Discharge Performance of Domestic Water Heater

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ABSTRACT

Water is generally heated in domestic buildings using an immersion-type electric water heater (EWH) which includes a thermostat installed at the bottom of the tank. Although these systems are powered by electricity, which is more costly than solar water heating, they are nonetheless extensively utilized because of their convenience and low installation costs.

The thermostat position and water set-point temperature are critical for efficient and economic usage of electric water heaters. Accordingly, the impact of locating the thermostat at three different altitudes, namely near the bottom, middle, and top of an EWH, is investigated in this work. In addition, the effect of thermostat set temperature at the bottom of the tank on the EWH's performance is tested experimentally. During the experiments, the heated water was discharged at a rate of 5 L/min, and data was collected. The discharge efficiencies for the thermostat position at the bottom are found to be higher, whereas the discharge efficiencies for the thermostat positions in the center and towards the top are quite similar but lower than the one near the bottom.

Water heating for home usage with solar energy is also a well-known and practical technology that is widely used. Most available systems, on the other hand, have the solar collector and the hot water storage tank as distinct components, requiring plumbing and additional thermal insulation for both. Combining the solar collector and the hot water storage tank into one unit eliminates extra insulation, piping, and hot spots, and also it requires less space to install the system in buildings. Also, the integrated solar collector water heaters can be used in colder climates without

antifreeze solution since there is no risk of freezing like in the pipes of flat plate solar collectors. Accordingly, a novel trapezoidal-shaped integrated solar water heater is developed and tested in this part of the study. In comparison to the previous design, the new one allows the end-user to install and use it in a smaller area while maintaining the same efficiency and cost savings compared to the conventional design.

The temperature profile inside the new storage tank is measured with 33 thermocouples for two different volumetric flow rates, 5 L/min, and 10 L/min, and compared to the temperature profile inside the old storage tank. Based on the results, the highest solar intensity and water temperature during the experiments were 890 W/m^2 and 54.6 °C, respectively.

Keywords: Electric Water Heater, Heat Storage, Thermal Stratification, Thermostat, Experimental, Natural Circulation, Integrated Solar Collector, Temperature Profile

ÖZ

Binalarda su ısıtma genellikle sıcak su tankı alt kımına yerleştirilen termostat bağlantılı elektrikli ısıtıcılarla sağlanmaktadır. Bu sistemler elektrik enerjisi kullanımından dolayı daha yüksek çalışma giderlerine sahip olmalarına rağmen, pratik olmaları ve düşük yatırım maliyetleri sebebiyle yaygın kullanılmaktadır. Elektrikli ısıtıcılı sistemlerde termostatın pozisyonu ve ayar sıcaklığı, bu sistemlerin verimli ve ekonomik kullanımı açısından kritik öneme sahiptir.

Bu bağlamda, çalışmanın ilk bölümünde termostatın sıcak su tankı içerisinde alt, orta ve üst kısma yerleştirilmesinin etkisi deneysel olarak incelenmiştir. Bunun yanında, termostatın tank alt kısmına yerleştirildiği durumda, thermostat ayar sıcaklığının elektrikli su ısıtıcı performansına etkisi de analiz edilmiştir. Deneysel çalışmada su 5 L/dak debide deşarj edilmiş ve bu çalışma koşulunda veri kaydı yapılmıştır. Termostatın alt kısma yerleştirildiği durumda deşarj verimi daha yüksek bulunurken, orta ve üst kısma yerleştirildiği durumlarda birbirine yakın verimler elde edilmiştir.

Bina uygulamalarında güneş enerjisi ile su ısıtma da yaygın olarak kullanılan pratik bir teknolojidir. Ancak bilinen güneş enerjili su ısıtma sistemleri, güneş kollektörlerinin ve sıcak su tankının ayrı ayrı yer aldığı ve her iki ünite için boru, bağlantı ekipmanları ve izolasyon malzemelerinin gerekli olduğu uygulamalardır. Güneş kollektörü ve sıcak su tankının tek bir ünite olarak birleştirilmesi, ilave izolasyon ve borulama gereksiniminin azalması, kayıpların azalması, ayrıca sistemin kurulum alanının en aza indirgenmesi için avantaj sağlamaktadır. Bunun yanında, düz palakalı kollektörlerde olduğu gibi borulama sistemi bulunmadığı için, entegre güneş enerjili ısıtıcı, borularda donma problemini antifriz kullanıma gerek duymadan önleyebilmektedir. Bu bağlamda, çalışmanın bu bölümünde yenilikçi trapez-şekilli entegre güneş enerjili bir su ısıtıcı üretilmiş ve test edilmiştir. Hedeflenen tasarım kullanıcıya herhangi bir verim ve ekonomik kayıp olmadan, daha küçük alana güneş enerjili ısıtıcı yerleştirme imkanı verecektir.

Geliştirilen sistemde, 33 adet sıcaklık sensörü kullanarak depodaki suyun sıcaklığı 5 litre/dakika ve 10 litre/dakika debilerde ölçülerek depodaki suyun sıcaklık profili çıkarılmıştır. Elde edilen sonuçlar geleneksel sıcak su tanklarındaki sıcaklık profili ile karşılaştırmalı olarak incelenmiştir. Deneyler sırasında ölçülen en yüksek güneş ışınımı ve tank su sıcaklığı 890 W/m^2 ve 54.6 °C olarak belirlenmiştir.

Anahtar Kelimeler: Elektrikli Su Isıtıcı, Isı Depolama, Isıl Tabakalaşma, Doğal Sirkülasyon, Entegre Güneş Kollektörü, Sıcaklık Profili

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C_p	Specific Heat at Constant Pressure, (kJ/kg.K)
DHW	Domestic Hot Water System.
EWH	Electric Water Heater
E_{st}	Initial Energy Stored in the Tank, (kJ)
E_{out}	Energy Contained in the Water Leaving the Storage Tank Through the Outlet Valve Up to Time t, (kJ)
H	Height of the Hot Water Storage Tank (m)
kW	Kilowatt
L	Liter
Sec	Second
T_{in}	Cold Inlet Water Temperature, (°C)
T_j	Temperature Measured by the Thermocouple j, (°C)
T_{max}	Measured Maximum Water Temperature, (°C)
$T_{out}(t)$	Temperature of Water Measured in the Pipe Near The Outlet Valve at Time t, (°C)
T*	Dimensionless Temperature
T(z,t)	Instantaneous Local Water Temperature at a Height of z and the Time of t, (°C)
t*	Dimensionless Time,
t_{total}	Total Time Required for Discharging/Charging One Tank Volume of Water at a Given Flow Rate.
V	Volume, (m^3)

V_{Cold}	Volume of Cold Water, (m^3)
VFR	Volumetric Flow Rate of Water During the Discharging/Charging Process, (m^3/sec)
$V_{Mixture}$	Volume of Warm Water, (m^3)
V_{st}	Volume of Water Stored in the Tank, (m^3)
V_{hot}	Volume of Hot Water Discharged for One Person Quick Shower, (m^3)
z	Height of Control Volume Element (m)
z/H	Dimensionless Height
ρ	Water Density, (kg/m^3)
η	Discharging Efficiency, (%)
θ	Dimensionless Drawn-off Temperature Profile

Chapter 1

INTRODUCTION

1.1 Background and Problem Description

Domestic hot water supply is crucial in buildings, where different sources such as electric, gas, or solar energy are mostly used. Despite solar energy being preferable, it is very limited in the winter period while it is most needed. Therefore, gas or electricity is used as a backup to heat the water to the desired set temperature when solar radiation is insufficient. Electric heaters become the only choice in locations where there is no or limited natural gas availability. In such cases, temperature control of the hot water tank becomes crucial to minimize electric energy consumption. Despite significant advancements that have been achieved in the field of domestic water heating, there is still room for efficiency improvement, which could be obtained through the consideration of process design (*i.e.*, integrated collector design) and control (*i.e.*, temperature regulation).

In that regard, this study concerns two different applications of domestic water heating. First, cylindrical hot water storage where the effect of thermostat position on the performance of a cylindrical domestic water heater is studied, and the second one is, the integrated solar water heater (ISWH) in which the hot water storage tank solar collector unit is combined in a trapezoidal shape at which the performance analysis of the developed system has experimented under real climate conditions.

1.2 Cylindrical Hot Water Storage

Many families globally use EWH, for generating and storing hot water. In the north side of Cyprus, the EWHs are produced as 120 L standard volumetric size. The storage tanks are equipped with a backup immersion type 3 kW electrical heater, which is vertically inserted at the bottom part of the tank. In such systems, water is heated by utilizing solar energy and in winter, an electrical heater is used to boost the water temperature when solar energy is not sufficient during the daytime. In North Cyprus, such water heating units are widely used both in detached houses and apartments as illustrated in Figure 1. Despite in summer, there is no need for auxiliary heaters due to the high solar radiation, in winter time hot water is mostly produced by operating electric heaters. In this regard, any performance improvement in the electric water heating performance could provide significant energy and cost savings for the occupants.

Figure 1: View of the solar/electric water heating units in Cyprus

1.3 Solar Water Heating

The Turkish Republic of Northern Cyprus is located between 34° and 36° north latitude and 32° and 35° east longitude of Greenwich. In the coldest months of the year, mean daily solar radiation ranges from 2.3 kWh/m^2 in December and January to 7.2 kWh/m^2 in July [1]. Because of its location, the climate is moderate and sunny. In Cyprus, solar energy is primarily used for water and air heating and also for the generation of electricity using solar photovoltaic panels.

Water heating by utilizing solar energy for domestic use at present is a well-established technique. This is largely due to the regular daily demand for hot water by the people. Based on the operation they are classified into two types passive and active. These can be further classified as direct and indirect types.

Figure 2. depicts a passive solar water heater setup. Above the collector is the hot water storage tank. Because of the density difference created when the water in the collector is heated by the sun, it moves to the storage tank from the collector, and the cold water in the tank enters the collector from the bottom. Thereby, the water circulation will continue as the collector is heated by the sun, and no pumping of water is required. When solar energy is not available, a backup electric heater is utilized to keep the water warm.

If a thermosyphon system is not possible to be installed due to climatic or structural constraints, an active solar heating unit (forced-circulation) is utilized, as shown in Figure 2b. The hot water storage tank is not necessarily installed above the collector, it can be placed at any suitable location outside the living building for safety concerns. The water is circulated between the collector and the storage tank by using a circulating pump. In case the collector temperature is greater than the storage tank temperature, a differential controller module that measures the water temperature at the top of the collector and the bottom of the storage tank turns on the pump. A photovoltaic panel and a dc pump can also be employed for water circulation. The photovoltaic panel will only activate the pump if solar radiation exceeds a certain threshold, obviating the need for a differential controller and temperature sensors. During the night, a check valve is fitted to prevent circulation in the reverse direction.

In a direct or open loop solar water heating system, shown in Figure 2.c, the storage tank and the collector are at atmospheric pressure, and the cold water from the storage tank is drawn directly and circulated through the collector to be heated and return to the storage tank, the heated water is directly used in the domestic application.

In an indirect or closed loop system, the collector and the storage tank are separated by a heat exchanger, as shown in Figure 2.d. The solar collector will heat the fluid in the system and transfer the heat with a heat exchanger to the storage tank for domestic use.

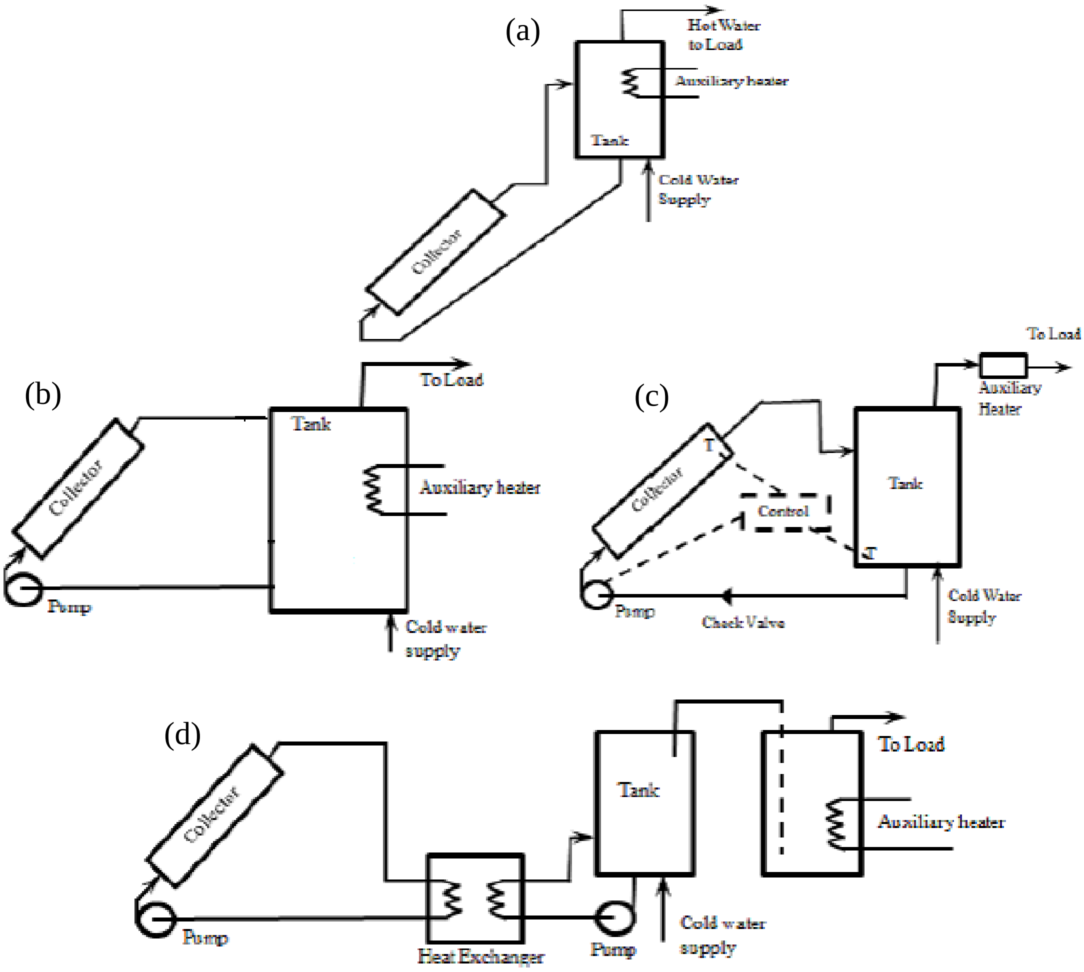


Figure 2: Schematic view of different solar water heaters [2]: (a) Passive (thermosyphon) system, (b) Active system, (c) Direct system, (d) Indirect system

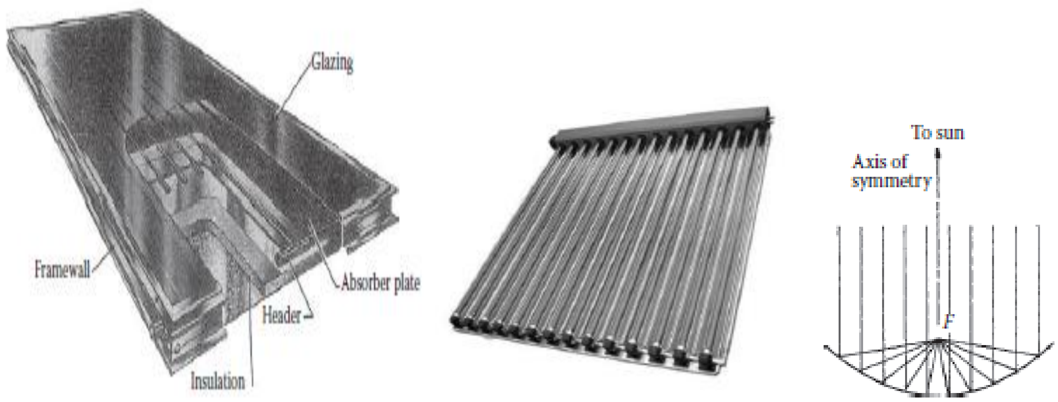
1.3.1 Solar Collectors

Solar energy collectors can be grouped into three types based on the type of energy collection: flat plate, Figure 3a, evacuated tube, Figure 3b, and concentrating collectors, Figure 3c.

A flat plate collector is a boxed shape as shown in Figure 3a. It consists of (i) a black-colored collector surface with liquid circulation passages, that absorb the solar radiation, (ii) a transparent plastic or glass glazing (which transmits the short wavelength of solar radiation and blocks the long wavelength solar radiation from the absorber), (iii) a heat transfer medium (generally water for domestic water heating applications), and (iv) insulation on all the other sides to prevent losses by conduction and convection.

Figure 3b shows an evacuated tube collector with numerous rows of glass tubes connected to a header pipe. To prevent heat loss through convection and conduction, each tube is vacuumed. A dark flat metal fin is fitted as an absorber to a metal pipe that is circulating a fluid (alcohol or purified water) inside the glass tube.

Concentrated solar panels, as shown in Figure 3.c, are used to focus the sunlight on an absorber called a receiver, by using lenses or mirrors the sunlight is concentrated on the small receiver to heat the fluid to a high temperature. These types of collectors could be designed either to focus the radiation on a point or a line at a focal distance.



(a) (b) (c)

Figure 3: Different types of solar collectors [3]: (a) Flat plate, (b) Evacuated tube, (c) concentrated collectors

1.3.2 Integrated Solar Water Heater

As shown in Figure 4a, (i.e., existing flat plate solar water heater) most of these water heating systems consist of a grid of water-carrying tubes bonded to an absorber plate, referred to as the solar collector, and a separate storage tank. The thermosyphon system is not highly efficient due to unavoidable losses as a result of conduction, convection, and radiation caused by temperature differences, as well as causing problems due to leakage and corrosion. Due to the separate storage tank and absorber unit, the cost of this system is significant.

The built-in storage type ISWH is an attractive alternative to the thermosyphon system since it combines the storage volume and the collector in a single device. As illustrated in Figure 4b, the integrated system under consideration in this study is trapezoidal, with solar panels and hot water storage incorporated more compactly. The lack of a vertical storage tank lowers the cost of the solar water heater while also removing the aesthetic objections to roof-top installations.

(a)

(b)

Figure 4: Types of solar water heater systems (a) existing system, and (b) new system

1.4 Aim and Objectives of the Study

The primary aim of the present study is to experimentally investigate the performance of a cylindrical domestic EWH and an ISWH under different operating conditions. Accordingly main objectives of the study are as follows;

- To explore the energy savings of an EWH in a storage tank by employing multiple thermostats (at the bottom, middle, and top) instead of a single thermostat at the bottom. With this modification, it is proposed to provide better demand side management for hot water usage in buildings, by realizing control of the volume of heated water thereby minimizing the heat losses. Besides the advantage of saving energy, another merit of using multiple thermostats at different levels is reducing the heating time of water which is making the process more practical for the end-users. This could be achieved by setting the desired temperature on the thermostat located at the medium or top part (depending on the required hot water volume), thereby allowing only the water above a certain level of the tank to be heated.
- To study the thermal performance of the domestic EWHs at different thermostat temperatures. To reach this aim, the thermostat is set to different charging temperatures, and the impact of the thermostat set point temperature on heat storage efficiency was experimentally investigated.
- To design, manufacture and test a new compact ISWH system. The traditional cylindrical shape of the storage is replaced by a trapezium shape which includes the storage and the solar collector. Three electric heaters, with 1500 Watt capacity, are used, one at the bottom in the conventional vertical position and two on the side in a horizontal position to increase the efficiency. The system is tested in both electric heating mode and solar heating mode. The performance of the system in both modes is investigated through thermodynamic analysis.

1.5 Novelty of the Study

Despite thermal stratification and heat transfer enhancement methods having been widely investigated for cylindrical hot water storage tanks, studies on thermostat configurations (i.e. using multiple thermostats, using different thermostat set point temperatures) for controlling and optimizing the heat storage charging/discharging processes are missing in the literature. Accordingly, in the present study, using multiple thermostats at different elevations is considered for advanced control of the heat storage charging process. Besides, the impact of different thermostat set point temperatures was applied for determining optimal operating conditions of hot water storage tanks under different cases. It is worth mentioning that no relevant research was found in the literature, investigating the effect of thermostat position and its set point temperature on the performance of EHWs.

In addition, to the best of author's knowledge, no full study has been performed on ISWHs under North Cyprus climate conditions, investigating the ISWH performance. Therefore, study outcomes could provide a significant contribution towards the development of more efficient, compact, and economic hot water production and storage units for buildings.

1.6 Organization of the Thesis

The background, aims and objectives, and novelty of the study are presented in Chapter 1. Previous studies on EWH and ISWH are discussed in Chapter 2. In Chapter 3, developed experimental systems and applied experimental methodology were described. Chapter 4 presents the experimental analysis results on EWH and ISWH also discussions of the results are provided. Chapter 5 provides an overview of the study with key outcomes presented. In addition, future work on EWH and ISWH is presented.

Chapter 2

LITERATURE SURVEY

2.1 Previous Studies on Cylindrical Hot Water Storage Systems

The electrical kind of heater is the most commonly used heating element for hot water storage systems [4], whether it is for a single tank or an auxiliary storage tank (parallel or series). Fernándes-Seara et al. [5] and McMenamy et al. [6] have shown that the heating efficiency of such systems has very high values over 85%. The only disadvantage of electric heating systems is the high electric energy consumed to generate the hot water required. However, with the advancement of sustainable on-site electric generation (i.e with photovoltaic panels), electric heaters could find wider application potential in dwellings in close future for hot water production.

The thermal performance of the storage tank is affected by the mixing rate of the generated hot water and the incoming cold water in such systems. In a vertical tank, Aviv et al. [7] investigated the mixing of the input cold water with the hot water. Researchers suggested using a horizontal baffle above the vertical incoming water jet at the bottom of the tank. They found that for very low volumetric flow rate (VFR) (i.e.,2-3 L/min) of the incoming cold water, the baffle is not required, however for higher VFRs (5-7 L/min) one baffle is found to be sufficient to have a uniform mixing and establishing the stratified temperature distribution. They found that the placement of a baffle is a more efficient and economically feasible solution compared to the dual tank approach.

Thermal stratification has been examined extensively by numerous researchers [8] and might be regarded as an alternative strategy for reducing the influence of the mixing problem in EWHs. The cold and hot water are divided without the need for physical separation when thermal stratification occurs. Due to the differing densities of hot and cold water during the heating process, it naturally establishes itself. The hot water due to its low density will move to the top and the cold water which is at a higher density will move to the bottom part of the storage tank, establishing a thermal gradient. That thermal gradient is called thermocline and it keeps the hot water at an upper part of the denser cold water in a form of thin layers without any need for physical separation. When hot water is discharged (from the upper part) and cold water is introduced (from the down part), the formed thermocline is disrupted. Many factors influence the pace of thermocline degradation, including the rate of hot water discharge in the tank, the geometrical configuration of outlet and intake water ports, and the aspect ratio of the heat storage tank.

The thermal stratification can be altered by the intake port of incoming cold water and the aspect ratio of the storage tank, according to Hegazy [9]. They proposed a wedged type intake diffuser in which the entering cold water does not interfere with the hot water. The new design has reduced the rate of mixing of hot and cold water by establishing a cold water disc partition at the bottom of the tank by directing the cold water flow toward the tank base. With this new design, the rate of disturbance of the thermocline was reduced and the drawn-off discharge efficiency improved. The thermal performance of the tank was also increased by increasing the aspect ratio of the tank and decreasing the discharge rate.

Sezai et al. [10] investigated the effect of heater location on the thermal performance of a storage type EWH having 120L of volume. They found that, when the heating element is horizontally placed on the side/lateral surface of the storage tank, only the part of water above the heating element could be heated, whereas the cold water below the heater does not affect by the heating process. They advised using a supplementary heating element positioned horizontally at the tank lateral surface below the uppermost 50 L volume for energy conservation in such large capacity EWHs with the heating element put vertically at the bottom half of the tank. They recommended turning on the second heating element when only a little amount of hot water is necessary (i.e., <50L), and turning on the bottom heater when a larger amount of hot water is required (i.e., >50L).

There are several studies in the literature on parametric optimization and dynamic control of hot water thermal storage systems. Rahman et al. [11] Performed parametric analyses on a water thermal storage tank. In the study, the impact of the vertical height and location of heating and cooling also the impact of water VFR on the heat storage performance were investigated. The study demonstrated that increasing the height of either a hot or cold heat exchanger increases the temperature of the output cold water, albeit the gain in temperature was found to be modest beyond a height of z/H=0.75. Assari et al. [12] examined how the placement of the fluid's entrance and exit affected thermal performance in a cylindrical storage tank. The location of the hot water entrance to the tank was found to have a significant impact on performance. Due to decreased mixing of hot and cold water, improved performance was gained when the vertical height of the heating location was increased.

