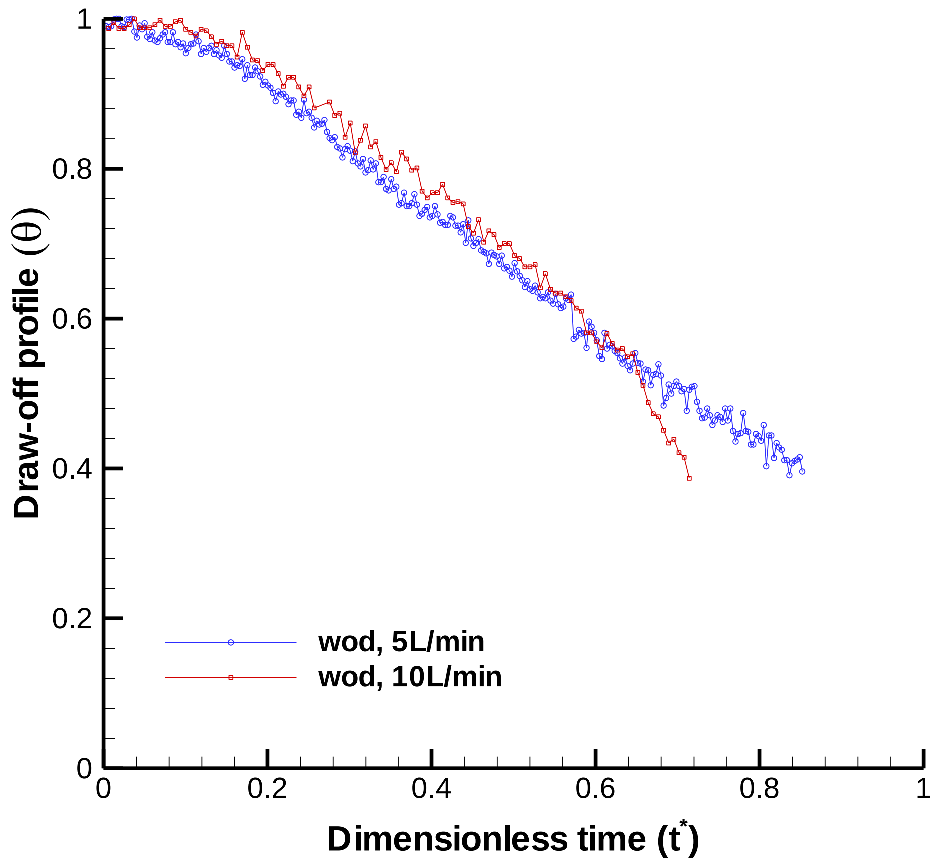


Figure 4.9. Comparison of the draw-off temperature profiles for different discharging rates of 5 and 10L/min.

respectively, while it is 0.72, 0.66, and 0.60 for wod, w1d, and, w2d tests for flow-rate of 10L/min respectively. This was determined by considering the fraction of the hot water within the tank is one since the entire tank would be heated.

The discharging efficiency of the triangular ISWH is calculated by Eq. 2.3. Figure 4.10 presents the overall discharging efficiency for two flow-rates versus number of persons that can take a shower during the solar heating process. It can be seen that the overall discharging efficiency increases with increasing the number of persons who can take a shower during the solar heating process. Moreover, the overall discharging efficiency for 5L/min flow-rate is more than that of 10L/min indicating that the discharging efficiency decreases if the flow-rate increases. The maximum overall discharging efficiency was found to be about 98% for w2d case with5L/min flow-rate.

The maximum temperature of hot water leaving this system, triangular ISWH, was found to be 54°C with a temperature difference of 29°C. These values are subjected to change from day to day as noticed during the experiments. However, the maximum average water temperature and average temperature difference for all the days of experiments were 51°C and 24°C respectively. These results are greater than the results obtained by Mohamad A.A. [40] who found that the maximum average water temperature was 42°C at 17:00. This was attributed to the increasing in the area of the absorber plate by extending it 10cm from the two sides and bottom, as expected. Therefore, the amount of heat received from the sun would be more as a higher surface area will be exposed to the solar radiation.

The collection efficiency of the triangular ISWH was also calculated in terms of cumulative efficiency. The cumulative system efficiency is defined as the total energy