In a recent study, Booysen et al. [13] studied three different thermostat control strategies using dynamic modeling. Investigated strategies were aimed to provide the desired output temperatures from the water tank with maximum possible energy savings. Study results showed that with the demonstrated thermostat control strategies energy savings in the range of 8-18% could be obtained. Roux et al., [14] developed a dynamic control strategy for EWHs by consideration of hot water consumption patterns and different set point temperatures. It was found that the investigated demand-driven control method could provide 14% energy savings in water heating applications. Huang et al. [15] looked at the effect of thermostat position, heat loss ratio, and system layout on the performance of hot water storage tanks. It was discovered that a higher thermostat location improves the performance of a hot water tank with reduced heat loss. Lower thermostat performance was shown to be more suitable for stabilizing the charging process and producing greater performance in the case of high heat loss. Fernández-Seara et al. [16] experimentally investigated four different control strategies for charging the hot water storage tank. Different control valves and different VFRs were used in the analysis. Study results showed that the control strategy of the domestic hot water production system significantly affects the thermal performance of the hot water storage tank.

2.2 Previous Studies on ISWH

Because of their ease of use and inexpensive maintenance, electric water heating systems (EWH) are the preferred method of generating hot water for many families around the world. The only disadvantage of this type of EWH is that energy consumption is high to provide enough hot water for a fast shower (i.e., <50L). As Hiller et al. [17] stated, this kind of hot water storage system is designed at a large scale to ensure hot water availability. For instance, it is a widely accepted approach to consider that only 70% of the heated water inside the tank is possible to recover at a useful temperature level (>40 °C)

Tully [18] investigated the impact of electrical backup heater size in a natural circulation type DHW system for Pretoria, South Africa. Results showed that without electrical back up the performance of the solar DHW system is insufficient. However, it was found that; when a 1 kW backup heater is fitted it could provide competitive performance with heat-pump in terms of demand side management. Sezai et al. [10] evaluated the impact of heating-element position in a 120L EWH.

When the heating element was powered and placed horizontally at the lateral surface of the storage tank, thermal stratification occurred. The hot water zone occupied the volume above the heating element within a thin thermocline layer above the heating element, while the down part of the tank with cold water remained untouched. In such 120 L capacity EWHs with the main heating element situated vertically at the tank bottom, they recommended utilizing a secondary heating element positioned horizontally at the tank lateral surface below the highest 50 L water volume for energy conservation. When only a limited amount of hot water is needed, the second heating element is activated. for a 6-minute shower, 50 L of water (at a minimum 40°C) is sufficient, whereas 50 L of water (at a minimum 55°C) is suitable for a 5-minute use in the kitchen sink, according to Turkish Standards. They recommend changing the thermostat set-point of the auxiliary heating element if a larger volume of hot water is demanded, so that this 50 L of hot water, when mixed with mains cold water at the fixtures, generates a significantly larger amount of warm water at the specified temperature.

Water heating by solar energy for domestic or industrial usage is one of the applications of solar energy. In Cyprus for domestic applications generally, the thermosyphon solar heaters with flat plate collectors where the water pipes are fixed on the absorber plate and cylindrical storage tank installed above the collectors are used even at remote places where there is no electricity Figure 2.3a.

In a recent study, Yassen et al. [19] tested an integrated solar water heating unit with a corrugated absorber. The daily thermal efficiency of the investigated system was found in the range of 59-67%. Saint et al. [20] presented a comprehensive review of different types of ISWHs and investigated different heat retention strategies applied in these systems. Souliotis et. al. [21] developed three different types of compound parabolic collector-based ISWHs and compared their performance with flat plate thermosyphon units. Results showed that compound parabolic type ISWHs provide higher yearly efficiencies. Wang et al. [22] developed a novel ISWH based on lap-joint-type micro-heat pipe arrays. The maximum thermal efficiency is obtained as 61.5% with the highest thermal power output of 1.32 kW. In another study, Garnier et al. [23] performed computational fluid dynamics simulations on a building-integrated collector-storage type solar water heater. The maximum efficiency of the investigated system was found 30% at a solar radiation rate of 0.4 kW/m^2. Souliotis et al. [24] experimentally investigated the thermal performance of an ISWH under partial vacuum. The night thermal loss coefficient of the developed unit was found between 1.60-1.62 W/K. Researchers also stated that the vacuum pressure has the most significant impact on the developed ISWH performance. Chaabane et al. [25] performed transient simulations on an ISWH unit combined with latent heat storage. Results showed that; using phase change material in the ISWH system reduces the heat losses at night time thereby enhancing the thermal performance. Singh et al. [26] reviewed the recent developments in ISWH systems. In that study, the main parameters affecting the ISWH performance, heat retention strategies for such systems also future directions on ISWH technology are evaluated. Harmim et al. [27] have developed a unique integrated collector storage solar water heater with a parabolic reflector for building façade applications. The daily efficiency of the developed system is found in the range of 36.4-51.6% for wintertime operation. The increase in the water temperature was also obtained as 27 °C under clear sky conditions.

Chapter 3

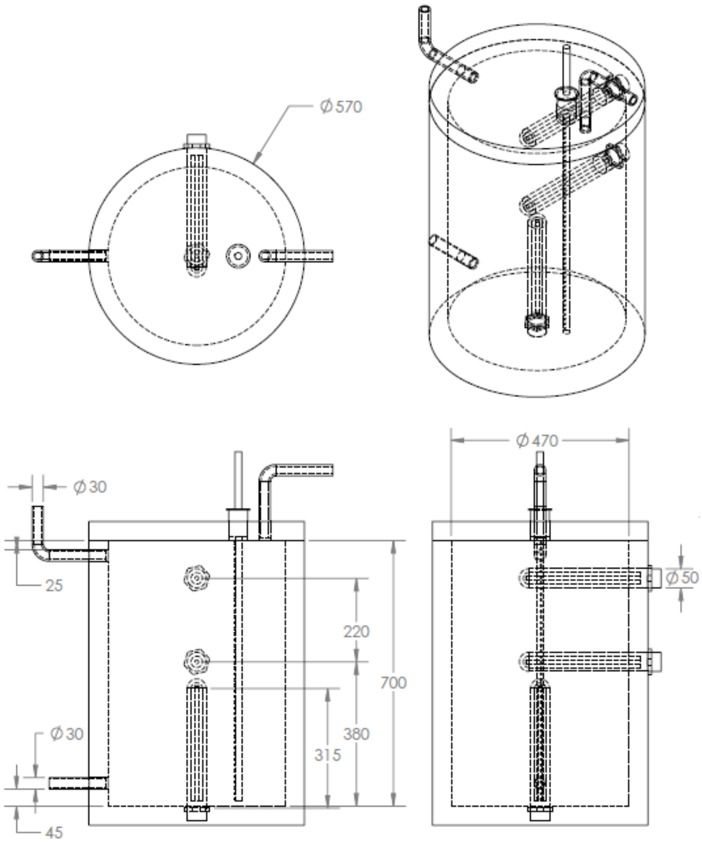
MATERIALS AND METHODS

3.1 Test Equipment for Cylindrical Water Storage Tank

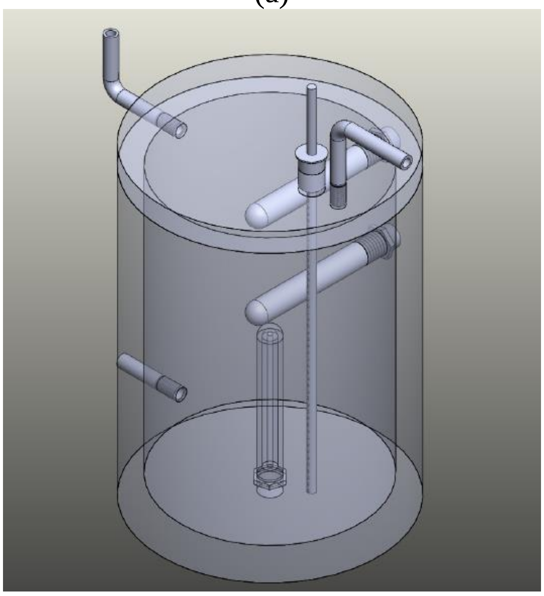
Figure 5 shows the test equipment, which is mainly composed of a cylindrical storage tank having a volume of approximately 121 L. The tank is manufactured from zinc-plated (galvanized) steel sheet metal by arc welding technique with an internal diameter (D) of 470 mm and a height (H) of 700 mm, and thus has an aspect ratio of 1.489. The cylindrical body of the tank is made by rolling the steel sheet metal, and the two lids for the top and the bottom are made by cutting two discs from similar material having a thickness of 2 mm. The cold water inlet port is located, 60 mm above the bottom of the tank. The diameter of the inlet and outlet ports is 3/4 inch. The cold water inlet port is placed on the lateral surface of the cylindrical body in the radial direction while the outlet port for hot water discharge is placed at the top surface of the storage tank. Any pressure increase inside the tank is prevented by attaching an expansion pipe on the lateral side, 40 mm from the top surface of the tank. The whole tank is insulated by covering it with 35 mm thick fiberglass wool. Finally to protect the insulation and to avoid contamination of the users, the storage tank is covered with a 0.5 mm galvanized steel sheet metal from all sides.

An immersion-type screw plug heater, with a 3 kW power rating is used to heat the water. The heating element and the thermostat socket are assembled on a common threaded plug as one unit. This unit is fixed on the threaded socket which is butt welded at the bottom lid of the storage tank. The thermostat is utilized for controlling the water temperature inside the tank. For investigating the impact of the thermostat position on the performance of EWH, two more threaded sockets are butt-welded at the vertical cylindrical surface for mounting thermostats. The performance tests have been performed for three different thermostat positions; namely A, B, and C. At position A (z/H=0.37), the thermostat is mounted in the vertical position at the bottom part of the tank, where the heater is placed. For investigating positions B and C, the thermostat is placed horizontally on the lateral surface of the storage tank, at heights of 380 mm (z/H=0.54) and 600 mm (z/H=0.86), respectively. A 1 m^3 volume constant head-elevated tank is used for cold water supply to provide steady-flow conditions during the experiments. Accordingly, as the tank acts as a steady state control volume, VFRs of hot and cold water were the same during the experiments.

A total of 33 T-type thermocouples were used to measure the temperature distribution inside the tank. These thermocouples were equally spaced and fixed on a rectangular cross-section of a plexiglass rod, which is placed vertically in the axial direction through a sealed opening from the top part of the tank, as shown in Figure 5. The distance between each thermocouple is 2 cm. Another set of 6 thermocouples was attached to a horizontally placed non-metallic rod, which was inserted through a side hole at a height of 380 mm above the bottom (z/H=0.54) surface of the tank. The horizontal distance between each thermocouple is 5 cm. To monitor the charging and discharging water temperatures, three thermocouples were installed in the inlet and three in the outlet ports. A data-acquisition unit connected to a PC is used to read and record the temperature readings with a time interval of 3 minutes for the heating period (charging) and 5 seconds for the discharging period for all tests. Calibration tests were also performed to determine the errors and accuracies of the thermocouples. According to the testing results, the accuracies of the thermocouples used for temperature readings were obtained as $\pm 0.15°C$.



(a)



(b)

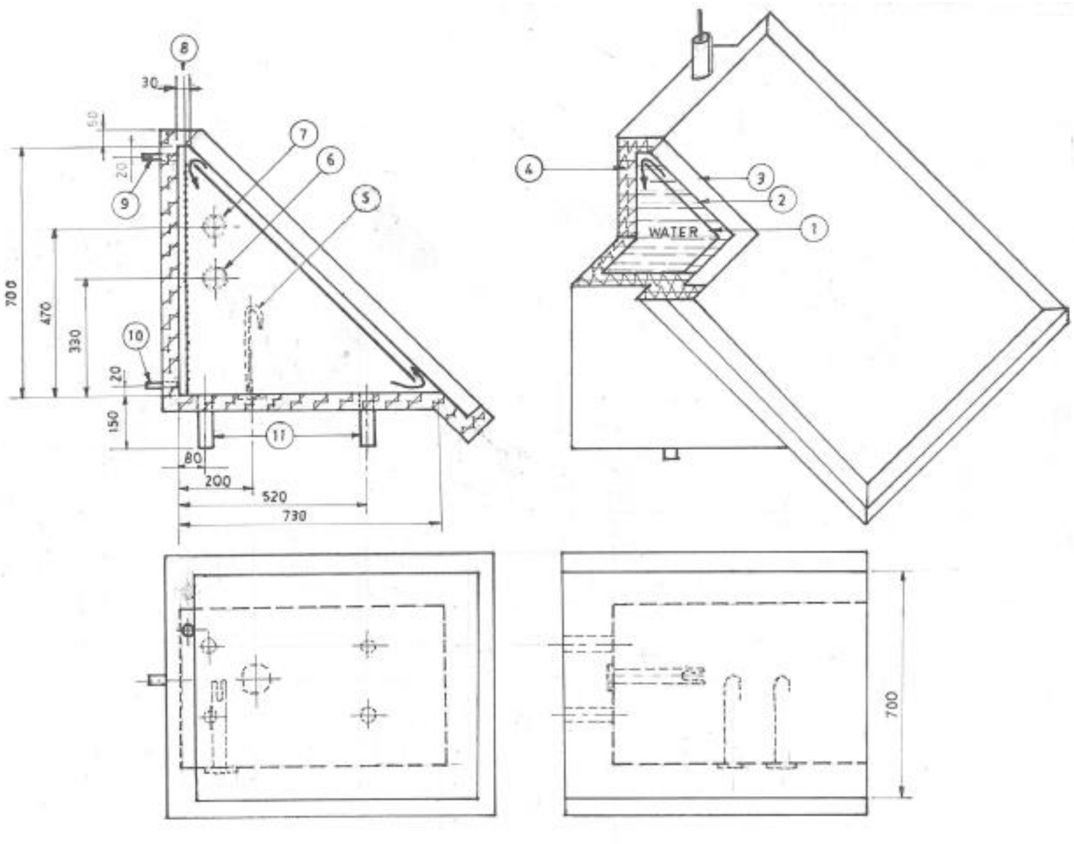
Figure 5: (a) Cross-sectional, (b) 3D view of the storage tank

3.2 Test Equipment for Integrated Solar Water Heater

3.2.1 The Storage Tank

The technical drawing views of the new design of ISWH are shown in Figure 6. The trapezoidal-shaped tank is manufactured from 2 mm steel sheet metal and constructed with the metal arc welding method. It was well-insulated from all sides with 35 mm thick fiberglass except the inclined glass face. The tank has a profile view of a trapezoidal cross-section. The height and width at the back are 700 mm and 500 mm respectively. The top and bottom horizontal dimensions are 30 mm and 730 mm respectively. The hypotenuse gives a length of 990 mm and an inclined angle of 45°. All these will give the tank volume of 133L in capacity. A sheet of baffle plate mounted 25 mm away parallel to the absorber plate, creates a water passage to enhance the buoyancy force and reduce the heat loss by conduction during the night times.

The cold water enters the storage tank from the back side, above 20 mm of the down part of the tank. The output pipe for hot water is located at the upside of the tank. Both the inlet-outlet ports are 3/4 inches in diameter of galvanized standard-steel pipes, attached to the tank surface via welding. A 1-inch diameter standard galvanized steel vent pipe is connected to the tank top surface at a position of 50 mm away from the side of the tank. It allows the pressure build-up in the tank to escape to the air during the heating period and acts as a guide for the thermocouples bar to go into the tank and keeping them in a vertical position. To produce hot water during the times when solar energy is limited or unavailable (i.e., nighttime, cloudy periods), a 3kW power rating screw plug type immersion electric-resistance heating element is used. The thermostat and heating element are integrated as a single module which could be easily attached to the rank via the flange welded on the tank surface. Three heating elements are attached to the tank. Heater A (z/H=0) is placed at the bottom surface in a vertical position, heater B (z/H=0.47) at the near middle in a horizontal position, and heater C (z/H=0.67) near the top, on the side surface in a horizontal position.



(1) Baffle plate, (2) Absorber plate, (3) Glass cover, (4) Thermal insulation, (5) Heater A, (6) Heater B, (7) Heater C, (8) Thermocouples, (9) Outlet pipe, (10) Inlet pipe, (11) Support Legs,

Figure 6: Cross-sectional view of the integrated solar water heat

3.2.2 Data Acquisition System

33 T-type thermocouples were used to measure the temperature distribution of the water, at 20 mm intervals from the bottom of the tank. These thermocouples are fixed on a plexiglass rectangular bar. Additionally, 6 thermocouples were utilized

for recording the tank inlet-outlet water temperature variations (3 for the inlet and 3 for the outlet). Based on the performed calibration, the accuracy of the thermocouples was found to be ±0.15°C. A data-acquisition system connected with thermocouples was used for the measurement and recording of the water temperatures during the tests.

The Omega (OMB Multiscan-1200) data logger and the EXP 11A expansion port instruments were used in this study to record the signals generated from the thermocouples as shown in Figure 7. The data acquisition system of type OMB-Multiscan-1200 is capable of recording the data every 5 seconds at the discharging and every 30 minutes during the heating test periods.

Figure 7: The Omega Data acquisition during the experiment

3.2.3 Pyranometer

A pyranometer is an instrument used to measure the intensity of solar radiation on any planar surface. The Eppley pyranometer was used to measure the solar radiation received by the inclined ISWH surface. It is connected to a voltmeter (EX410 digital) as shown in Figure 8, and the radiation is read in millivolt values (mV).

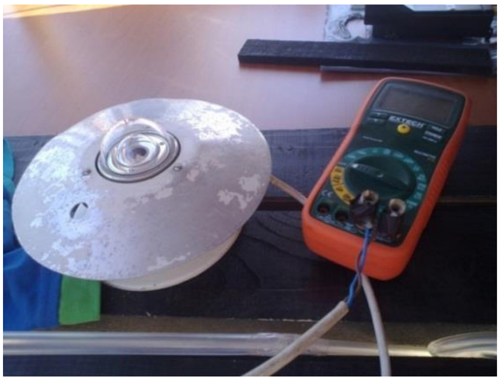


Figure 8: Epply pyranometer and the EX410 digital voltmeter

3.2.4 Absorber Plate

The absorber is designed as a flat plate from 2 mm thick copper sheet metal. It is integrated into the angled front side of the trapezoidal storage tank. For enhancing the heat transfer area, fins with 100 mm length were added to the three edges of the plate, two on the inclined side and one at the bottom edge respectively. It has dimensions of 1090 mm x 700 mm with a surface area of 0.763 m^2. The surface of the absorber plate is painted in black to enhance its solar emissivity. A 3 mm transparent glass sheet is integrated on the top side of the absorber. The distance from the glass cover to the absorber was fixed to be 25 mm to reduce the heat losses from the glass cover. All sides, except the front glass, were insulated by using a glass fiber insulation blanket to prevent heat losses. Another thin galvanized sheet metal, 0.35mm thickness, is covered all around the tank insulation for preventing the glass fiber from getting wet on rainy days.

3.3 Experimental Procedures

3.3.1 Experimental Procedure of Cylindrical Hot Water Storage

Experiments were performed for a VFR of 5 L/min. A flow control valve is used after the inlet port to adjust the VFR to the set value. Required draw-off rates were also adjusted by using a graduated burette and stopwatch before starting the tests.

Throughout the experiments, an electrical heater, which is vertically installed to the bottom part of the tank, is employed to heat the water. In the first part of the experiments, the heater was controlled by the thermostat positioned at points A, B, and C, which was set to switch off the heater at a temperature of 80°C. For the second part, the thermostat was positioned at A, of which the set-point temperature was changed by employing a thermostat regulator for switching off the heater at different temperatures.

Before starting, the tank is emptied. Then, water is recirculated through the tank by opening both the outlet and the inlet valves. The recirculation process is continued for 10 minutes for the water to achieve temperature uniformity inside the tank. Then the inlet and outlet valves are closed and then the electrical heater is tuned on for the water heating process to start. During the heating period, the water temperature change is recorded with a time interval of 3 minutes. In the system, as soon as the water temperature at the upper part of the tank rises to 80°C, the thermostat automatically turns off the heater. Then the inlet and outlet valves are opened to start the discharge process at constant charging VFR (5 L/min). The discharge temperature is recorded every 5 seconds in this discharging period. In each experiment, discharging process ends once the discharged water temperature falls to 40 °C. Such a procedure is applied due to the reason that 40 °C is considered the minimum comfortable temperature for having a shower in residential buildings.

3.3.2 Exprimental Procedure for the ISWH

All the experiments were conducted on the roof of the department building during the summer month of July. The solar heating experiments were carried out at the daytime from 08.00 am to 5.00 pm to ensure solar energy will affect the heating experiments.

By adjustment of the attached flow control valve, water VFR is maintained at the desired level. For measuring the water draw-off rates (0-20 L/min), a rotameter, stop-watch, and a scaled cylinder were used.

Tests were performed at 5 and 10 L/min draw-off rates for the heating/discharging tests. For every new test, the tank is filled with cold water and 10 minutes is allowed for the water to circulate to have a uniform temperature distribution for thermocouple calibration. The inlet and outlet valves are closed and then tests are started. The temperature inside the tank is recorded every 3 minutes during the heating period by the heaters and for the solar heating every 30 minutes until the afternoon time 5.00 pm.

The discharging process started by fully opening the inlet and outlet valves at the set charging VFR. The discharge temperature was recorded at every 5-second of time intervals and the discharging process was stopped once the water discharge temperature was <40°C. As mentioned earlier the reason is that 40 °C is considered the minimum suitable temperature for taking shower.

Chapter 4

EXPERIMENTAL INVESTIGATIONS ON EWH AND ISWH

4.1 Governing Equations

During the experiments, the temperature of each thermocouple layer inside the tank was recorded before the discharge process. This will give the total energy stored in the tank which is obtained by adding all the elemental energies calculated by consideration of the temperature difference between the thermocline layer, T_j, and cold inlet water temperature, T_{in} by the use of Equation 1;

$$E_{st} = \sum_{j=1}^{33} \left(\rho V C_p\right)_j (T_j - T_{in}) \quad (1)$$

where V is the element volume of layer j, ρ is the density of water of layer j and C_p is the specific heat of layer j, which are recorded by thermocouple j.

The energy content of outlet water from the storage tank at the time t, is determined by Equation 2 as follows;

$$E_{out} = \int_0^t \rho V C_p (T_{out}(t) - T_{in}) dt \quad (2)$$

where $T_{out}(t)$ represents the outlet water temperature at the time *t*. The calculated energy via Equation 2 represents the difference in the energy content of outlet water relative to the inlet water energy.

The storage tanks' performance for all cases is evaluated by determining the discharging efficiency as shown in Equation 3. The discharge efficiency, η, is considered as the ratio of the extracted thermal energy from the storage tank (until the discharge water temperature falls to a certain set point temperature) to the total thermal energy of the water before discharging. In the present study, this set point temperature is considered as 40°C. Accordingly, the discharging efficiency is determined as follows;

$$\eta = \frac{E_{out}}{E_{st}} \tag{3}$$

This discharging efficiency represents the useful energy extracted from the heat storage tank and utilized for hot water needs. Theoretically, the maximum discharging efficiency is 100%, which can be achieved by a well-insulated tank with negligible losses to the surroundings. In such a case heat loss from the hot fluid to the cold fluid through mixing is also considered negligible. However, in real applications both heat losses to the environment and heat losses to the cold fluid as a result of the mixing of hot and cold fluid occurs. Consequently discharging efficiency drops, thereby energy input to the storage tank in the charging cycle could be partially recovered in discharging cycle at above a certain temperature.

The temperature of the water inside the tank is represented with the dimensionless temperature T*, which is obtained via Equation 4 as follows;

$$T^* = \frac{T(z,t) - T_{in}}{T_{max} - T_{in}} \tag{4}$$

where T(z,t) illustrates the local water temperature at a certain level of the tank and at any particular time of t. T_{max} shows the maximum water temperature inside the tank, which also corresponds to the initial outlet water temperature in discharging process.

The dimensionless temperature, $T_{out}(t)$, indicates the variation of hot water temperature coming out of the heat storage tank and it is obtained with Equation 5 as follows;

$$\theta = \frac{T_{out}(t) - T_{in}}{T_{out}|_{t=0} - T_{in}} \quad (5)$$

where θ is the drawn-off profile.

The dimensionless time, t*, is the ratio of any particular charging/discharging duration to the total charging/discharging time. Consequently, it could be also considered as the volumetric ratio of withdrawn water from the tank to the total volume of the tank. t^* is calculated with Equation 6.

$$t^* = \frac{t}{t_{total}} \quad (6)$$

where t_{total} illustrates the charging/discharging duration of the water tank for the considered flow rate of water.

The required time could be determined via Equation 7;

$$t_{total} = \frac{V_{st}}{VFR} \quad (7)$$

where V_{st} and VFR are the volumetric capacity of the tank and VFR of water respectively.

50 L. of warm water is taken as the standard amount required to have a shower at 40°C [28]. The hot water required to withdraw from the storage tank, for one-person shower, is obtained by considering the energy balance and the mass balance of the mixing water.

$$(\rho\ V\ Cp\ \Delta T)_{Hot} + (\rho\ V\ Cp\ \Delta T)_{Cold} = (\rho\ V\ Cp\ \Delta T)_{Mixture} \quad (8)$$

In terms of volume and temperature, it can be simplified as below,

$$V_{Hot}\, T_{Hot} + V_{Cold}\, T_{Cold} = V_{Mixture}\, T_{Mixture} \quad (9)$$

and the mass balance

$$(m)_{Hot} + (m)_{Cold} = (m)_{Mixture} \quad (10)$$

In terms of volume, it can be simplified as below,

$$V_{Hot} + V_{Cold} = V_{Mixture} \quad (11)$$

where, $V_{Mixture} = 50L$ and

$T_{Mixture} = 40\ °C$

Based on Equation 9 and Equation 11, the volume of discharge/charge hot water required for one person shower is obtained as shown in Equation 12 below.

$$V_{hot} = \frac{2000-50T_{in}}{T_{out|t=0}-T_{in}} \quad (12)$$

where V_{hot} is the volume of hot water required for one person to shower. Here;

$T_{in} = T_{Cold}$

$T_{out|t=0} = T_{Hot}$

$2000 = V_{Mixture} T_{Mixture}$

4.2 Performance Analysis for Cylindrical Hot Water Storage

Testings were carried out to for investigating storage tank performance operating with an electric heater installed at the bottom. In the analysis three different thermostat locations were considered for controlling the electric heater namely; A (bottom), B (middle), and C (top). The VFR of water is set to 5 L/min in discharging tests.

For the thermostat positions A, B, and C, the distribution of water temperatures at the end of the charging (before discharging) process is displayed in Figure 9. A uniform water temperature distribution inside the tank, which is highly desirable, is observed. The slight drop in water temperature near the tank bottom surface is due to the heat losses through metal piping and the support bars of the electric heater via conduction. These metallic components act as cooling fins thereby causing heat losses which affect the storage tank performance negatively.

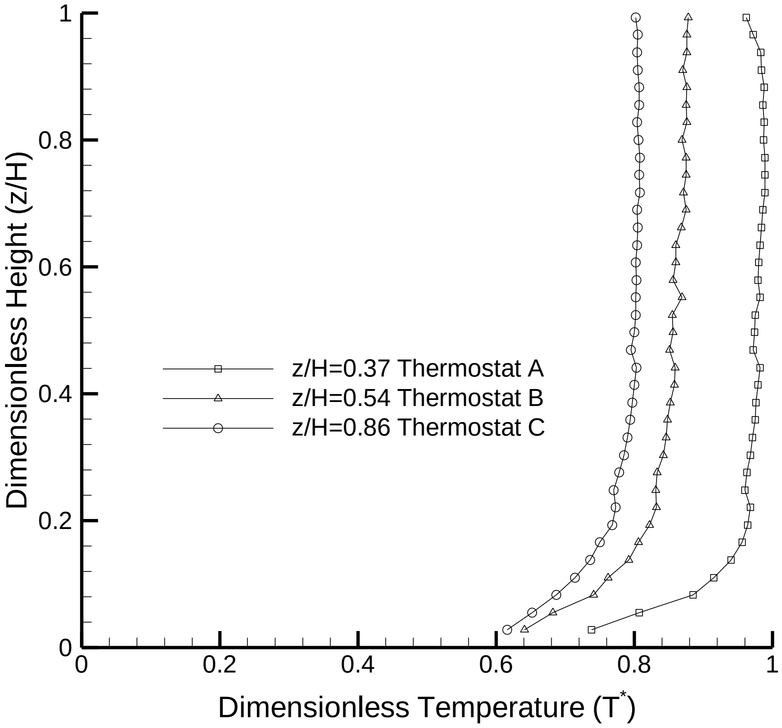


Figure 9: Temperature distribution of water inside the storage tank for thermostat positions A, B, and C before discharging cycle.

As seen in Figure 9, the case corresponding to the thermostat position at A has higher water temperatures than those of the thermostat position at B and C. As a result of these temperature differences, the charging/discharging time for thermostat positions B and C is less than that of A as shown in Figure 10a. The discharge efficiencies are found to be higher for the thermostat position at A, while the discharge efficiencies of thermostat locations at B and C are very close but lower than that of A. The numerical values are 93.77% for thermostat location at A, and 83.65% – 85.80% for thermostat locations B and C, respectively. These results indicate that thermal stratification is maintained better during the discharge process when the thermostat is at the bottom (location A) of the tank, resulting in lower heat losses to the bottom cold water due to mixing.

The variations of the drawn-off temperature for two thermostat positions were calculated using Equation 5 and are illustrated in Figure 10b. The experimental results were illustrated for the conditions where the temperature of outlet water from the tank is > 40 °C. For the case corresponding to the thermostat position at A, the withdrawn water volume was close to the tank volume whereas for the cases of thermostat positions B and C the volume of the withdrawn water was nearly 50% and 25% respectively of the total tank volume. This is due to the reason that the total volume of the heated water (during charging) decreases for the order of thermostats A, B, and C, depending on their positions inside the tank. As a result, discharging durations for thermostats A and B was nearly 25 and 22 minutes respectively (See: Figure 10-b) whilst for thermostat C it was approximately 16 mins. In addition, the dimensionless temperature range gets more narrow for the order of thermostat positions A, B, and C. For the same order of thermostat positions, the initial volume of hot water gets less, and thereby temperature drop rate of hot water (due to mixing with incoming cold water) for thermostat positions B and C was higher compared to thermostat position A. However, over the late fast cooling period, temperature drop rates were found in close approximation for all considered thermostat positions.

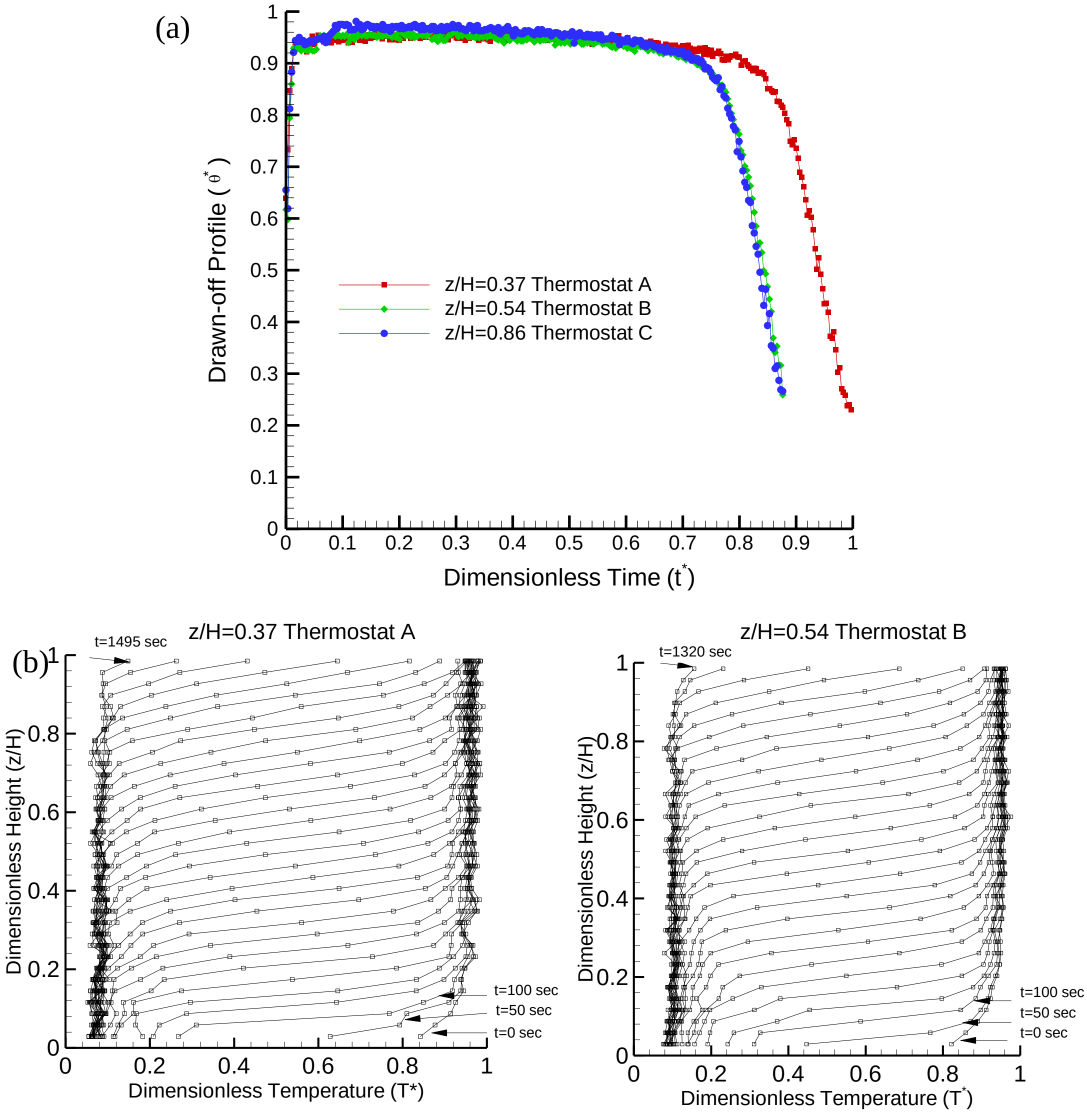


Figure 10: (a) Drawn-off Profile inside the storage tank during discharging period for different thermostat locations, (b) Temperature profiles inside the storage tank for thermostats located at positions A and B during discharging

The temperature variations along the vertical axis of the tank during the heating processes corresponding to the cases of thermostats located at A and C are illustrated in Figure 11. The water temperature inside the tank starts to increase from the inlet temperature (T_{in}) value to the maximum value (T_{max}) during the heating process. The temperature rises nearly uniformly with time during the heating processes as observed from the very small vertical temperature gradients. The time required to heat the tank to the desired temperature is reduced by 18 min when the thermostat is positioned at

B or C, instead of at A.

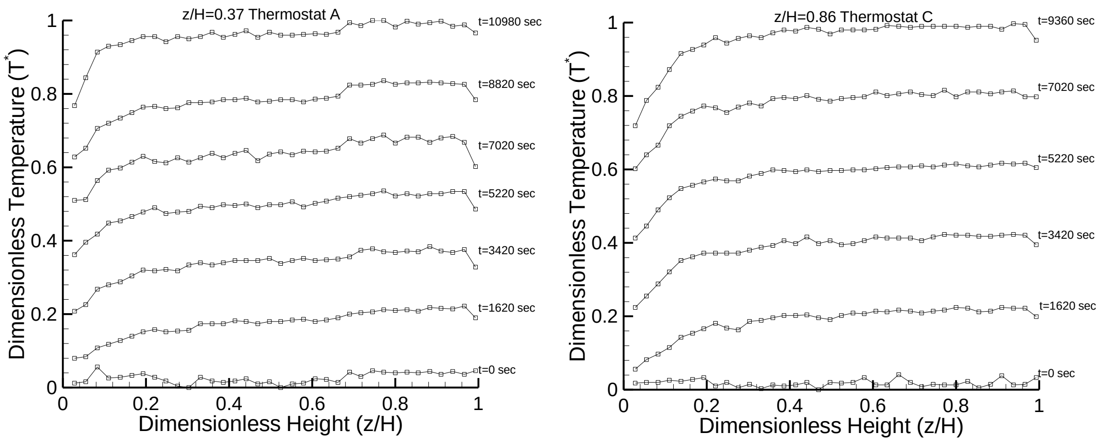


Figure 11: Temperature distribution in the storage tank during the heating period for different time intervals for thermostat located at positions A and C

Figure 12 shows the temperature distribution along the horizontal direction. The temperature distribution is rather uniform indicating intense recirculation in the tank during heating. Figure 13 shows the variation of discharge temperature with time for different temperature settings of the thermostat at position A. Five different thermostat settings were selected as temperature set points. Among all, four of the settings were in the low-temperature range varying between 40-55 ˚C and one of them was 80 ˚C. Here, the main purpose was to investigate the impact of set point temperature on (i) characteristics of the drawn-off temperature profile (ii) water temperature distribution inside the storage tank, and (iii) discharge efficiency of the water tank. The selection of set points both at a low-temperature range (40-55˚C) and at a high temperature (80˚C) enables analyzing the performance variation (*i.e.*, discharge efficiency) of the hot water tank with the increasing thermostat set point temperatures. Furthermore, it was also proposed to determine the number of people be able to take shower at different thermostat set point temperatures.

As illustrated in Figure 13, a rather uniform drawn-off temperature is obtained for all the cases indicating that thermal stratification is also maintained at lower thermostat settings which prevent the mixing of hot water at the top part of the tank with the incoming cold water.

The vertical temperature distribution in the storage tank for different temperature settings of the thermostat located at position A is shown in Figure 14. In all cases, the temperature in the storage tank is rather uniform at the end of the heating process.

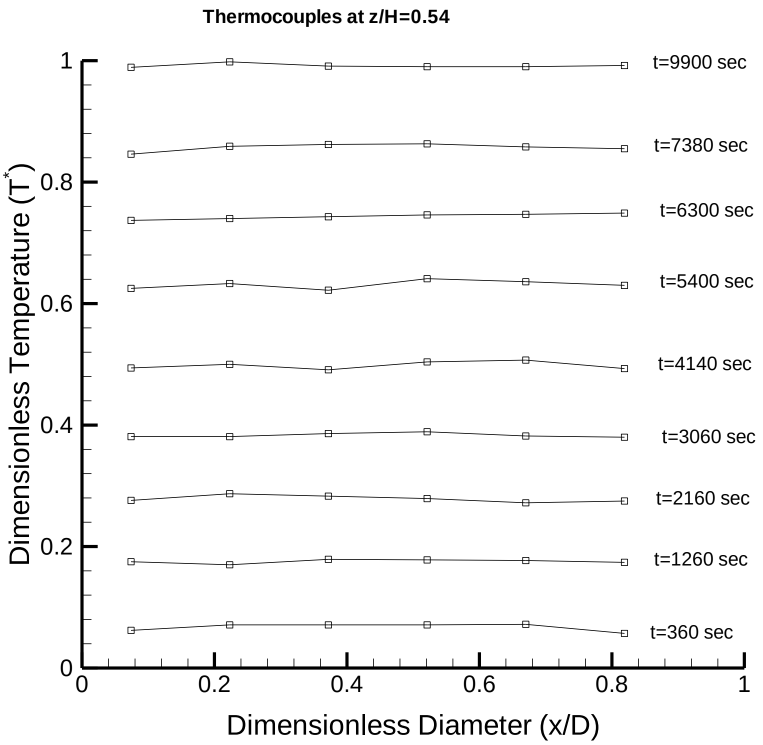


Figure 12: Temperature distribution in the heating period for horizontal thermocouples at different time intervals

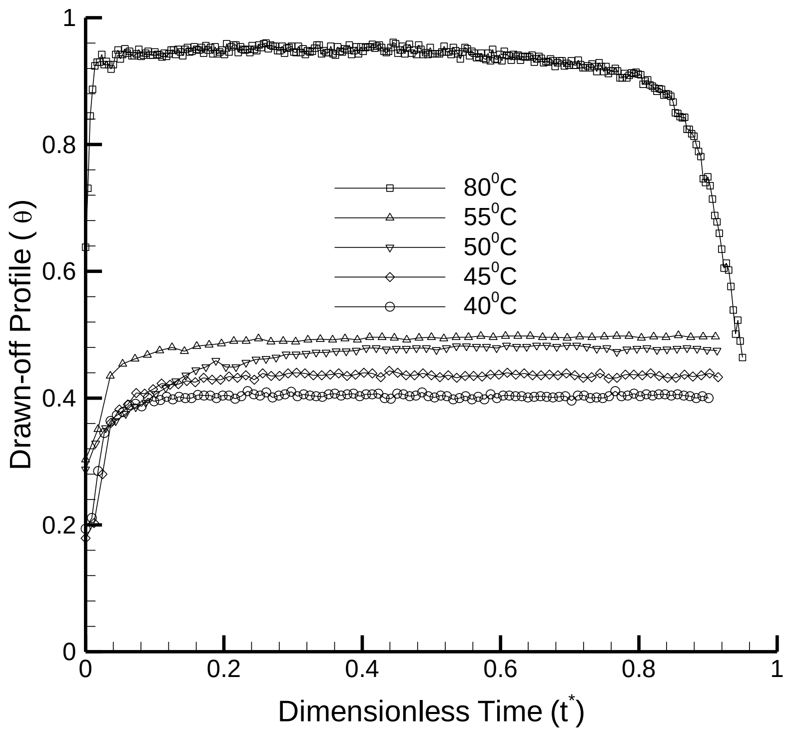


Figure 13: Drawn-off Profile in the storage tank during discharging period for different temperature settings with a thermostat located at position A

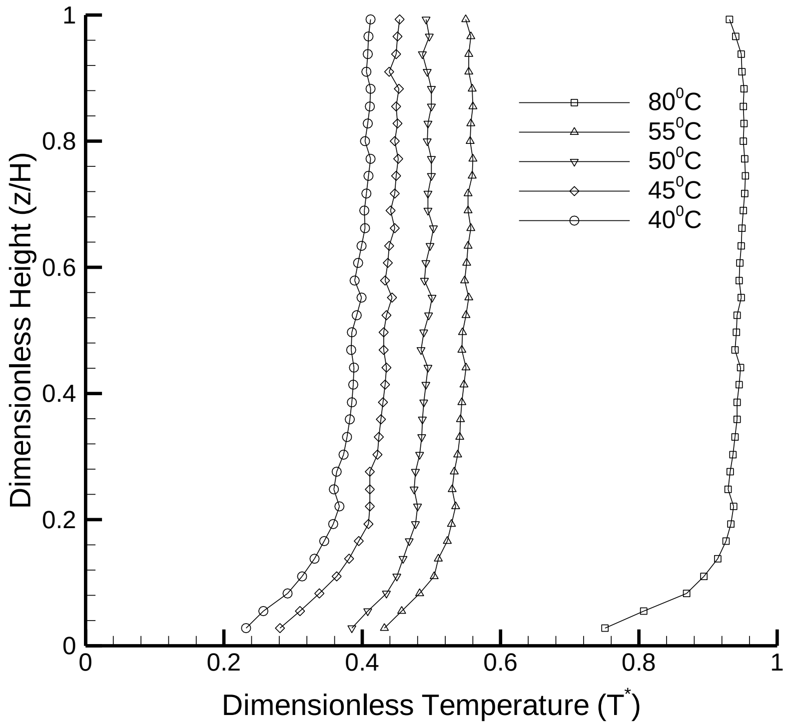


Figure 14: The temperature distribution in the storage tank at different temperature settings for the thermostat located at position A

At higher thermostat settings, it is expected that more energy can be stored in the storage tank. As a result, the maximum number of people who can shower with water from the same storage tank will increase at higher thermostat settings.

On the other hand, discharge efficiency will also be affected by the thermostat setting. Figure 15 shows the discharge efficiency of the EWH for different thermostat settings together with the maximum number of people who can shower by consuming all the stored hot water inside the tank. It is observed that the efficiency decreases at higher thermostat settings, although more people can take shower with the full charge of the storage tank. A thermostat regulator, fixed inside the house, can be used to adjust the thermostat temperature setting depending on the number of people willing to take shower.

In this study, the VFR of water was set to 5 L/min in discharging tests. Therefore, the impact of water VFR on drawn-off temperature profile and discharge efficiency has not been investigated. However, it is expected that; with the increase in discharge VFR, the temperature of the withdrawn water will show a drop at an earlier stage for thermostat positions A and B. On the other hand, for thermostat position C, the drawn-off temperature profile is expected to be minimally dependent on the discharge water VFR according to the study performed by Sezai et al. [10]. Furthermore, based on the same study, discharge efficiency for 5 L/min and 10 L/min VFRs were in close approximation for the thermostat position A. For thermostat positions B and C, discharge efficiency with 5 L/min discharge VFR was nearly 8% higher compared to the efficiency with 10 L/min VFR. Accordingly, it could be concluded that in real-life applications, at high VFRs, discharge performance of the hot water tank could show a slight decrease in the case where thermostats at locations B or C are used. For the case of using thermostat A, the discharge performance is expected to be similar for different

VFRs.

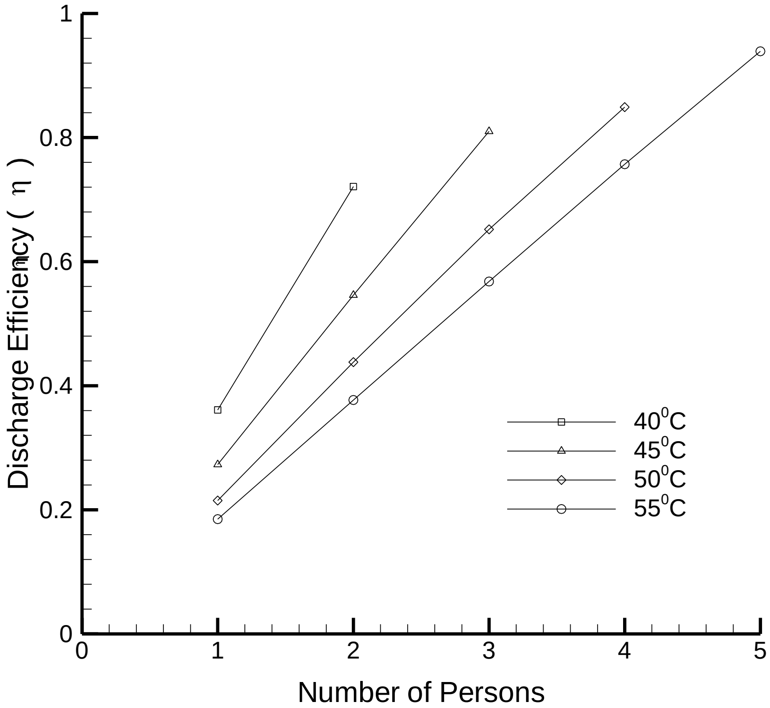


Figure 15: Discharge Efficiency of the EWHs for different thermostat settings.

From the economical perspective, results showed that depending on the amount of hot water requirement, using the optimum thermostat set point temperature could provide considerable energy and cost savings. For example, in the case that hot water is needed for 1 person to take shower, setting the thermostat to 40 ˚C instead of 55 ˚C could increase the efficiency from 18% to 36%. As a result, yearly economic savings between 100-150 could be achieved. Similarly, if hot water for two people is required for taking shower, again selecting 40 ˚C as the set point temperature could increase the efficiency in the range of 36→72% and the same amount of yearly cost savings could be achieved. If the number of people to take shower is 3, selecting 45 ˚C (optimum set temperature for 3 people) instead of 55 ˚C could result in 80-120 annual cost savings. For 4 people or more, the thermostat set point temperature should always be >50 ˚C and in such cases efficiency of heat, and storage is >75%. Therefore achievable cost savings are very limited.

It is worth mentioning that the proposed method does not require any additional costs as the conventional domestic EWHs are already equipped with a thermostat. Therefore, based on the obtained results, optimizing the thermostat set point temperature could be a potential method to provide energy and cost savings in building applications. According to the 'water supply regulations' [29], the minimum hot water supply temperature to the shower should be 41 ˚C, which is the selected minimum thermostat set point temperature in this study. However in real applications, to prevent the production and growth of legionella bacteria, water is heated to a minimum temperature of 60 ˚C. When lower thermostat set point temperatures are selected, as investigated in this study for achieving cost savings, other water treatment methods such as copper and silver ionization or biocide treatments [30,31] should be considered.

4.3 Performance Analysis for ISWH

The solar heating tests started in the morning time at 08.00 am and finished at 5.00 pm for two different VFRs 5 L/min. and 10 L/min. The thermocouples and the solar intensity readings were recorded every half hour during the heating process, and at the discharging/charging process, and the thermocouple readings were recorded every 5 sec. interval, the first discharging/charging was performed at 12.30 pm. at noon time (12:30 pm).

Different solar heating tests have been performed with the ISWH. They are tests for one-person showers, two-person showers and the third one is three discharges at 40°C. All the discharge tests started at 12.30 pm with different periods with two different

VFRs of 5 L/min. and 10 L/min. respectively.