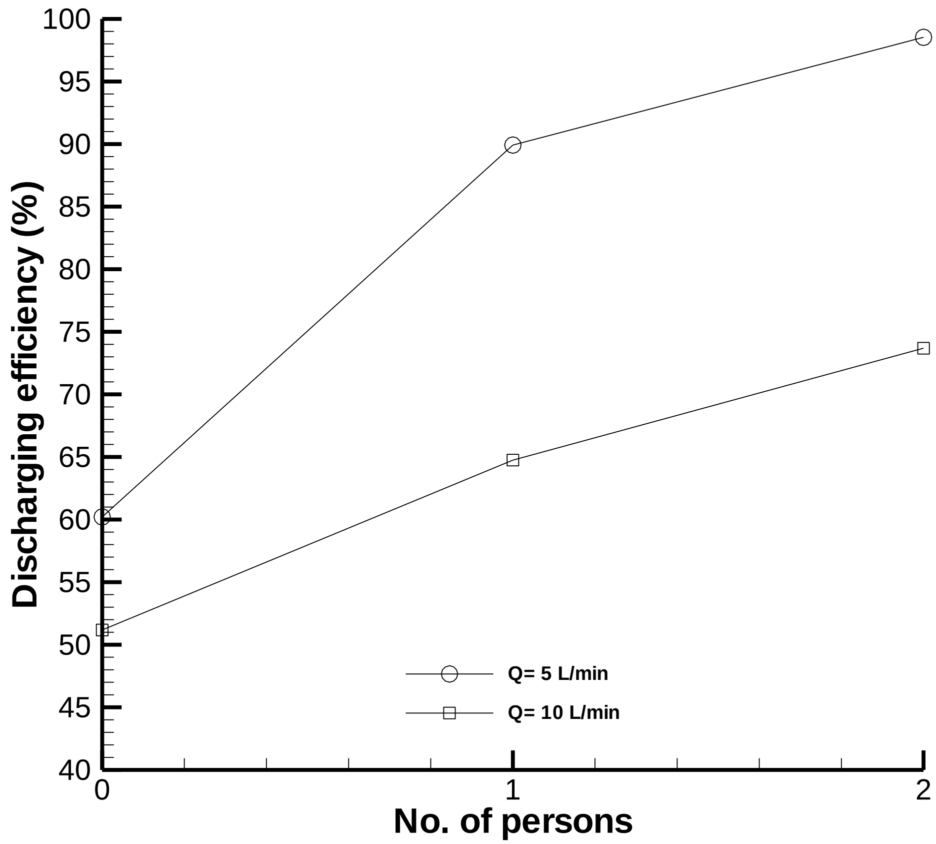


Figure 4.10. The overall discharging efficiency of the triangular ISWH versus number of persons can take a shower during solar heating process for 5 and 10L/min flow-rates.

stored in the storage tank for each hour, Eq. 2.1, divided by the total energy incident on the system for each hour, which is expressed in the following equation

$$E_{\text{incident}} = A \int_{t_1}^{t_2} I \, dt, \tag{4.1}$$

where *A*, *I*, and *t* are collector area, solar intensity, and time of measurement respectively. Thus, the cumulative system efficiency is

$$\eta_{\text{cum}} = \frac{E_{\text{st}}}{E_{\text{incident}}} \tag{4.2}$$

The hourly variation of the cumulative efficiency for this ISWH is presented in Figure 4.11. The maximum cumulative efficiency recorded was at 11:00 to 12:00 then it is decreases continuously. As can be seen, the cumulative efficiency for the two cases, w1d and w2d, decreases when amount of water withdrawn during heating period then increased. The decreasing of the cumulative efficiency was due to the decreasing in the energy stored within the storage tank at that time since the water temperatures decreased. However, the maximum cumulative efficiency was 73% which is more than that obtained by Soponronnarit et al. [37] and Mohamad A.A. [40]. This was attributed to the high water temperatures inside the storage tank and more solar intensity received from the sun.

The amount of warm water which is required for one person to take a shower is 50L at 40°C, as mentioned in the previous chapter [46]. Table 4.1 shows the number of persons who can take a quick shower for different solar heating cases, wod, w1d, and w2d. These results were determined from the total hot water storage in the tank after the heating process. For the two cases, w1d and w2d, number of persons who can take a shower during the solar heating process were added to the number of persons who can take a shower at 17:00.

Table 4.1. No. of persons can take a shower for different solar heating tests.