Figure 16 illustrates the average solar intensity versus experiment daytime for the tests with two different VFRs. Although the solar intensity will vary from day to day due to the variance of weather conditions, the maximum average intensity of 860 W/m^2 is observed during the noon period in which the first discharge started. The solar intensity for 5 L/min. discharge is recorded as 886 W/m^2, and for 10 L/min. discharge as 856 W/m^2. The difference in the average solar intensity between the two discharge processes was very small (30 W/m^2), therefore the solar intensity recorded during the experiment days can be considered stable for both cases.

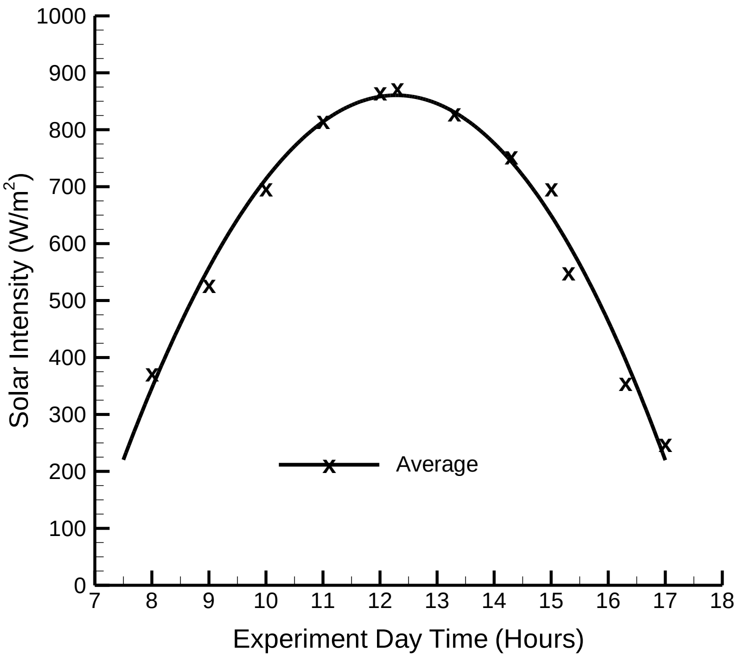


Figure 16: Average solar intensity during the experiment days.

The temperature distribution in the storage tank for one-day solar heating is shown in Figure 17. It can be seen that the water temperature will increase faster during the morning period until noon time. This is due to the increase in the solar intensity where it reaches its maximum value at noon time and gets nearly stable after 3.00 pm until

5.00 pm. At that time experiment was terminated. During the afternoon heating period, although the solar intensity drops down, the hot water in the tank will continue to be heated by the hot absorber plate before discharging the system completely. The low density of heated water rises on the top and the upper temperature gets higher than the lower part of the storage tank. The water temperature inside the tank during the 4.00 pm - 5.00 pm period remained almost the same since the solar intensity was at its lowest level at this time of the day. This case was also mentioned by Al-Talib et al. [32] in their study.

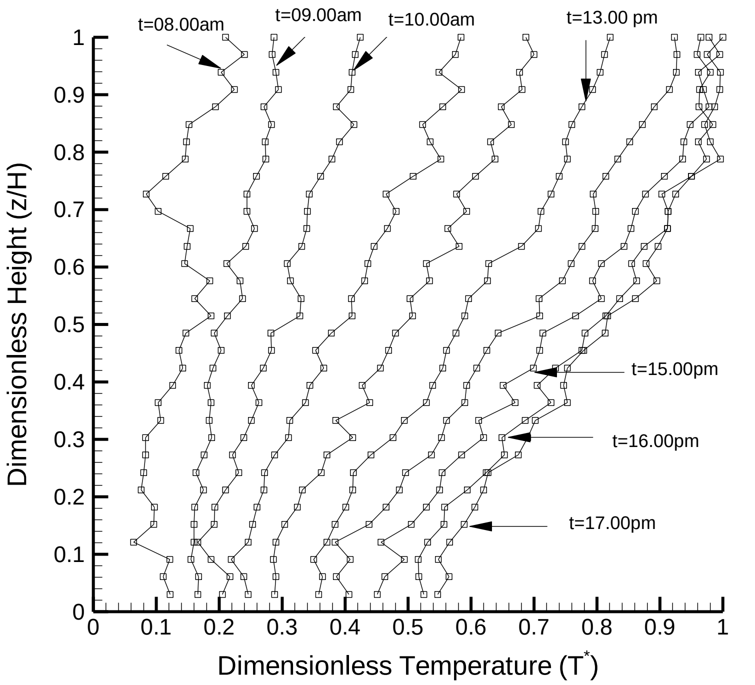


Figure 17: Temperature distribution in the tank during the solar heating period

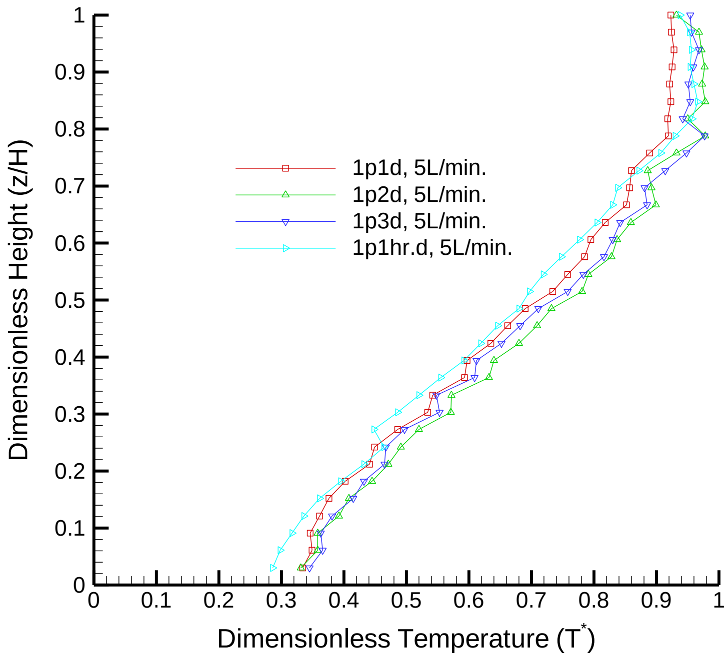
4.3.1 One-Person Tests

Four different tests were performed for this case. Three of these including one person one discharge (1p1d), one person two discharges (1p2d), and one person three discharges (1p3d) were conducted by Hussam S. Naufeld [33]. The one-person-every-hour discharge (1p1hrd) test was conducted in the present study and obtained results are presented in the following section.

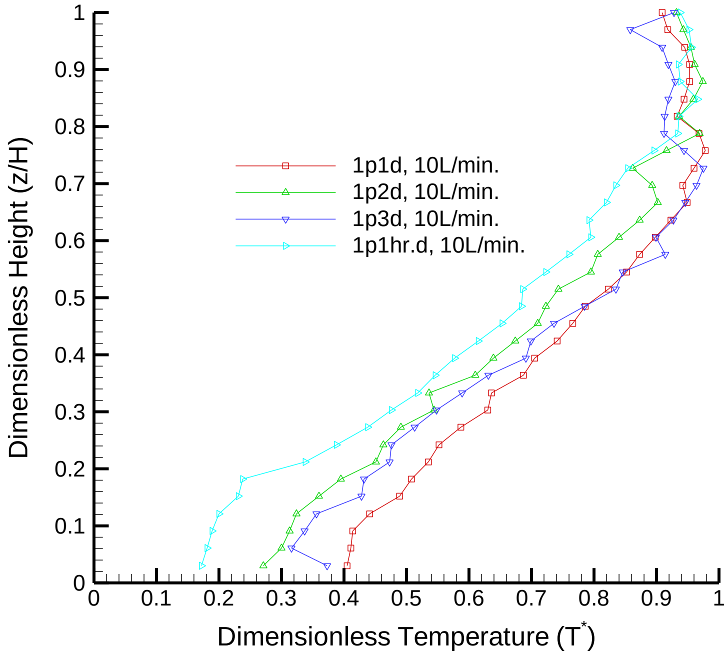
4.3.1.1 The One Person Every Hour Discharge Test (1p1hr.d)

1p1hrd is the test at which the discharges are performed for one person shower at 12.30 pm, 1.30 pm, 2.30 pm, 3.30 pm, and 5.00 pm, and then discharged completely until the outlet temperature drops to 40°C.

Figure 18 depicts the water temperature distribution for the four solar heating tests (1p1d, 1p2d, 1p3d, and 1p1hr.d) right before the discharging process began (5.00 pm) for VFRs of 5 and 10 L/min (a-b). Except for the 1p1hr.d at 10 L/min, the temperature profile remains fairly close for both VFRs. In this situation, the six discharge processes cause a large volume of cold water to enter the system, lowering the bottom level temperature more than the other periods, but the water temperature profile in the middle and top levels of the tank does not affect it. This indicates that the amount of hot water withdrawn for a single-person shower at various times (12.30 pm, 1.30 pm, 2.30 pm, 3.30 pm, 4.30 pm, and 5.30 pm) will not affect the temperature profile at the top level. Because the absorber plate's heating effect will be maintained by solar heating, the hot water level will not be disturbed, and the hot water remaining in the storage tank will be greater than the hot water discharged, the water entering the storage tank will not be too much to cool the water in a large amount, causing the water temperature on the upper side to rise.



(a) Temperature distributions before discharge for the VFR 5 L/min.

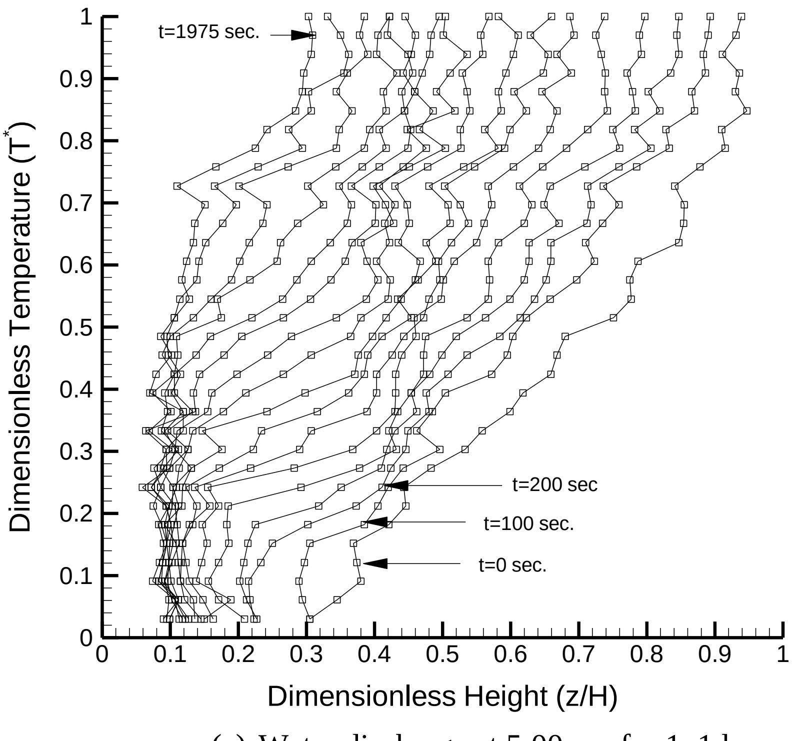


(b) Temperature distributions before discharge for the VFR 10 L/min.

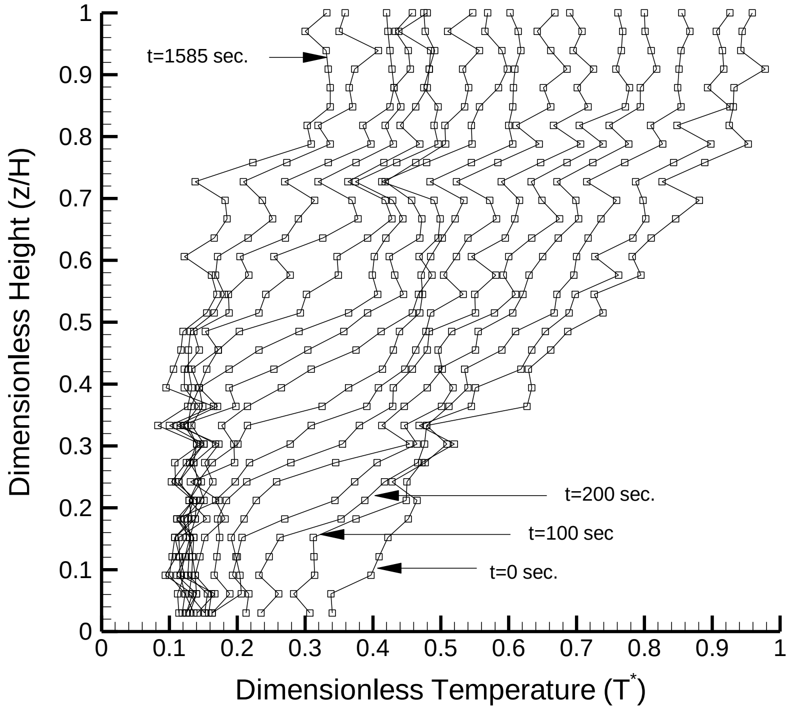
Figure 18: Temperature distributions before discharge for different heating experiments

Figure 19(a-d) and Figure 20(a-d) illustrate the transient temperature distribution of the water in the storage tank during the discharging/charging process for t>0 for different water discharging procedures at different VFRs of 5 L/min. and 10 L/min., respectively. The thermocline layer formed after 100 seconds for a VFR of 5 L/min, as cold water entered from the bottom and hot water discharged from the top. The thermocline, however, is formed after 50 seconds at a VFR of 10 L/min, as illustrated in Figure 20. (a-d).

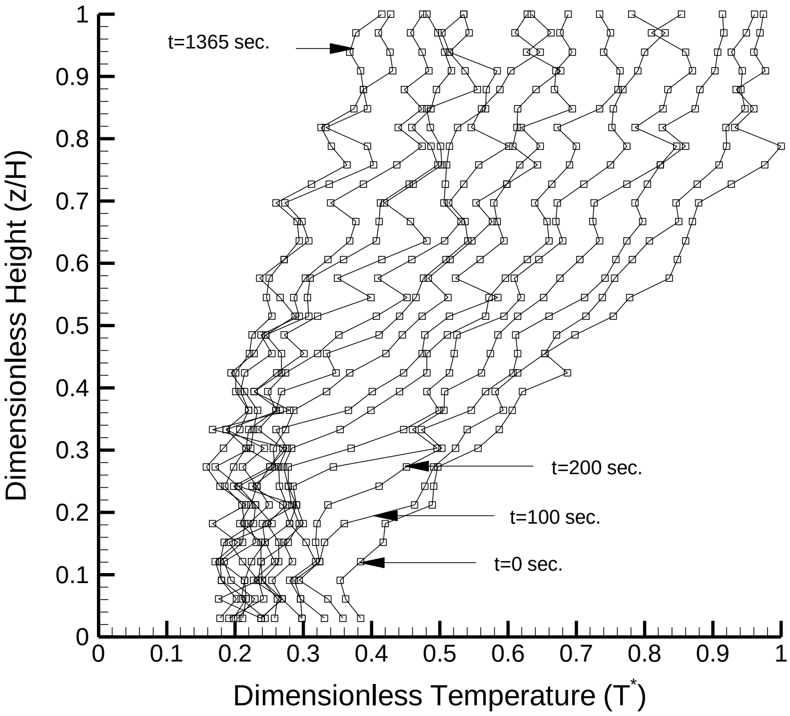
The thermocline layer is thin at first, as seen in figures 24 and 25, and will vanish when the outlet water temperature in the tank declines owing to mixing with incoming cold water until the discharging/charging process reaches 40°C. Figure 20 shows how the time required to discharge hot water decreased over time as the number of withdrawn processes increased and the VFR increased (a-d).



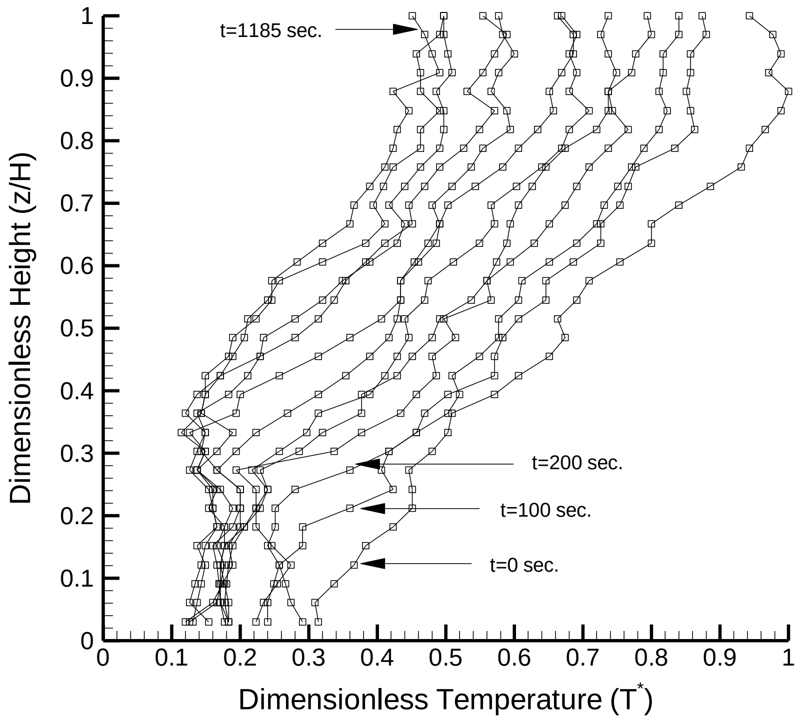
(a) Water discharge at 5:00 pm for 1p1d.



(b) Water discharge at 5:00 pm for 1p2d.

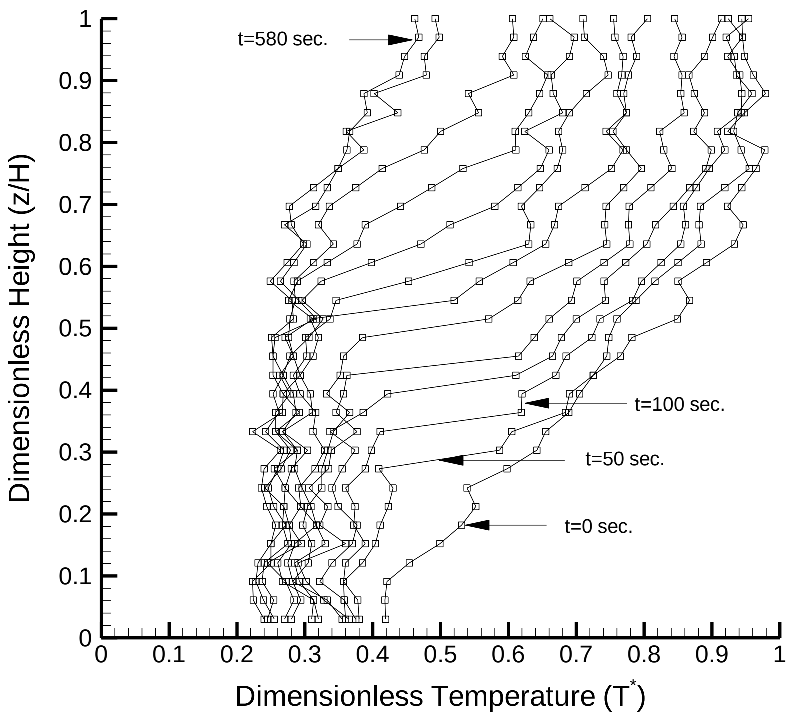


(c) Water discharged at 5:00 pm for 1p3d.

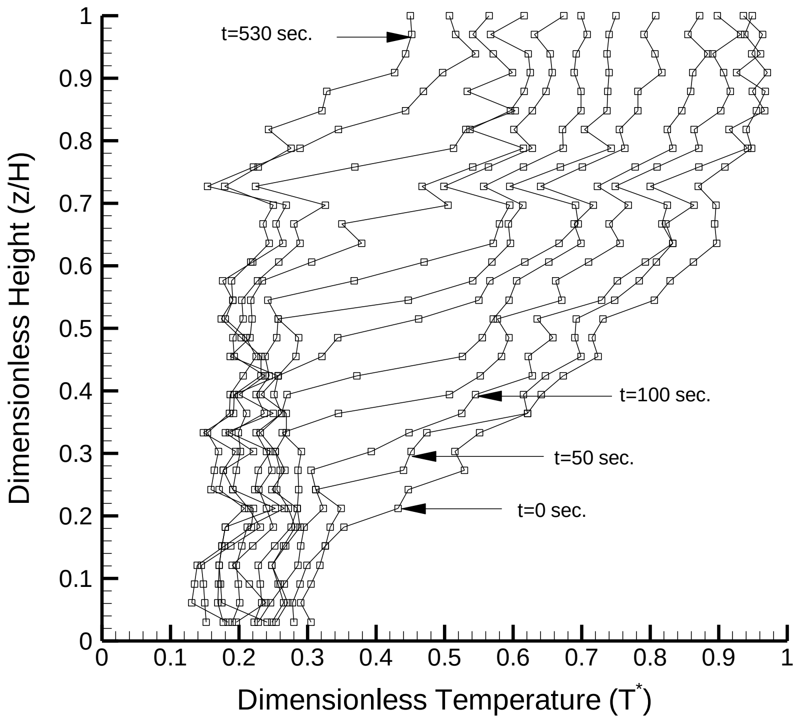


(d) Water discharged at 5:00 pm for 1p1hr.d.

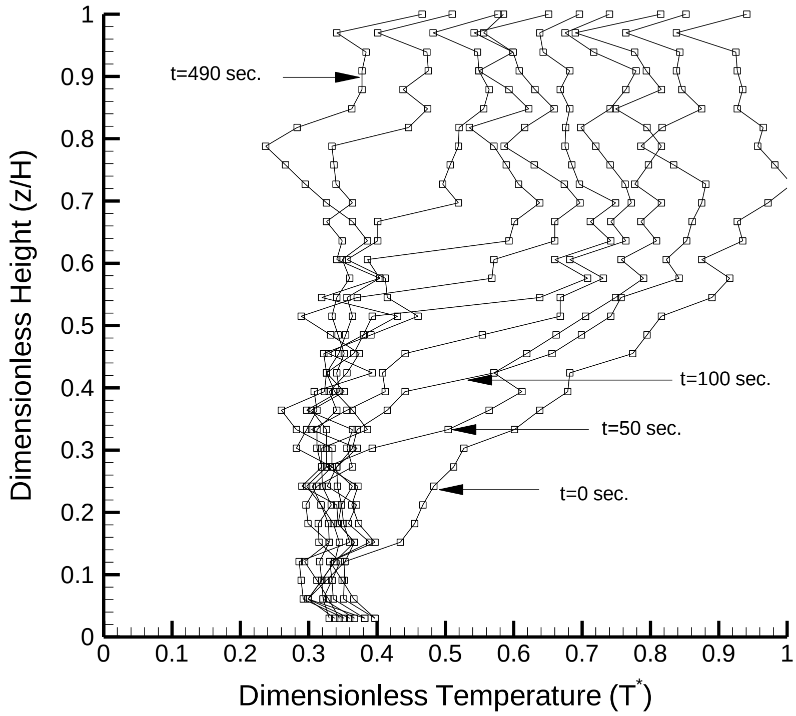
Figure 19: Temperature distribution in the storage tank prior to discharge at flow-rate 5L/min. for (a)1p1d, (b)1p2d, (c) 1p3d and (d) 1p1hr.d



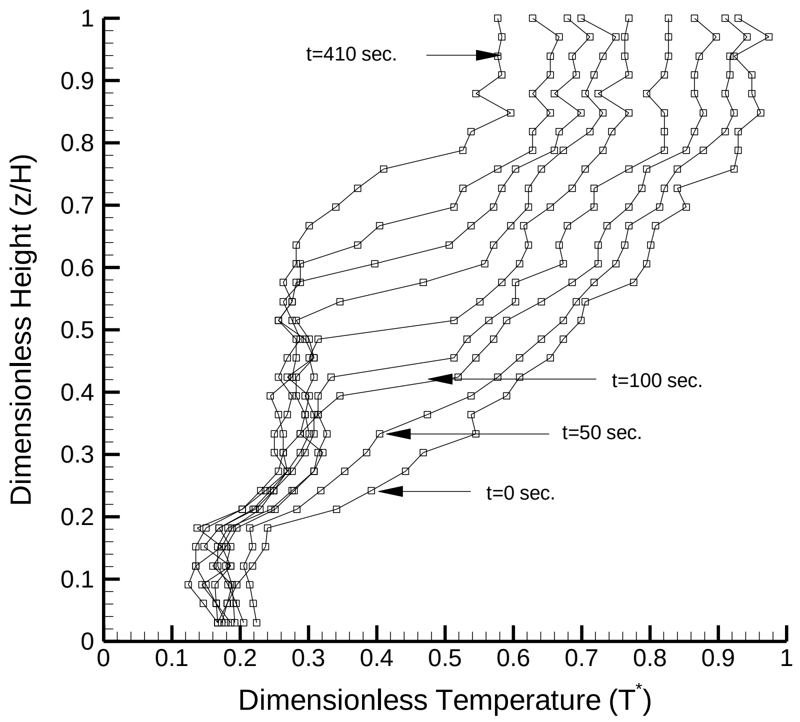
(a) Water discharge at 5:00 pm for 1p1d.



(b) Water discharged at 5:00 pm for 1p2d.



(c) Water discharge at 5:00 pm. For 1p3d.



(d) Water discharge at 5:00 pm for 1p1hr.d

Figure 20: Temperature distribution in the storage tank before discharge at flow-rate 10L/min. for (a)1p1d, (b) 1p2d, (c) 1p3d and (d) 1p1hr.d

Figures 21 and 22 depict drawn-off water temperature profiles depending on t^* for several solar heating tests, 1p1d, 1p2d, 1p3d, and 1p1hr.d, respectively, with VFRs of 5L/min and 10 L/min. Discharge tests were conducted until the temperature dropped below 40°C, and all discharge tests come to a halt. The drawn-off profiles for the four tests are displayed in a tank that is moderately stratified. The temperature of the drawn-off fluid continues to drop. This is due to the vertical temperature gradient inside the tank, while cold water enters at the bottom inlet and hot water exits through the top exit. As the VFR increases, the time required to release the hot water reduces (Figure 22). The discharged volume of hot water from the tank is always lower than the overall volume of the storage tank, as illustrated by the curves in Figures 21-22. For 5 L/min, the total volume discharged is 1p1d (16.4 L), 1p2d (41.1 L), 1p3d (62.8 L), and 1p1hr.d (39.5 L), and for 10 L/min, the total volume discharged is 1p1d (22.45 L), 1p2d (43.20

L), 1p3d (67.59 L), and 1p1hr.d (58.22 L). This indicates that around 12.30 p.m. and 2.30 p.m., the system may offer extra hot water during the heating process. The total volume of discharged hot water for different flow rates during the heating period 12.30 pm - 5.00 pm is shown in Table 1 below.

Table 1: Total volume of hot water discharged for one person from the ISWH

Discharge Cases	Amount of hot water volume discharged (L)	
	5 L/min.	10 L/min.
1p1d	16.4	22.45
1p2d	41.1	43.20
1p3d	62.8	67.59
1p1hr.d	39.5	58.22

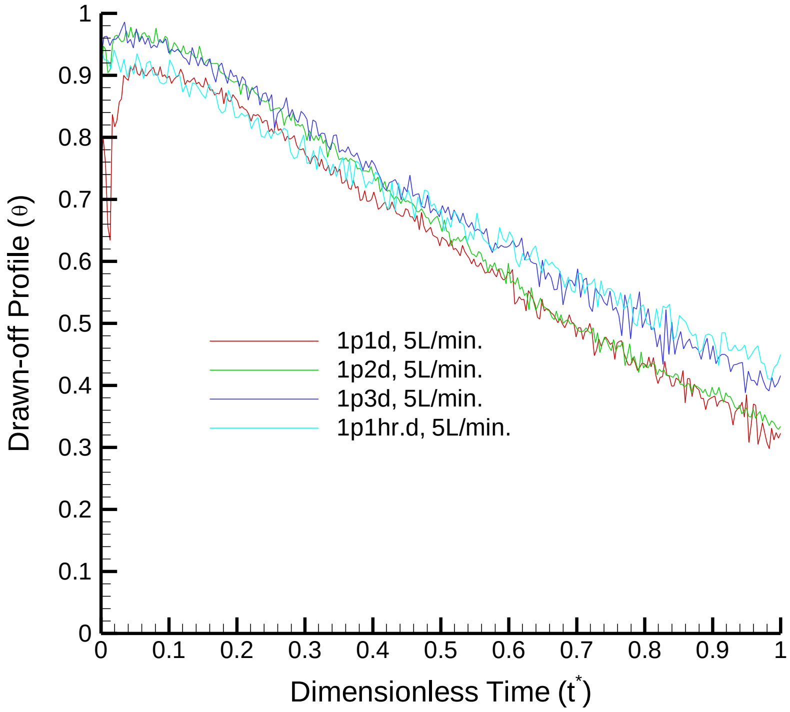


Figure 21: Drawn-off temperature profiles versus t^* for solar experiments at 5 L/min VFR

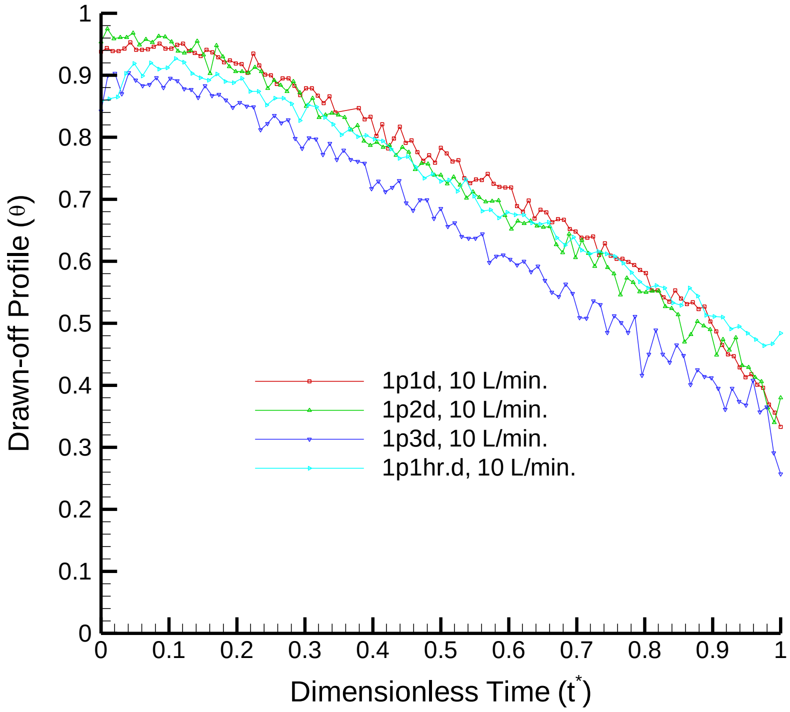


Figure 22: Drawn-off temperature profiles versus t* for solar experiments at 10 L/min VFR

The hot water leaving the ISWH reached a maximum temperature of 54.7 °C at 5.00 pm, where the temperature difference (outlet-inlet) was 32°C. The observed numbers are susceptible to fluctuate day-to-day basis due to variations in solar intensity. The highest and lowest temperatures recorded were 52.2°C and 31°C, respectively. These findings outperform those of Mohamad A. A. [34], who obtained a maximum temperature of 42°C at 5.00 pm. More promising results in the present study were due to the reason that the absorber plate was enlarged by 100 mm on two sides and the bottom, compared to the ISWH system investigated by Mohamad A.A [34]. As a larger absorber surface area is exposed to solar radiation in this study, solar energy gain is enhanced.

4.3.2 Two Persons Tests

All the tests started at 8.00 am and ended at 5.00 pm afternoon. Solar heating data was recorded every 30 minutes while the discharge/charge data were recorded every 5 seconds. The first discharge/charge was performed at 12.30 pm at noon time, and the last discharge/charge took place at 5.00 pm. The ISWH is then fully discharged/charged until the outlet temperatures drop to 40°C. The two-person tests are briefly explained below.

4.3.2.1 Two Persons Two Discharge Test (2p2d)

It is the test at which two discharges/charges are performed for the two-person shower, one at 12.30 pm and the other at 5.00 pm, and then discharged/charged completely until the outlet temperature drops to 40°C.

The water temperature profiles before the discharge/charge started, for the VFRs 5 and 10 L/min. are shown in Figure 23. The temperature profiles of the two cases are the same for both discharge/charge periods of 12.30 pm and 5.00 pm. It can be said that the amount of hot water withdrawn for two persons shower will not change the water temperature in the tank. But for the 5.00 pm case, more hot water was collected inside the water storage tank than in the 12.30 pm case. This is, due to the continuous heating effect of the absorber plate in the afternoon period, although the solar intensity is decline during this period. It can be concluded that the absorber plate had sufficient thermal energy to heat the mixed water from 12.30 pm until 5.00 pm to a larger volume amount.

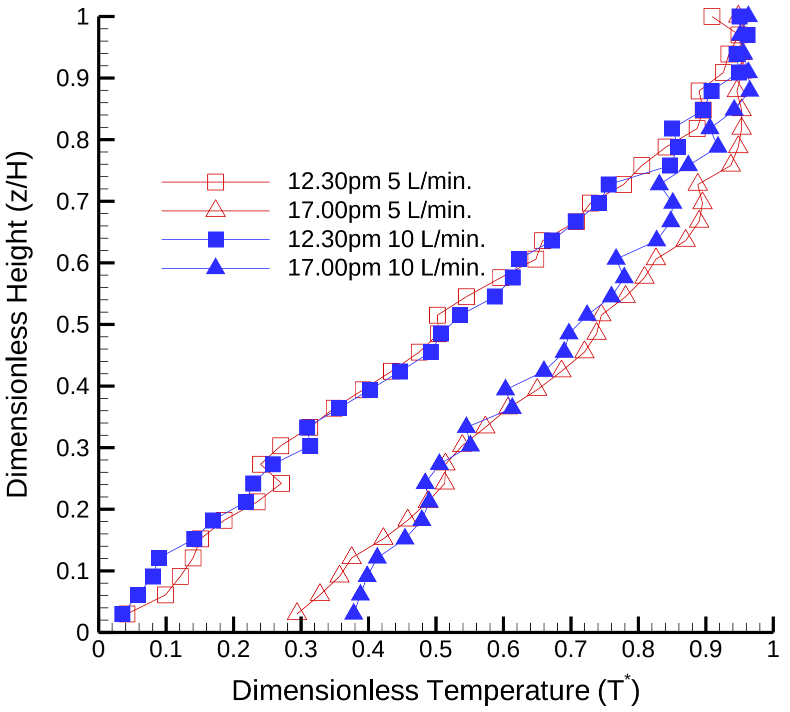
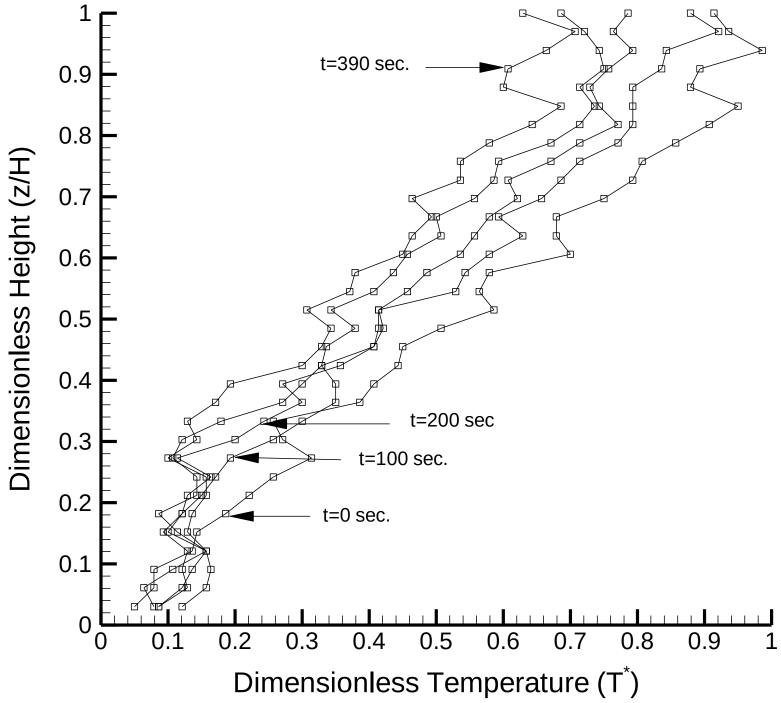
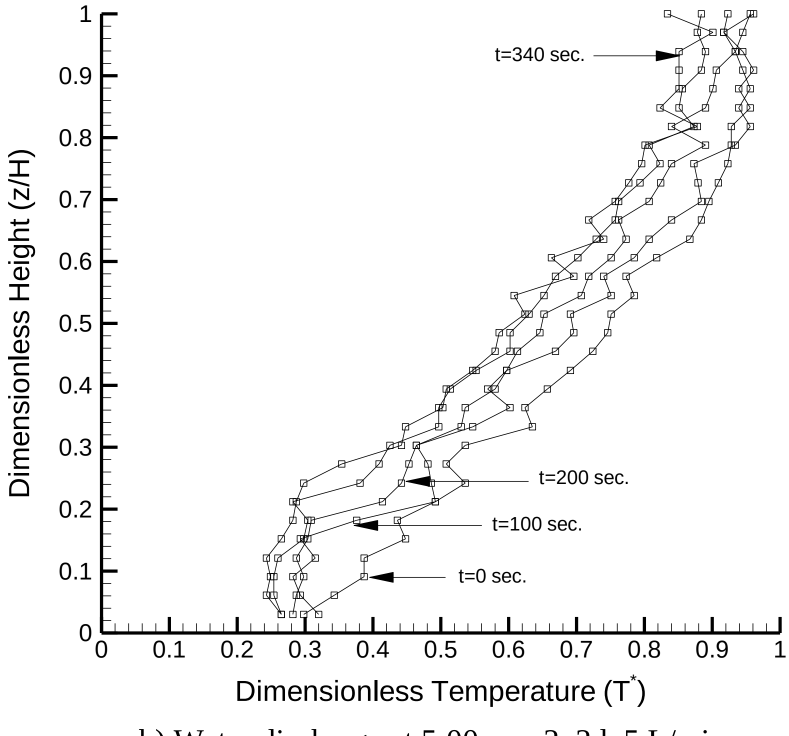


Figure 23: Solar heating temperature distributions before discharge/charge for different VFRs 5 and 10 L/min. of 2p2d case.

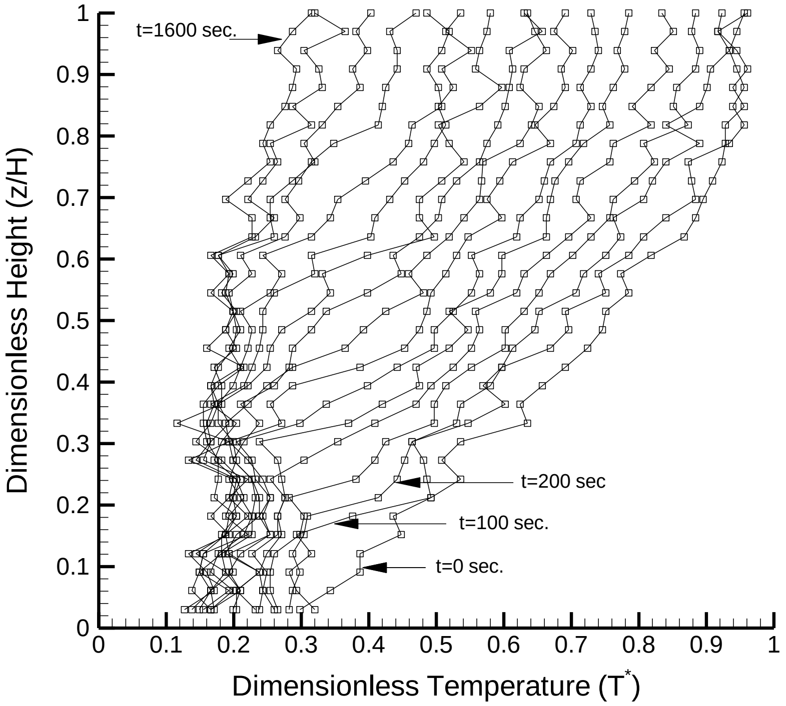
Figure 24-25 shows the transient temperature variations of the water inside the tank during the discharge/charge processes for t>0 for water discharging processes at VFRs of 5 and 10 L/min (a-c). The thermocline layer formed after 100 seconds, as shown in Figure 24(a-c), when cold water entered from the bottom and hot water discharged from the top. However, with the 10 L/min. VFR, the thermocline is formed after 50 seconds, as shown in Figure 25(a-c), due to the rapid mixing of the existing hot water in the tank and the incoming cold water. The thermocline layer is quite thin at the start, and it will dissipate as the outlet water temperature in the tank declines owing to mixing with incoming cold water until the discharging/charging process is stopped at 40°C, as shown in Figure 24-25. (c). The time it took to discharge the hot water decreased as the number of withdrawn processes increased and the VFR increased.



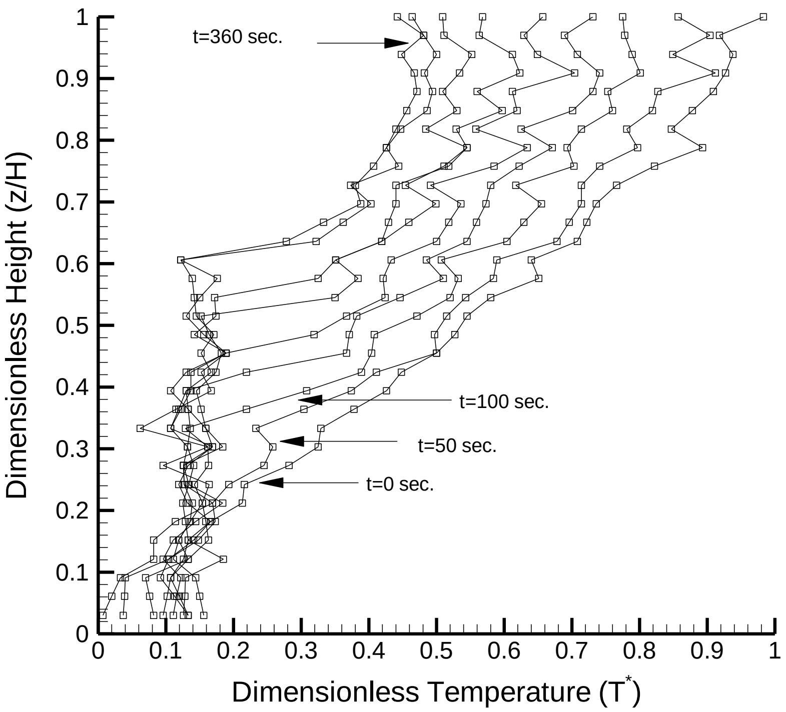
a) Water discharge at 12.30 pm, 2p2d, 5 L/min.



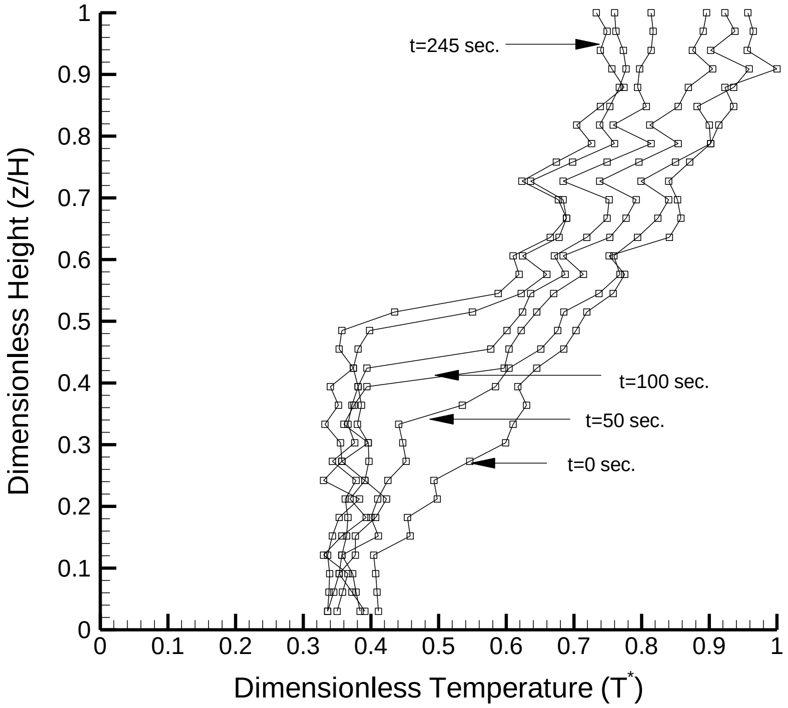
b) Water discharge at 5:00 pm, 2p2d, 5 L/min.



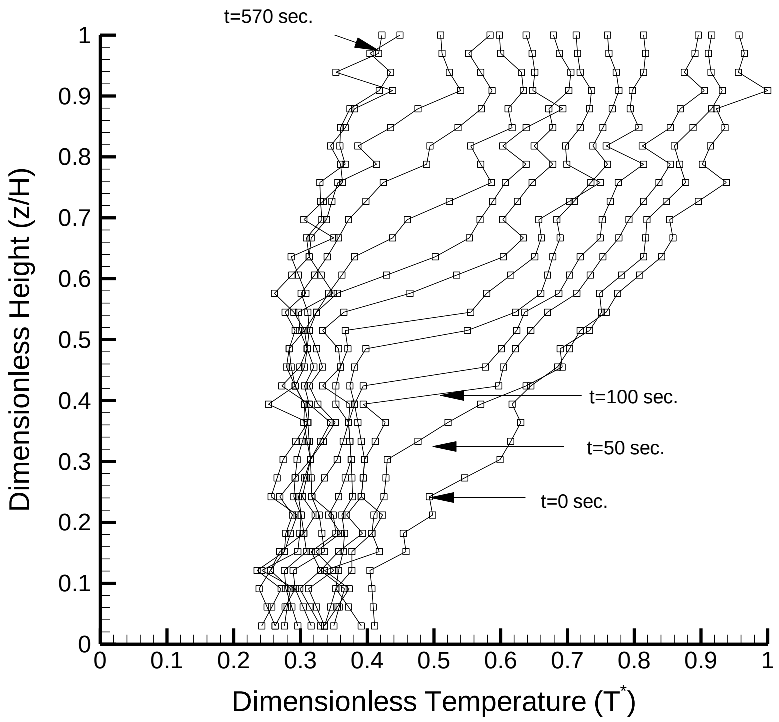
c) Water discharged completely at 5:00 pm, 2p2d, 5 L/min.
Figure 24: Transient temperature distributions for 2p2d, at flow-rate 5L/min.
(a) 12:30, (b) 2:30, (c) 5:00



a) Water discharge at 12.30 pm 2p2d, 10L/min.



b) Water discharge at 5.00 pm, 2p2d, 10L/min.



c) Water completely discharged at 5:00 pm, 2p2d, 10L/min.
Figure 25: Transient temperature distributions for 2p2d, at flow-rate 10L/min.
(a) 12:30, (b) 2:30, (c) 5:00

Figure 26 depicts the temperature profiles of drawn-off water as a function of t* for discharging and charging at 12.30 pm and 5.00 pm, respectively, with VFRs of 5 L/min and 10 L/min. The drawn-off temperature continues to drop, with a larger reduction in the temperature profile at 12.30 pm for both VFRs. Because of the thermal differential in the vertical direction inside the tank, when cold water enters from the bottom intake and hot water exits from the top exit, the temperature drops from the top to the bottom. As the VFR increases, the time required to discharge the hot water reduces. This causes a drop in the water temperature inside the tank. The heat transfer rate from the hot water to the entering cold water increases because the water removal rate is high. The heat transfer rate for the first withdrawal at 12.30 pm is higher than the second withdrawal at 5.00 pm for both VFRs.

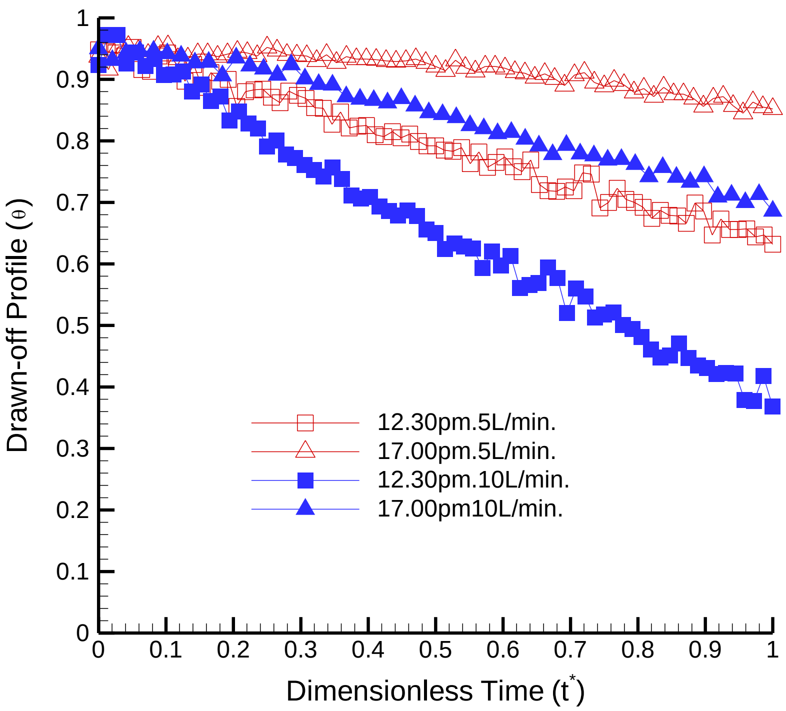


Figure 26: Drawn-off temperature profiles versus t* for different solar heating and VFRs for 2p2d tests

4.3.2.2 Two Persons Three Discharge Tests (2p3d)

It is the test at which three discharges/charges are performed for the two-person shower at 12.30 pm, 2.30 pm, and 5.00 pm, and then discharged/charged completely until the outlet temperature drops to 40°C.