Solar heating test	No. of persons can take a shower
Wod	5
w1d	6
w2d	6

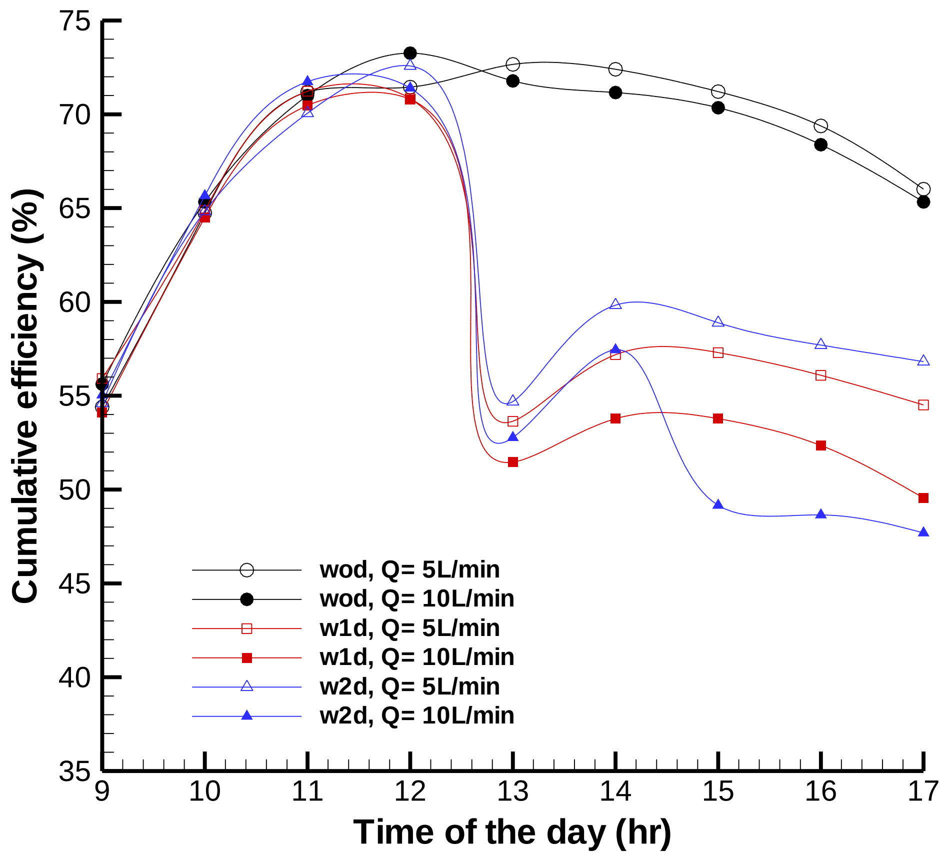


Figure 4.11. Hourly variation of the cumulative efficiency for the new ISWH.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 General Discussions and Conclusion

A new triangular storage domestic electric water heater with solar collector was designed, manufactured, and investigated experimentally. The performance of this device was tested under prevailing weather conditions in Famagusta (Cyprus) during the summer months in order to investigate the feasibility of utilizing this ISWH in North Cyprus. Electrical and solar water heating tests were also conducted in this study.

For the electrical water heating, three electric-resistance heating elements were used to heat water, A at bottom, B at mid and C at top of the tank. The results pointed out that when the heating element mounted at the tank side (location B and C), there are two distinctive zones of the temperature in the tank after the process of heating. The zone of hot water which is resides above the heating element and cold water zone stills approximately not affected at the tank bottom. A thermocline layer separates these zones across which there is a high temperature and density changes. For this case, the hot water amount (more than 40°C) stored in the storage tank is almost same to the amount of the water residing above the heater. Therefore, the position of the auxiliary heating element can be calculated easily according to the hot water needs.

The efficiency of the discharging for the auxiliary heating element installed on the side wall is 85.18% for a draw-off rate of 5L/min, while the discharging efficiency of the heating element mounted at the bottom of the storage tank was 92.21%. It can be seen that, there is a little difference between the two values, but a high difference in the discharging efficiency was found in case of doubling the flow rate especially for the heating element at C, which decreased by 21.96%.

On the other hand, solar heating tests presented acceptable results since the transient temperature distributions showed a moderate stratified tank for different tests and discharging rates (5 and 10L/min). The fraction of the hot water stored within the tank, which can be withdrawn above 40°C, was found to be less than the water volume stored in the tank for all tests, which is because of the thermal losses from the tank. However, discharging amount of water, for one or two persons taking a shower, at 12:00 and 14:00 improved the performance of this type of ISWH. The maximum discharging efficiency was 98% for two discharging at 12:00 and 14:00 with a flow-rate of 5L/min. The maximum average temperature obtained in this study was 51°C with a temperature difference of 24°C. Moreover, the maximum collection efficiency was 73% with a highest daily solar radiation of 893W/m^2.

The number of persons who can take a quick shower also calculated for electrical and solar heating processes. It was found that, warm water, 50L at water temperature of 40°C, can be supplied to take a quick shower for one-time use if the heater located at position C. For same amount of warm water, 5-8 persons can take quick showers in succession if the heater mounted at A, whereas 2 or 3 persons can take showers if the heater is mounted at B. Therefore, this will give the chance to the user to toggles between the heating elements according to the amount of hot water needed. On the other hand, 5 or 6 persons can take a shower if the water heated by the sun.

In conclusion, using this type of solar water heater will be possible to save energy. This was by using a secondary heating element mounted at the top of the tank. Using electric heater at different positions in ISWH will give the possibility of heating water when there are no solar rays. The application of this system in a country like North Cyprus is worthwhile since there is a high number of students study there. That is, this system can meet their demands as well as it can be used in any house or apartment in North Cyprus since it can be manufactured easily with low initial cost which is around TL1000- TL1500.

5.2 Suggestion for future Work

This research has been carried out to achieve its set objective and in the process; areas for future work have been identified. These suggested areas are believed to improve the efficiency of the ISWH for a better performance when further researches are carried out. The recommendations are highlighted as follows.

- More investigation can be done to check the performance of the ISWH after withdrawn amount of water, that is sufficient for taking a shower, each one hour after 12:00 to 17:00, as well as check the availability of hot water at 17:00.
- Further investigation can be done to study the heat-losses during night-time from this type of ISWH. This can be achieved by examining the hot water availability after waiting amount of time, from 1 to 24hrs.
- Two glass covers can be used to increase the heat retaining inside the storage tank by decreasing the heat-losses from the top.
- The extra 10cm extended of the absorber plate for this study may be examined for the rectangular storage tank and compare it with triangular tank.

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