Figure 27 shows the water temperature profile before the discharge/charge started, for the VFRs of 5 and 10 L/min. The same temperature profiles for the three cases, 12.30 pm, 2.30 pm, and 5.00 pm, were observed for both discharge/charge rates of 5 and 10 L/min. It is observed that the amount of water withdrawn for the two-person shower will not change the water temperature to a significant value. But for the 5 L/min, 5.00 pm discharge case, more hot water collected inside the water storage tank than the other cases. This is due to the continuous heating effect of the absorber plate in the afternoon period. Although the solar intensity declined during this period, the absorber plate had sufficient thermal energy to heat the mixed water after 12.30 pm, and from 2.30 pm until 5.00 pm to a larger volume value.

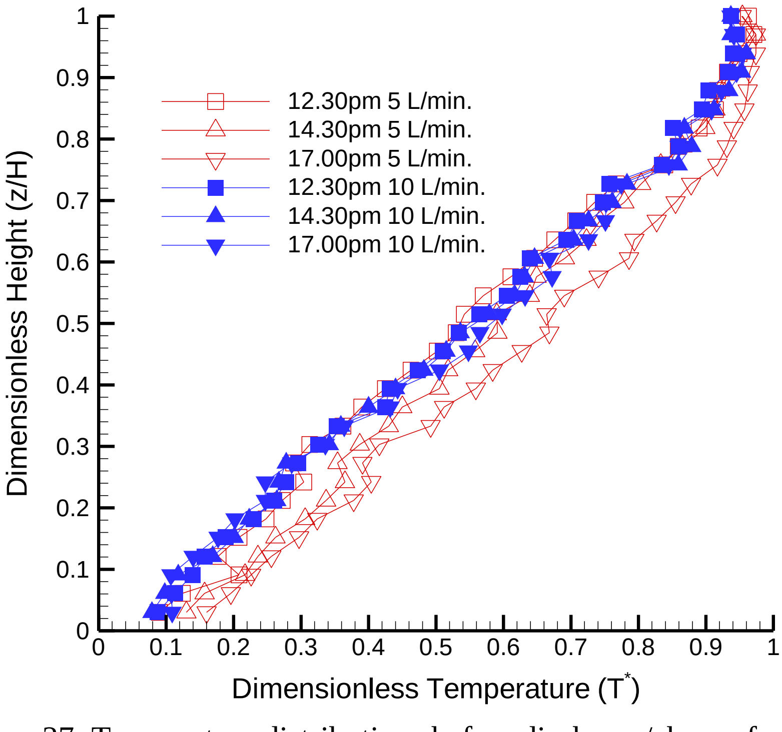
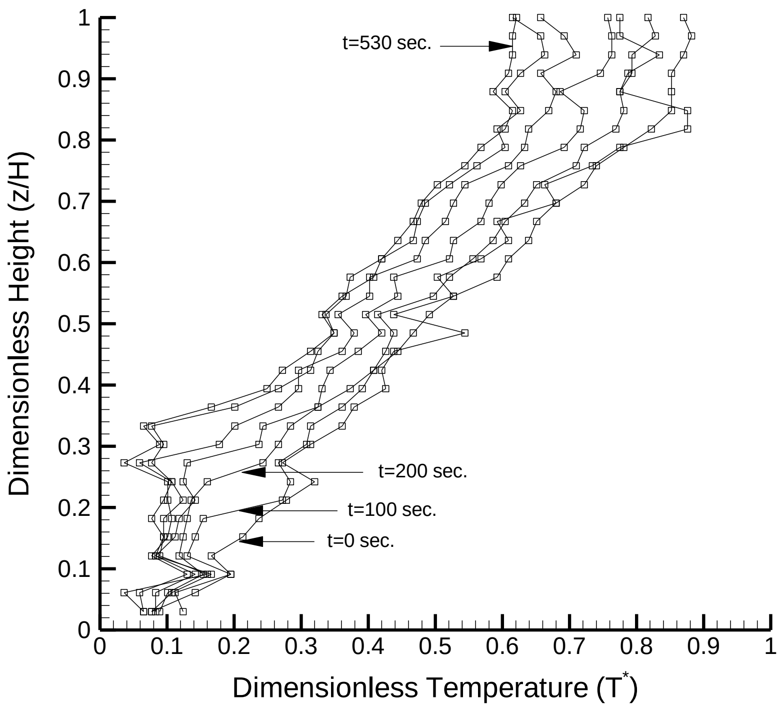


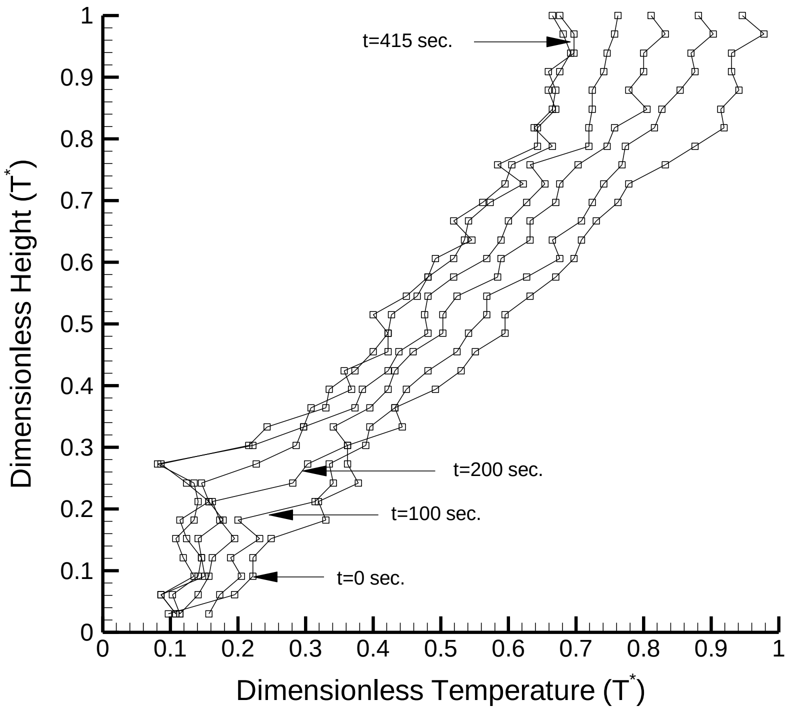
Figure 27: Temperature distributions before discharge/charge for 2p3d tests

Figure 28(a-d) depicts the transient temperature distribution of the (2p3d) water in the storage tank during the discharging/charging process for t>0, for a VFR of 5 L/min. After 100 seconds, the thermocline layer formed as cold water entered from the bottom, and hot water was expelled from the top for each step. The thermocline, however, is formed after 50 seconds at a VFR of 10 L/min, as illustrated in Figure 29. (a-d).

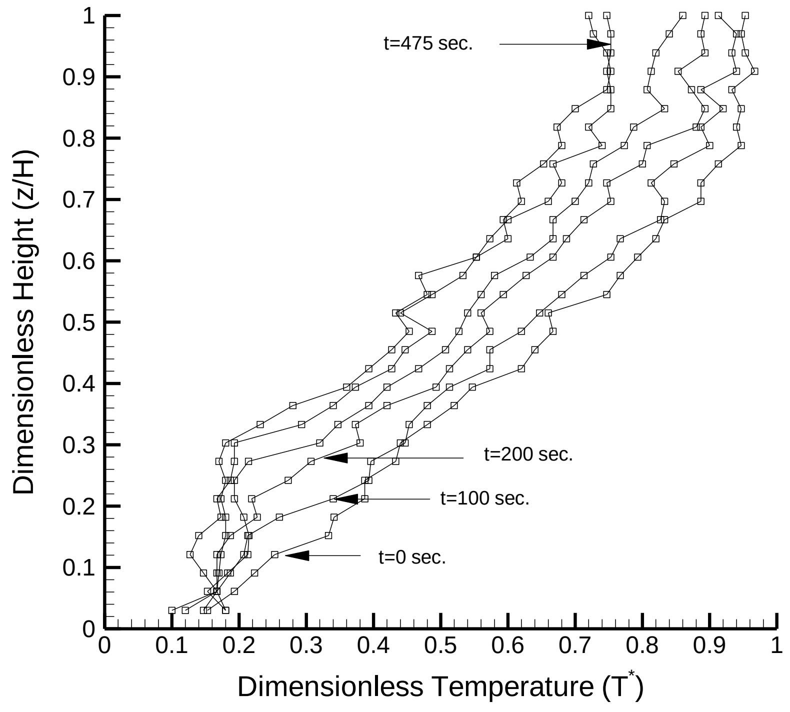
The thermocline layer is thin at first, as illustrated in Figure 29(d), and will dissipate as the outlet water temperature in the tank declines owing to mixing with incoming cold water until the discharging/charging process is stopped at 40°C. Figure (30-31) d shows how the time it took to discharge the hot water decreased as the number of withdrawn processes increased and the VFR increased.



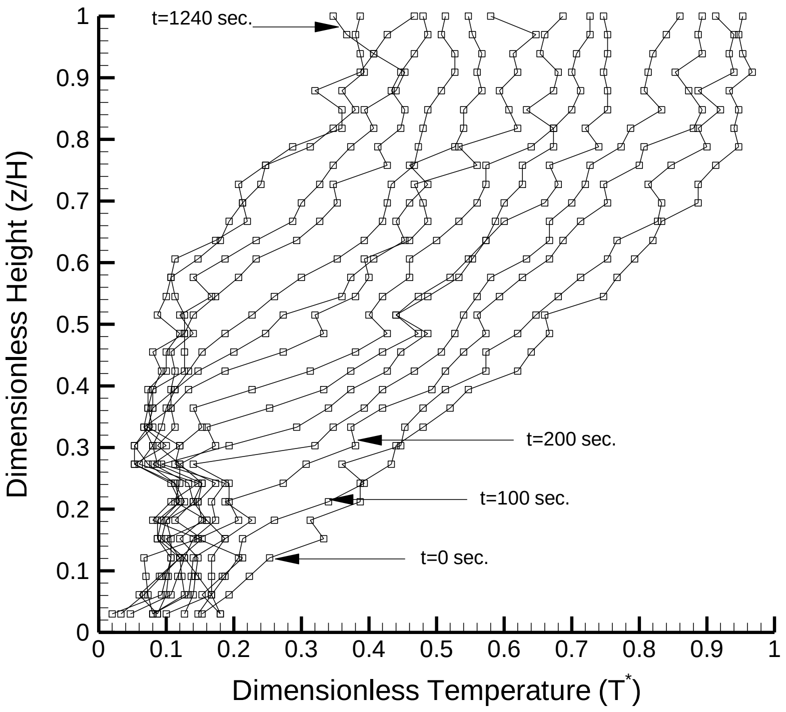
a) Water discharge at 12.30 pm, 2p3d, 5 L/min.



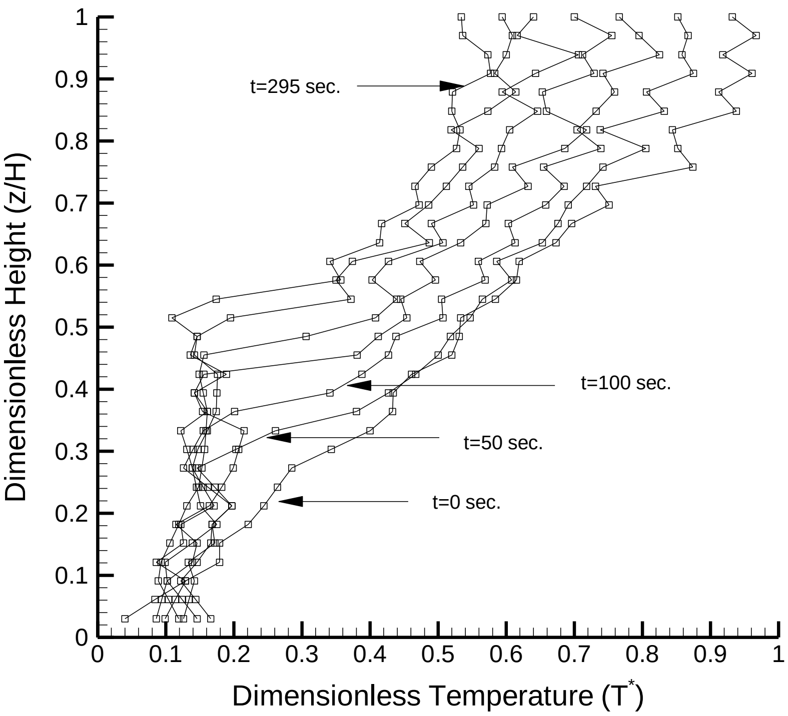
b) Water discharge at 2:30 pm, 2p3d, 5 L/min.



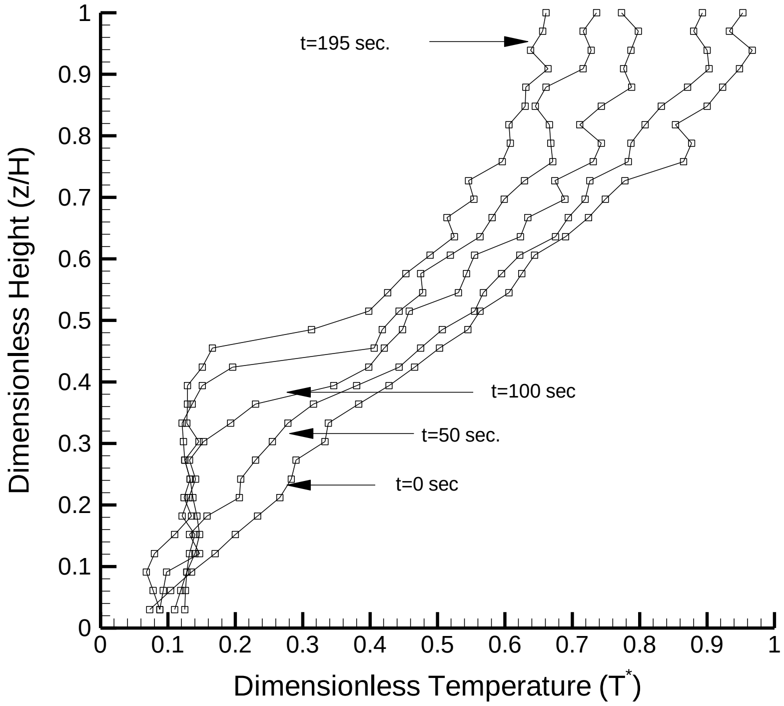
c) Water discharge at 5:00 pm, 2p3d, 5 L/min.



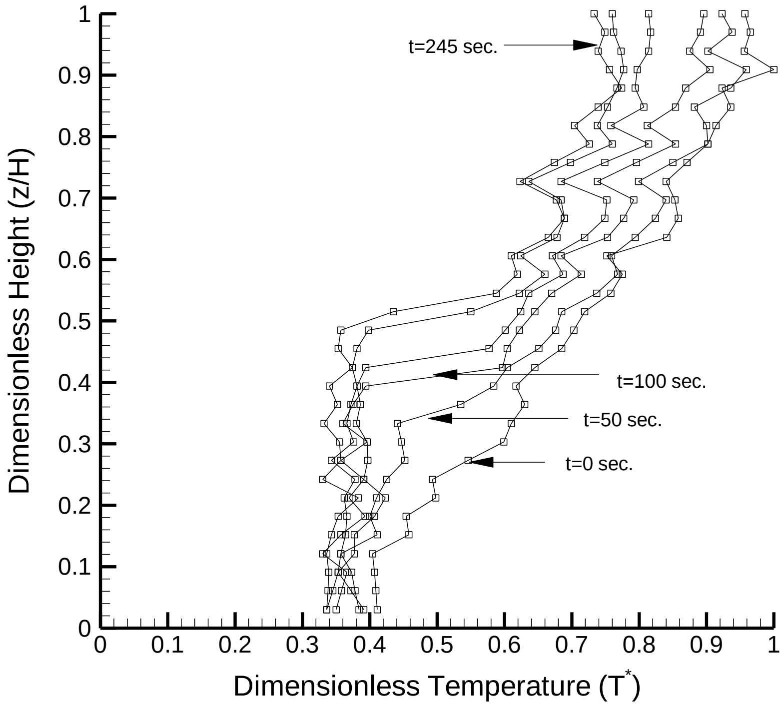
d) Water discharged completely at 5:00 pm, 2p3d, 5 L/min.
Figure 28: Transient temperature distributions for 2p3d, at flow-rate 5L/min.
(a) 12:30, (b) 2:30, (c) 5:00 and (d) 5:00C



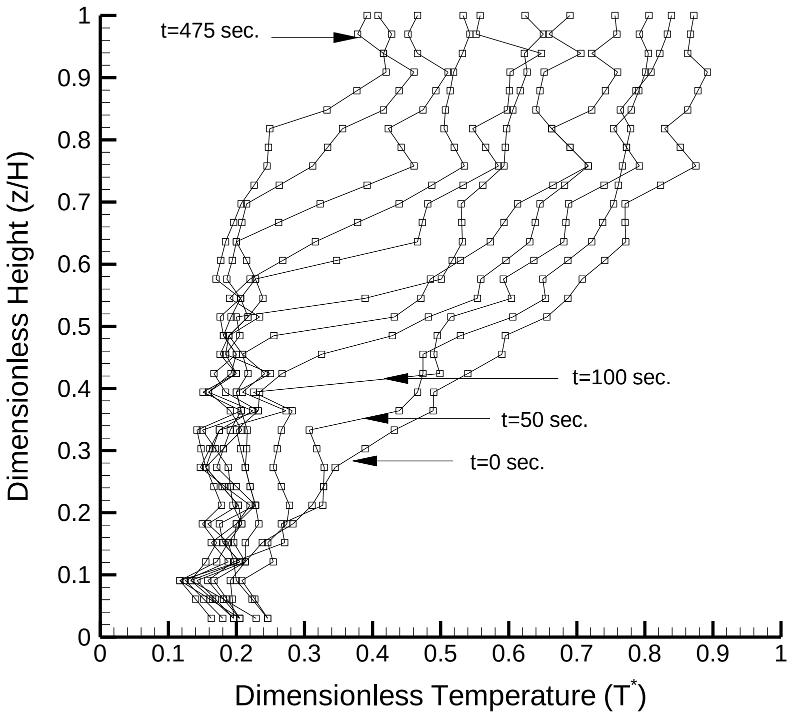
a) Water discharge at 12.30 pm, 2p3d, 10 L/min.



b) Water discharge at 2:30 pm, 2p3d, 10 L/min.



c) Water discharge at 5:00 pm, 2p3d, 10 L/min.



d) Water completely discharged at 17.00pm, 2p3d, 10 L/min.
Figure 29: Transient temperature distributions for 2p3d, at flow-rate 10 L/min.
(a) 12:30, (b) 2:30, (c) 5:00 and (d) 5:00C

Figure 30 illustrates the drawn-off water temperature profiles for the discharging/charging at 12.30 pm, 2.30 pm, and 5.00 pm, with VFRs of 5 L/min and 10 L/min, respectively, as a function of the t^*. The temperature of the drawn-off fluid continues to drop. The temperature drops from the top to the bottom when cold water enters from the bottom intake and hot water exits from the top exit due to the thermal differential along the vertical direction inside the tank. Because the high rate of water removal also enhances the heat transfer rate between the two water streams (cold water entering and hot water in the tank), the water temperature inside the storage tank shows a decreasing trend.

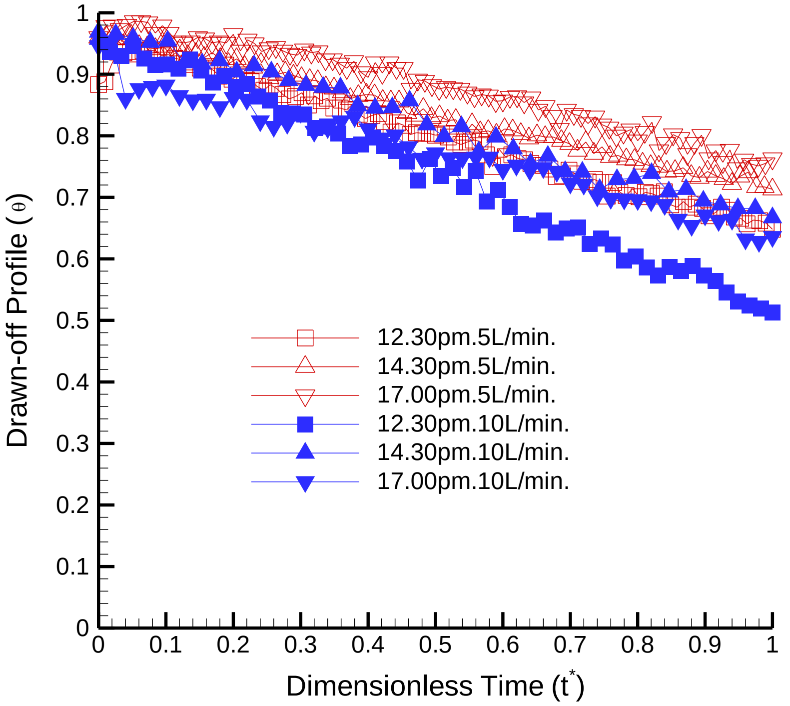


Figure 30: Drawn-off temperature profiles versus t* for different solar heating and VFRs for 2p3d tests

Figure 31 depicts the drawn-off water temperature profiles depending on t* for two discharge and three discharge intervals for a two-person shower with a VFR of 5L/min and 10L/min, respectively. When the water temperature goes below 40°C, the discharge tests come to a halt. On the other hand, the drawn-off temperature continues to drop due to the thermal gradient from top to bottom of the tank. Table 2 illustrates the total volume of hot water discharged for two people showering at both VFRs during the heating periods of 12.30 pm-5.00 pm.

Table 2: Total volume of hot water discharged for the two-person shower from the ISWH

Discharge Cases	Amount of hot water discharged (L)	
	5 L/min.	10 L/min.
2p2d	32.22	58.28
2p3d	44.98	64.20

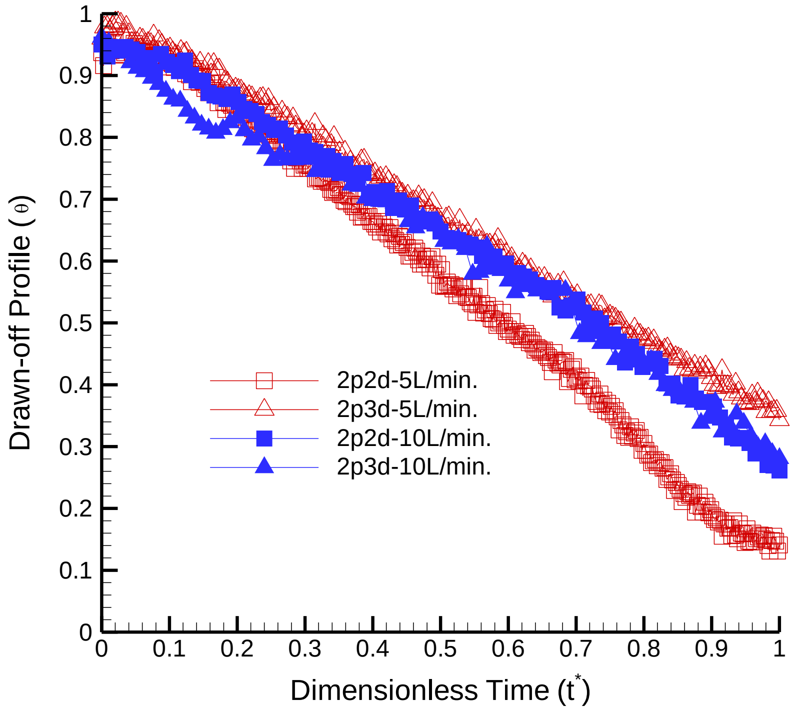


Figure 31: Drawn-off temperature profiles versus t* for two-person solar heating tests.

4.3.3 Three Discharges to 40°C (3d40deg)

It is the test at which three discharges/charges are performed until the temperature of the outlet water drops to 40°C at every three intervals of 12.30 pm, 2.30 pm, and 5.00 pm.

The water temperature profile before the discharge/charge started, is given in Figure 32 for 5 and 10 L/min VFRs. The temperature profiles of the three cases, 12.30 pm, 2.30 pm, and 5.00 pm, are very close for both discharge/charge periods at a flow rate of 5 and 10 L/min. It is observed that the amount of water withdrawn until 40°C will not change the water temperature to a significant value. But at 5 L/min. discharge/charge rate, for the 5.00 pm case, more hot water collected inside the water storage tank than in the other cases of 12.30 pm and 2.30 pm. This is due to the continuous heating effect of the absorber plate in the afternoon period, and the low

VFR of water mixing. For the 10 L/min. VFR, the hot water generated is at a lower quantity than the 5 L/min. VFR. In this case, twice a larger volume of cold water enters with a higher VFR, thus reducing the hot water temperature in the storage tank.

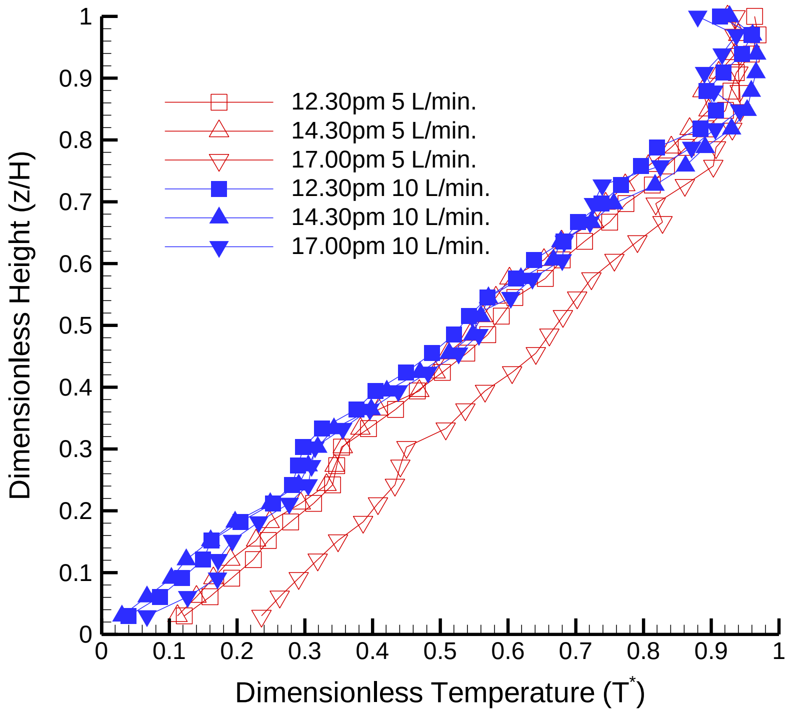


Figure 32: Temperature distributions before discharge/charge for 3d40deg. tests

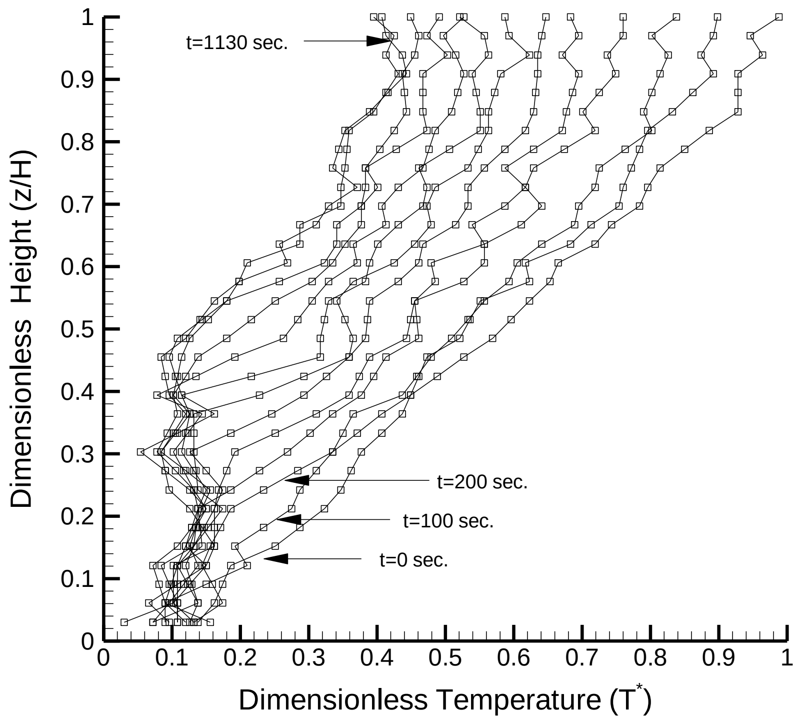
Figures 33(a-c) and 34(a-c) illustrate the transient temperature distribution of the (3d40deg) water in the storage tank throughout the discharging/charging process for t>0 for VFRs of 5L/min. and 10L/min., respectively. For the 5 L/min VFR, the thermocline layer formed after the 100th second, and for the 10 L/min VFR, it formed after the 50th second.

The thermocline layer is very thin in the initial period of the formation as shown and will vanish when the outlet water temperature in the tank drops due to the mixing with incoming cold water, until the discharging/charging process is stopped at 40°C. The time required to discharge the hot water reduced nearly twice as the withdrawal process increased for the VFR 10 L/min. Figure 34(a-b-c).

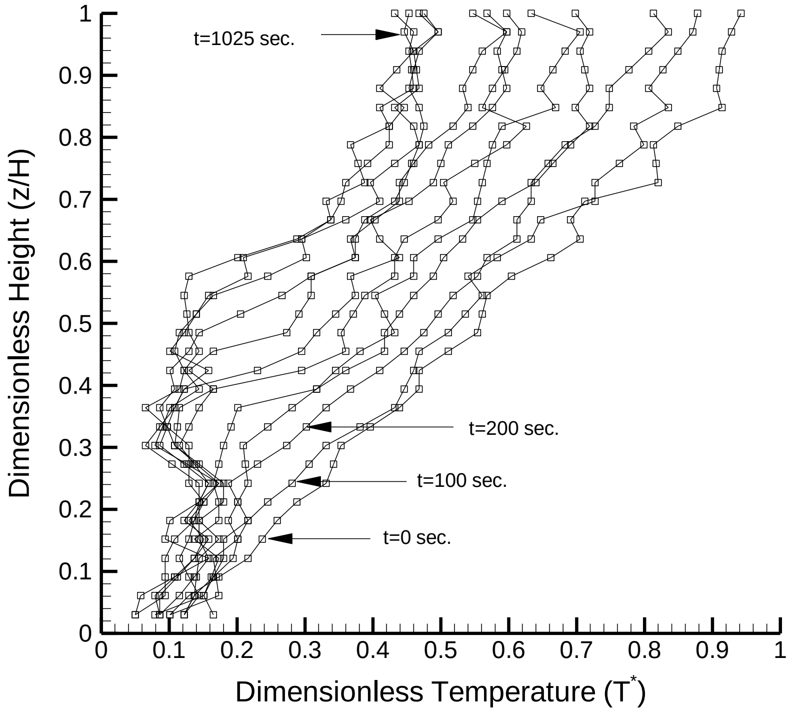
In all three discharge/charge operations the same amount of hot water was discharged/charged at different periods for both VFRs respectively. More hot water is collected for the low flow rate case and the total volume of water discharged for this case is shown in Table 3.

Table 3: Total volume of hot water discharged for 3d40deg case from the ISWH

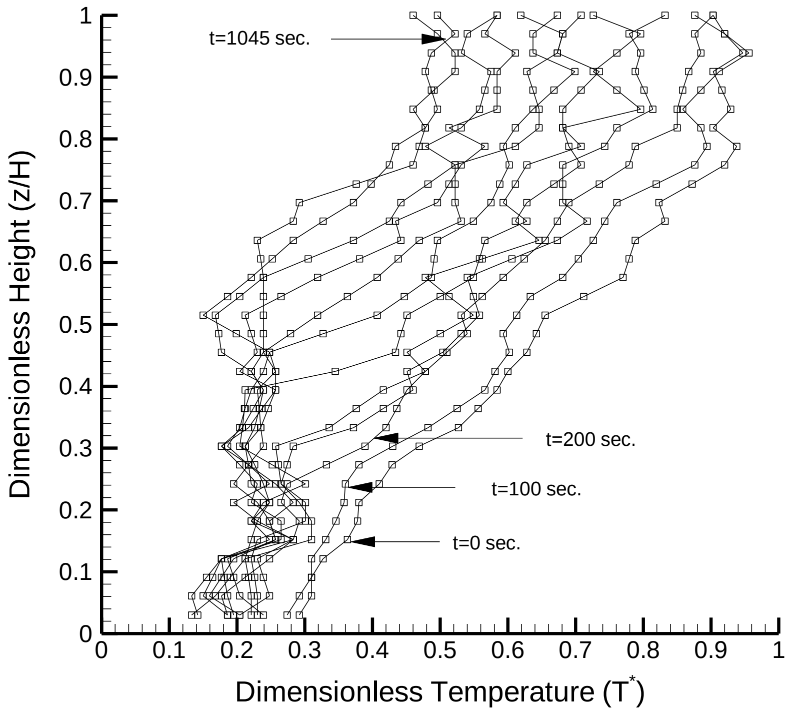
Discharge Cases	Amount of hot water discharged (L)	
	5 L/min.	10 L/min.
3d40deg	63.95	65.76



a) Water discharge/charge at 12:30 pm, 3d40deg. 5L/min.

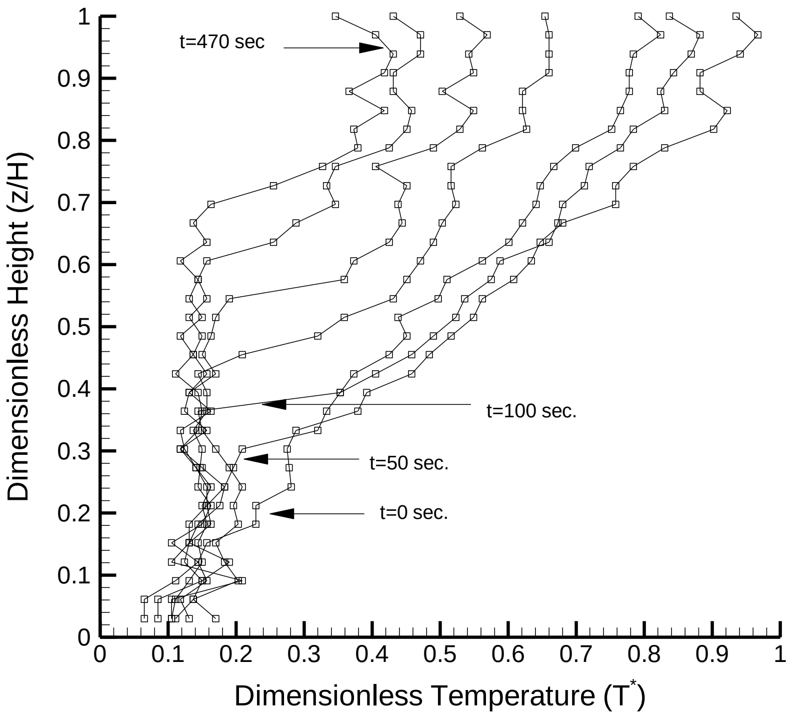


b) Water discharge/charge at 2:30pm, 3d40deg. 5L/min.

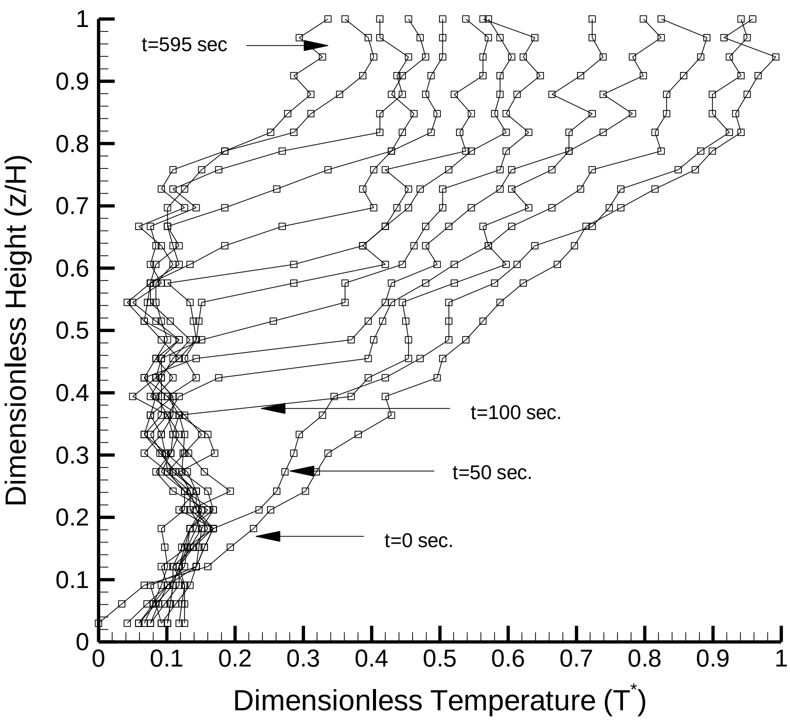


c) Water discharge/charge at 5:00 pm, 3d40deg. 5L/min.

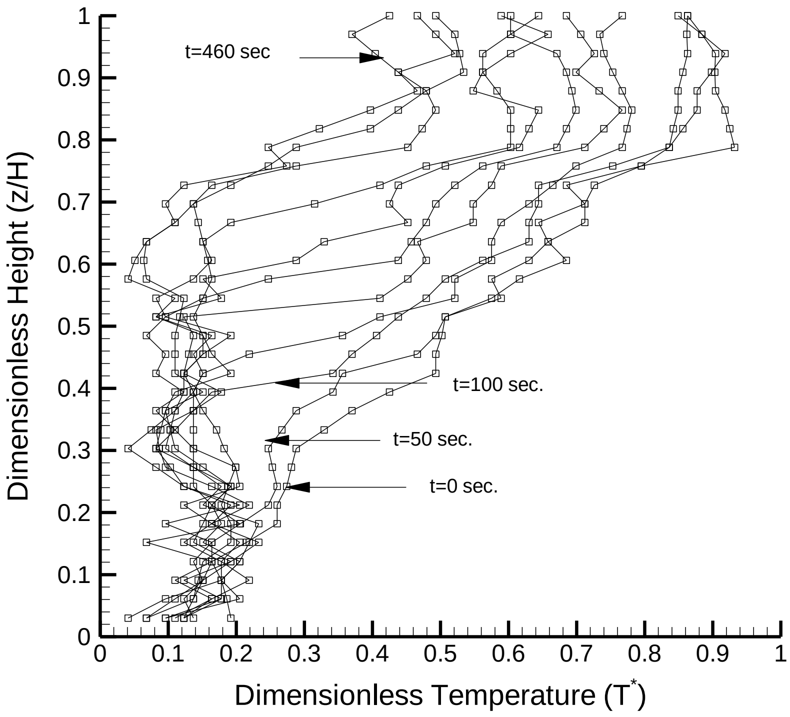
Figure 33: Transient temperature distributions inside the storage tank at the discharge/charge operation at 5L/min. for 3d40deg.



a) Water discharge/charge at 12.30 pm, 3d40deg. 10L/min.



b) Water discharge/charge at 14.30pm, 3d40deg. 10L/min.



c) Water discharge/charge at 5:00 pm, 3d40deg. 10L/min.

Figure 34: Transient temperature distributions in the storage tank at the discharge/charge operation at 10L/min. for 3d40deg.

Figure 35 illustrates the drawn-off water temperature profiles for the discharging/charging at 12.30 pm, 2.30 pm, and 5.00 pm, with VFRs of 5 L/min and 10 L/min, respectively, as a function of the t*. The temperature of the drawn-off fluid continues to drop due to the temperature gradient inside the tank. Because a high rate of water removal also increases the heat transfer rate between the two water streams (hot water and the entering cold water) the effect of large volume discharging/charging for 10 L/min. case to reach 40°C will contribute to lowering the hot water temperature in the storage tank.

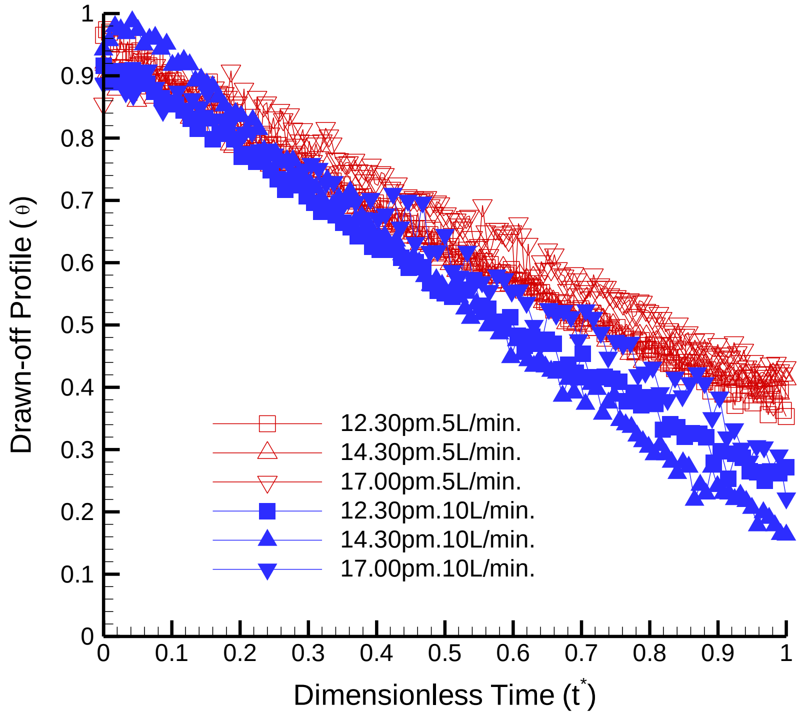


Figure 35: Drawn-off temperature profiles versus t* for 3d40deg. discharge solar heating tests.

The volume of the discharged hot water from the ISWH for different solar heating tests is shown in Table 4. The amount of hot water volume discharged drops as the number of discharge/charge tests increases both for one person and two persons. The maximum amount of hot water discharged was observed at 3d40deg 5L/min. case (63.95 L). and 1p3d 10L/min. case (67.59 L).

Table 4: Total volume of hot water discharged from the ISWH for different tests.

Discharge Cases	Amount of hot water discharged (L)	
	5 L/min.	10 L/min.
1p1d	16.4	22.45
1p2d	41.1	43.20
1p3d	62.8	67.59
1p1hr.d	39.50	58.22
2p2d	32.22	58.28
2p3d	44.98	64.20
3d40deg.	63.95	65.76

As demonstrated in Figures 36 and 37, the ISWH's collector efficiency is also calculated in terms of cumulative efficiency. It is calculated by dividing the total energy stored in the tank for each hour (Equation.1) by the hourly incident solar energy (Equation.13);

$$E_{incident} = A\int_{t_1}^{t_2} I dt \qquad (13)$$

Where; A is the surface area of the collector, I is solar intensity and t is time.

The overall (cumulative) efficiency of the system is;

$$\eta_{cum} = \frac{E_{st}}{E_{incident}} \qquad (14)$$

The cumulative efficiencies for all one-person tests are shown in Figure 36 and for two persons and 3d40deg tests in Figure 37. An increase in efficiency is observed from the starting time of the experiment and reached the maximum value of 64% and 55% at noon time (12:30 pm) for one-person and two-person showers respectively. From Figure 36, in the one-person shower case, with no intermediate discharge, 1p1d, the efficiency remains nearly constant until the discharge time at 5.00 pm. For the other three cases, the cumulative efficiency stays between the interval band 35% -50% at the intermediate discharge/charge operations, 12.30 pm, 2.30 pm, and 5.00 pm. respectively. From Figure 37, in the two-person shower cases, in the afternoon period, the drop in efficiency was observed between the interval band 20% - 40% at the intermediate discharge/charge operations, 12.30 pm, 2.30 pm, and 5.00 pm. As the number of discharge/charge operations increases more fluctuations in the energy were observed. At every test, two persons discharge/charge shows lower efficiency for the VFR 10L/min. Except for 3p40deg case, for both flowrates, the amount of hot water discharged/charged at every period is higher than the other cases causing the water temperature to drop lower to 40°C value also the absorber plate heat energy is not sufficient to heat the water to a higher value. this may be due to a large amount of water discharged/charged, cooling the absorber plate and causing hot water volume to decrease.

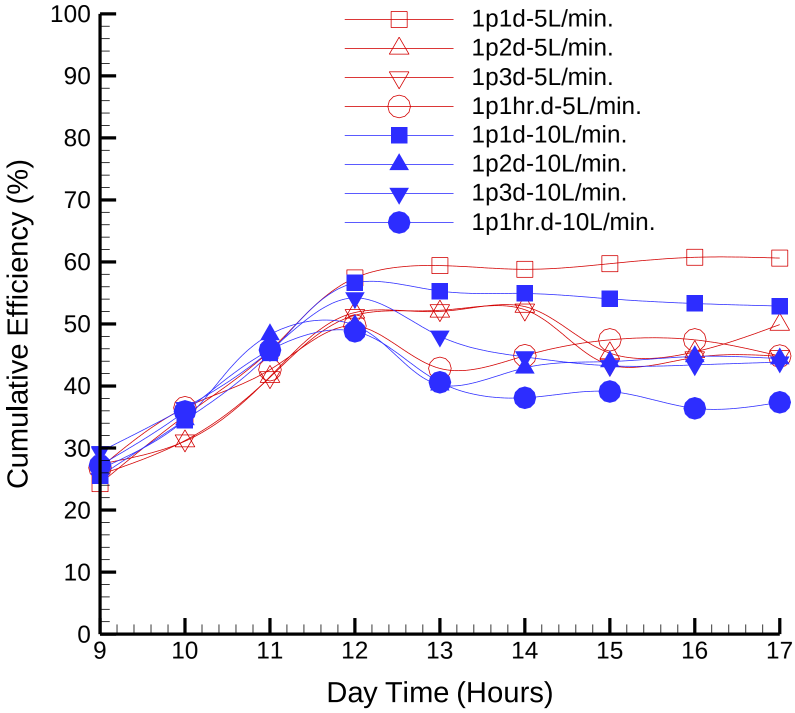


Figure 36: Hourly Cumulative Efficiencies of ISWH obtained from solar heating for one person discharge/charge tests.

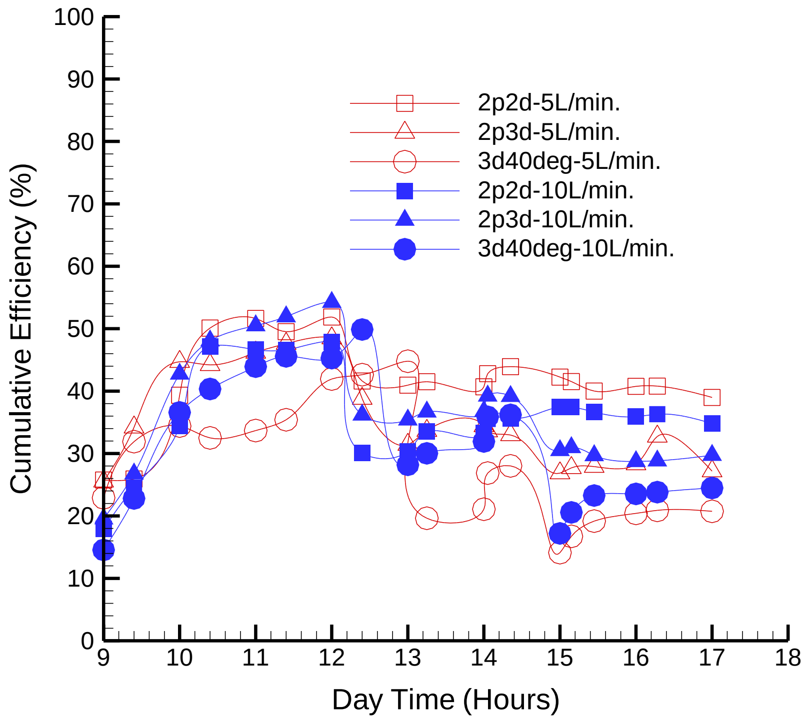


Figure 37: Hourly Cumulative Efficiencies of ISWH obtained from two persons and 3d40deg solar heating tests

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Experimental Investigation of EWH

A typical EWH, which is available in the local market in north Cyprus, is used to find out the effect of the thermostat location on the performance. Three different thermostat positions namely at heights A (z/H=0), B (z/H=0.54), and C (z/H=0.86) were used. In addition, the effect of the temperature setting of the thermostat at position A on the performance is investigated. The results showed that the tank, with the thermostat position at A, has a higher final water temperature than those of the thermostat position at B and C. For the case where the thermostats are placed at B and C, the fraction of the storage water withdrawn is smaller than that of the case corresponding to that of the thermostat at A. The time required to heat the tank to the desired temperature is reduced by 18 min when the thermostat is positioned at B or C compared to that of A.

The discharge efficiencies are found at 93.77% for the thermostat location at A, 83.65%, and 85.80% for thermostat locations at B and C, respectively. These results indicate that thermal stratification is maintained better during the discharging process when the thermostat is at the bottom (i.e., location A) of the tank, resulting in lower heat losses to the bottom cold water due to mixing.

It is found that, for the same set point temperature for all thermostats, the highest average temperature, also the highest amount of thermal energy storage inside the tank is achieved with thermostat A. With thermostats B and C, the amount of stored energy is nearly 15% and 20% less when compared with thermostat A.

Results also showed that; increasing thermostat set point temperature has a negative impact on discharge efficiency and depending on the number of people to take shower, the optimal set point temperature should be selected. For the increase of the set point temperature between 40→55 ˚C, efficiency becomes half. For 1-2 persons, the optimum set point temperature was found as 40 ˚C whereas, for 3,4 and 5 persons, it was determined as 45, 50, and 55 ˚C respectively.

In terms of cost savings, for up to 2 people, setting the thermostat to 40 ˚C instead of 55 ˚C could provide 100-150 $ cost savings per year. For 3 people thermostat could be set to a minimum of 45 ˚C (instead of 55 ˚C) which could also provide 80-120$ yearly savings. If the number of people to take shower is 4 or more, the cost savings potential is limited.

According to the study results, in domestic applications using a thermostat close to the bottom of the water tank (Thermostat A), improves thermal stratification and provides higher efficiencies. For example, 8% high efficiency was achieved with Thermostat A. On the other hand, depending on the hot water demand, selecting the optimum set point temperature enables a considerable amount of annual energy (400-600 kWh) and cost savings (80-150 $). However, for the case of selecting a set point temperature <60 ˚C, water treatment methods should also be applied to prevent any growth of legionella bacteria inside the storage tank.

5.2 Experimental Investigation on Trapezoidal ISWH

Experiments were conducted on the design and manufacture of a new trapezoidal storage home EWH with a solar collector. To evaluate the viability of using this ISWH, the performance was tested in Famagusta weather conditions throughout the summer months. Solar water heating tests were carried out and assessed in this study.

Based on the obtained results from several discharging tests with different VFRs of 5 and 10 L/min, the transient temperature distributions suggested a mild stratified tank, indicating promising results from solar heating experiments. The percentage of hot water held in the tank is above 40°C for a one-person shower at a rate of 5 L/min. The discharged amount of water for one- or two-persons taking showers between 12.30 pm and 2.30 pm was found to be (46-58) L. for the VFR of 5 L/min. and (58-64) L. for the VFR of 10 L/min. For all experiments, this was determined to be less than the water volume kept in the tanks, which increases the ISWH's performance. The maximum solar intensity and temperature were 890 W/m^2 and 54.6°C, respectively, and the maximum amount of hot water released over 40°C was 68L, which was 51 percent of the tank volume.

For electrical and solar heating procedures, the number of people who can take a rapid shower is also determined. It was found that if the heater is positioned at C (z/H=0.67), 50 L hot water at a temperature of 40 °C could be produced to take a one-time fast shower. In case the heater is mounted at A (z/H=0.0), 8 people can take a quick shower in succession, but 4 people can take a quick shower if the heater is mounted at B (z/H=0.47), and 2 people may take a quick shower if the heater is mounted at C (z/H=0.67). When there is no sun, this is a good opportunity for the user to turn on the heating components according to the amount of water required; on the other hand, when the water is heated by the sun, 5-6 people can shower at the same time.

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APPENDICES

Appendix A: Sample Fortran Program for Discharge Case

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  FOR THE SOLAR EXPERIMENT 10 LPM 40 DEG AT TIME 12.30       C
C  THIS PROGRAM WILL CALCULATE THE DISCHARGING PERFORMANCE    C
C  QS,THE ENERGY STORED IN THE TANK DURING THE HEATING PERIOD C
C  NR, THE NUMBER OF ROWS RECORDED DATA                       C
C  NC,THE NUMBER OF COLUMNS OF RECORDED DATA                  C
C  NT , THE NUMBER OF THERMOCOUPLES                           C
C  TIN, MINIMUM TEMPERATURE IN THE TANK                       C
C  TMAX, MAXIMUM TEMPERATURE IN THE TANK                      C
C  TIMES, TIME TAKEN TO DISCHARGE THE WATER                   C
C  Z, THE HEIGHT OF THE CONTROL VOLUME                        C
C  CV,THE CONTROL VOLUME                                      C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      PARAMETER (N=500,NR=107,NT=33,NC=42)
      REAL
a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12,a13,a14,a15,a16,
     * a17,a18,a19,a20,a21,a22,a23,a24,a25,a26,a27,a28,a29,a30,
     * a31,a32,a33,a34,a35,a36,a37,a38,a39,a40,a41
      INTEGER time
      DIMENSION a1(N),a2(N),a3(N),a4(N),a5(N),a6(N),a7(N),
     *a8(N),a9(N),a10(N),a11(N),a12(N),a13(N),a14(N),a15(N),
     *a16(N),a17(N),a18(N),a19(N),a20(N),a21(N),a22(N),a23(N),
     *a24(N),a25(N),a26(N),a27(N),a28(N),a29(N),a30(N),a31(N),
     *a32(N),a33(N),a34(N),a35(N),a36(N),a37(N),a38(N),a39(N),
     *a40(N),a41(N),TIME(N),T(N),Z(N),TS(N),TD(N),TIM(N),
     *CV(N),X(N),TI(N),CVOL(N)
C
C
      OPEN(55,FILE='discharge1230.txt')
      OPEN(8,FILE='enTEMP')
      OPEN(9,FILE='enSTEADY')
      OPEN(10,FILE='enDRAWNOFF')
      OPEN(11,FILE='en ENERGY')
      OPEN(12,FILE='EN dischargeDATAREAD')
      OPEN(18,FILE='ensamprot')
      OPEN(19,FILE='ENCONT VOL')
C
      DO  j=1,NR

read(55,*)TIME(j),A1(j),A2(J),A3(J),A4(J),A5(J),A6(J),A7(J),
     *
A8(J),A9(J),A10(J),A11(J),A12(j),A13(j),A14(j),A15(j),A16(j),
     *
A17(j),A18(j),A19(j),A20(j),A21(j),A22(j),A23(j),A24(j),A25(j),
     *
A26(j),A27(j),A28(j),A29(j),A30(j),A31(j),A32(j),A33(j),A34(j),
     * A35(j),A36(j),A37(j),A38(j),A39(j),A40(j),A41(j)
C     ,A42(j),A43(j),A44(j)


write(12,*)TIME(j),A1(j),A2(J),A3(J),A4(J),A5(J),A6(J),A7(J),
     *
A8(J),A9(J),A10(J),A11(J),A12(j),A13(j),A14(j),A15(j),A16(j),
     *
A17(j),A18(j),A19(j),A20(j),A21(j),A22(j),A23(j),A24(j),A25(j),
```

```
     *
A26(j),A27(j),A28(j),A29(j),A30(j),A31(j),A32(j),A33(j),A34(j),
     * A35(j),A36(j),A37(j),A38(j),A39(J),A40(j),A41(j)
C      ,A42(j),A43(j),A44(j)
        END DO
  33  FORMAT(I4,1X,999(F8.3,1X))
C
      TIN=34.60
      TMAX=49.90
      TIMES=470
      T2MT1=1/(TMAX-TIN)
C
C TO CALCULATE THE AVERAGE TEMP. OF THE STEADY STATE
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      SUM4=0.0
      SUM5=0.0
      SUM6=0.0
      SUM7=0.0
      SUM8=0.0
      SUM9=0.0
      SUM10=0.0
      SUM11=0.0
      SUM12=0.0
      SUM13=0.0
      SUM14=0.0
      SUM15=0.0
      SUM16=0.0
      SUM17=0.0
      SUM18=0.0
      SUM19=0.0
      SUM20=0.0
      SUM21=0.0
      SUM22=0.0
      SUM23=0.0
      SUM24=0.0
      SUM25=0.0
      SUM26=0.0
      SUM27=0.0
      SUM28=0.0
      SUM29=0.0
      SUM30=0.0
      SUM31=0.0
      SUM32=0.0
      SUM33=0.0
C      SUM34=0.0
C      SUM35=0.0
C      SUM36=0.0

      NN=12
      AN=NN
      onenn=1/AN
      do i=1,NN
      SUM1=SUM1+A1(i)
      SUM2=SUM2+A2(i)
      SUM3=SUM3+A3(i)
      SUM4=SUM4+A4(i)
```

```
      SUM5=SUM5+A5(i)
      SUM6=SUM6+A6(i)
      SUM7=SUM7+A7(i)
      SUM8=SUM8+A8(i)
      SUM9=SUM9+A9(i)
      SUM10=SUM10+A10(i)
      SUM11=SUM11+A11(i)
      SUM12=SUM12+A12(i)
      SUM13=SUM13+A13(i)
      SUM14=SUM14+A14(i)
      SUM15=SUM15+A15(i)
      SUM16=SUM16+A16(i)
      SUM17=SUM17+A17(i)
      SUM18=SUM18+A18(i)
      SUM19=SUM19+A19(i)
      SUM20=SUM20+A20(i)
      SUM21=SUM21+A21(i)
      SUM22=SUM22+A22(i)
      SUM23=SUM23+A23(i)
      SUM24=SUM24+A24(i)
      SUM25=SUM25+A25(i)
      SUM26=SUM26+A26(i)
      SUM27=SUM27+A27(i)
      SUM28=SUM28+A28(i)
      SUM29=SUM29+A29(i)
      SUM30=SUM30+A30(i)
      SUM31=SUM31+A31(i)
      SUM32=SUM32+A32(i)
      SUM33=SUM33+A33(i)
C      SUM34=SUM34+A34(i)
C      SUM35=SUM35+A35(i)
C      SUM36=SUM36+A36(i)
C      TOUT=TOUT+A36(i)
C      TIN=TIN+A37(i)
      end do

      t(1)=SUM1*onenn
      t(2)=SUM2*onenn
      t(3)=SUM3*onenn
      t(4)=SUM4*onenn
      t(5)=SUM5*onenn
      t(6)=SUM6*onenn
      t(7)=SUM7*onenn
      t(8)=SUM8*onenn
      t(9)=SUM9*onenn
      t(10)=SUM10*onenn
      t(11)=SUM11*onenn
      t(12)=SUM12*onenn
      t(13)=SUM13*onenn
      t(14)=SUM14*onenn
      t(15)=SUM15*onenn
      t(16)=SUM16*onenn
      t(17)=SUM17*onenn
      t(18)=SUM18*onenn
      t(19)=SUM19*onenn
      t(20)=SUM20*onenn
      t(21)=SUM21*onenn
      t(22)=SUM22*onenn
```

```
      t(23)=SUM23*onenn
      t(24)=SUM24*onenn
      t(25)=SUM25*onenn
      t(26)=SUM26*onenn
      t(27)=SUM27*onenn
      t(28)=SUM28*onenn
      t(29)=SUM29*onenn
      t(30)=SUM30*onenn
      t(31)=SUM31*onenn
      t(32)=SUM32*onenn
      t(33)=SUM33*onenn
C      t(34)=SUM34*onenn
C      t(35)=SUM35*onenn
C      t(36)=SUM36*onenn
C
C  DIMENSIONLESS HIGHT OF THE TANK
      H=0.700      ! height of tank
      HEL=H/NT    ! height of element in the tank
      ONEOH=1.0/H
      SUM=0.0
      DO j=1,NT
      SUM=SUM+HEL
      Z(j)=SUM*ONEOH
      END DO
C
C DIMENSIONLESS TEMP. TS=TEMP OF STORAGE used to draw the tsteady
curve
       DO j=1,NT
       TS(j)=(t(j)-TIN)*T2MT1
       END DO
C--WRITE INTO FILE ENSTEADY--to draw the tsteady curve
C   dimensionless height (z/H) versus dimensionless temperature
T^*
       DO j=1,NT
C       PRINT*,t(j),TS(j)
       WRITE(9,121)TS(j),z(j)
       END DO
 121   FORMAT(333(F6.3,2X,F8.3))
C
C DIMENSIONLESS DRAWN-OFF PROFILE TEMP. TD=TEMP OF DRAWN
C to draw the curve drawn-off profile
       DO j=13,NR
       TMMA43=1/(TMAX-A40(j))
       TD(j)=(A41(j)-A40(j))*TMMA43
       END DO
C-WRITE INTO FILE ENDRAWNOFF---to draw the drawn-off profile
curve
C      dimensionless time t^* versus dimensionless temperature
THETA
       DO j=13,NR
       ONEOTS=1/TIMES
       TIM(j)=time(j)*ONEOTS
C       PRINT*,'j',j,'TI(',j,')',TIM(j),'TD(j)',TD(j)
       WRITE(10,122)TIM(j),TD(j)
       END DO
 122   FORMAt(499(F8.4,2X,F8.3))
C
C CALCULATE THE ENERGY STORED
```

```
C  THE CONTROL VOLUME ,CV(j), CALCULATION
      CP=4.182
      SUMm=0.0
      CVO=0.0
      cvh=0.0
      HE=H/NT   !ELEMENT HEIGHT
      W=0.5     !ELEMENT WIDTH
C control volume
      DO j=1,NT
      SUMm=SUMm+HE
      x(j)=0.730-SUMm
      CV(j)=0.5*W*HE*(2*x(j)+HE)
      CVO=CVO+CV(j)
      CVOL(j)=CVO
      END DO
C  WRITE THE HEIGHT AND enCONT VOL DATA
       DO j=1,NT
       WRITE(19,*)J,X(j),CV(j),cvol(j)
       END DO
C
C   CALCULATE THE ENERGY STORED ,QS, IN THE TANK before discharge
      CP=4.182
      DO j=1,NT
      DEN=1000.83-0.0723359*t(j)-0.00361826*t(j)*t(j)
      SUM=SUM+DEN*CP*CV(J)*ABS(T(J)-TIN)
      END DO
      QS=SUM
C
C CALCULATING THE DRAWN ENERGY ,QD, FROM THE TANK
      SUM=0.
      DO j=13,NR
      VOL=10.0/(1000.*60)  !VOLUME FLOW RATE
      t(j)=(A40(j)+a41(j))*0.5
      DEN=1000.83-0.0723359*t(j)-0.00361826*t(j)*t(j)
      SUM=SUM+DEN*VOL*CP*(A41(j)-A40(j))*(TIME(j)-TIME(J-1))
C      WRITE(11,*)DEN,VOL,CP,a37(j),a36(j),(TIME(j)-TIME(J-1))
      END DO
C
C   CALCULATING THE EFFICIENCY
      QD=SUM
      EF=QD/QS
C
      WRITE(11,16)QS,QD,EF
  16  FORMAT('QST=',F10.2,2X,'QDRAW=',F10.2,2X,'EFFIC=',F10.4)

C      WRITE(11,17)TIN,TOUT
C  17  FORMAT('TIN =',F7.2,2X,'TOUT=',F7.2,2X,'TLAB=',F7.2)
C
C DIMENSIONLESS TEMP. IN THE TANK
      DO j=1,NR
      A1(j)=ABS(A1(j)-TIN)*T2MT1
      A2(j)=ABS(A2(j)-TIN)*T2MT1
      A3(j)=ABS(A3(j)-TIN)*T2MT1
      A4(j)=ABS(A4(j)-TIN)*T2MT1
      A5(j)=ABS(A5(j)-TIN)*T2MT1
      A6(j)=ABS(A6(j)-TIN)*T2MT1
      A7(j)=ABS(A7(j)-TIN)*T2MT1
      A8(j)=ABS(A8(j)-TIN)*T2MT1
```

```
      A9(j)=ABS(A9(j)-TIN)*T2MT1
      A10(j)=ABS(A10(j)-TIN)*T2MT1
      A11(j)=ABS(A11(j)-TIN)*T2MT1
      A12(j)=ABS(A12(j)-TIN)*T2MT1
      A13(j)=ABS(A13(j)-TIN)*T2MT1
      A14(j)=ABS(A14(j)-TIN)*T2MT1
      A15(j)=ABS(A15(j)-TIN)*T2MT1
      A16(j)=ABS(A16(j)-TIN)*T2MT1
      A17(j)=ABS(A17(j)-TIN)*T2MT1
      A18(j)=ABS(A18(j)-TIN)*T2MT1
      A19(j)=ABS(A19(j)-TIN)*T2MT1
      A20(j)=ABS(A20(j)-TIN)*T2MT1
      A21(j)=ABS(A21(j)-TIN)*T2MT1
      A22(j)=ABS(A22(j)-TIN)*T2MT1
      A23(j)=ABS(A23(j)-TIN)*T2MT1
      A24(j)=ABS(A24(j)-TIN)*T2MT1
      A25(j)=ABS(A25(j)-TIN)*T2MT1
      A26(j)=ABS(A26(j)-TIN)*T2MT1
      A27(j)=ABS(A27(j)-TIN)*T2MT1
      A28(j)=ABS(A28(j)-TIN)*T2MT1
      A29(j)=ABS(A29(j)-TIN)*T2MT1
      A30(j)=ABS(A30(j)-TIN)*T2MT1
      A31(j)=ABS(A31(j)-TIN)*T2MT1
      A32(j)=ABS(A32(j)-TIN)*T2MT1
      A33(j)=ABS(A33(j)-TIN)*T2MT1
C      A34(j)=ABS(A34(j)-TIN)*T2MT1
C      A35(j)=ABS(A35(j)-TIN)*T2MT1
C      A36(j)=ABS(A36(j)-TIN)*T2MT1
      END DO
C----
C     WRITING THE ABOVE DATA INTO FILE ,ENTEMP,
C     dimensionless temp T^* versus dimensionless time t^*
      ONEOTS=1/TIMES
      DO j=13,NR
      TIM(j)=time(j)*ONEOTS

WRITE(8,20)TIM(j),A1(j),A2(j),A3(j),A4(j),A5(j),A6(j),A7(j),
     *
A8(j),A9(j),A10(j),A11(j),A12(j),A13(j),A14(j),A15(j),A16(j),
     *
A17(j),A18(j),A19(j),A20(j),A21(j),A22(j),A23(j),A24(j),A25(j),
     * A26(j),A27(j),A28(j),A29(j),A30(j),A31(j),A32(j),A33(j)
C     ,A34(j),A35(j),A36(j)
      END DO
 20    FORMAt(999(F6.3,2X))
C
  44   FORMAT(F8.3,1X,400(F8.3,1X))
C     write into file ensamprot
C     dimensionless height (z/H) versus dimensionless temperature
T^*
      WRITE(18,44)z(1),(A1(I),I=12,NR)
      WRITE(18,44)z(2),(A2(I),I=12,NR)
      WRITE(18,44)z(3),(A3(I),I=12,NR)
      WRITE(18,44)z(4),(A4(I),I=12,NR)
      WRITE(18,44)z(5),(A5(I),I=12,NR)
      WRITE(18,44)z(6),(A6(I),I=12,NR)
      WRITE(18,44)z(7),(A7(I),I=12,NR)
      WRITE(18,44)z(8),(A8(I),I=12,NR)
```

```
      WRITE(18,44)z(9),(A9(I),I=12,NR)
      WRITE(18,44)z(10),(A10(I),I=12,NR)
      WRITE(18,44)z(11),(A11(I),I=12,NR)
      WRITE(18,44)z(12),(A12(I),I=12,NR)
      WRITE(18,44)z(13),(A13(I),I=12,NR)
      WRITE(18,44)z(14),(A14(I),I=12,NR)
      WRITE(18,44)z(15),(A15(I),I=12,NR)
      WRITE(18,44)z(16),(A16(I),I=12,NR)
      WRITE(18,44)z(17),(A17(I),I=12,NR)
      WRITE(18,44)z(18),(A18(I),I=12,NR)
      WRITE(18,44)z(19),(A19(I),I=12,NR)
      WRITE(18,44)z(20),(A20(I),I=12,NR)
      WRITE(18,44)z(21),(A21(I),I=12,NR)
      WRITE(18,44)z(22),(A22(I),I=12,NR)
      WRITE(18,44)z(23),(A23(I),I=12,NR)
      WRITE(18,44)z(24),(A24(I),I=12,NR)
      WRITE(18,44)z(25),(A25(I),I=12,NR)
      WRITE(18,44)z(26),(A26(I),I=12,NR)
      WRITE(18,44)z(27),(A27(I),I=12,NR)
      WRITE(18,44)z(28),(A28(I),I=12,NR)
      WRITE(18,44)z(29),(A29(I),I=12,NR)
      WRITE(18,44)z(30),(A30(I),I=12,NR)
      WRITE(18,44)z(31),(A31(I),I=12,NR)
      WRITE(18,44)z(32),(A32(I),I=12,NR)
      WRITE(18,44)z(33),(A33(I),I=12,NR)
C      WRITE(18,44)z(34),(A34(I),I=12,NR)
C      WRITE(18,44)z(35),(A35(I),I=12,NR)
C      WRITE(18,44)z(36),(A36(I),I=12,NR)
      STOP
      END
```

Appendix B: Sample Fortran Program for Heating Case

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C FOR THE SOLAR EXPERIMENT 10 LPM 1P 1HR AT TIME 12.30          C
C THIS PROGRAM WILL CALCULATE THE HEATING PERFORMANCE           C
C QS,THE ENERGY STORED IN THE TANK DURING THE HEATING PERIOD    C
C NR, THE NUMBER OF ROWS RECORDED DATA                          C
C NC,THE NUMBER OF COLUMNS OF RECORDED DATA                     C
C NT , THE NUMBER OF THERMOCOUPLES                              C
C TIN, MINIMUM TEMPERATURE IN THE TANK                          C
C TMAX, MAXIMUM TEMPERATURE IN THE TANK                         C
C TIMED, TIME SPENT TO HEAT THE WATER TO THE REQUIRED           C
C       TEMPERATURE                                             C
C Z, THE HEIGHT OF THE CONTROL VOLUME                           C
C CV,THE CONTROL                                                C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      PARAMETER (NR=8,NT=33,NC=42)
      REAL
a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12,a13,a14,a15,a16,
     * a17,a18,a19,a20,a21,a22,a23,a24,a25,a26,a27,a28,a29,a30,
     * a31,a32,a33,a34,a35,a36,a37,a38,a39,a40,a41
      INTEGER time
      DIMENSION a1(NC),a2(NC),a3(NC),a4(NC),a5(NC),a6(NC),a7(NC),

*a8(NC),a9(NC),a10(NC),a11(NC),a12(NC),a13(NC),a14(NC),a15(NC),

*a16(NC),a17(NC),a18(NC),a19(NC),a20(NC),a21(NC),a22(NC),a23(NC),

*a24(NC),a25(NC),a26(NC),a27(NC),a28(NC),a29(NC),a30(NC),a31(NC),

*a32(NC),a33(NC),a34(NC),a35(NC),a36(NC),a37(NC),a38(NC),a39(NC),
     *a40(NC),a41(NC),TIME(NC),T(NC),Z(NC),TS(NC),TIM(NC),
     *X(NC),CV(NC),CVOL(NC),XC(NC)
C
      OPEN(5,FILE='heat1230.txt')
      OPEN(8,FILE='HEAT-PRO')
      OPEN(9,FILE='HEAT-STORAGE')
      OPEN(10,FILE='HEAT-TEMP')
      OPEN(11,FILE='HEATING energystore')
      OPEN(12,FILE='HEATING DATAREAD')
      OPEN(19,FILE='heatCONT VOL')
C
C
      DO  j=1,NC
      READ(5,*)time(j),a1(j),a2(j),a3(j),a4(j),a5(j),a6(j),a7(j),

*a8(j),a9(j),a10(j),a11(j),a12(j),a13(j),a14(j),a15(j),a16(j),

*a17(j),a18(j),a19(j),a20(j),a21(j),a22(j),a23(j),a24(j),a25(j),

*a26(j),a27(j),a28(j),a29(j),a30(j),a31(j),a32(j),a33(j),a34(j),
     *a35(j),a36(j),a37(j),a38(j),a39(j),a40(j),a41(j)
C
PRINT*,j,time(j),a1(j),a2(j),a3(j),a4(j),a5(j),a6(j),a7(j),
C
*a8(j),a9(j),a10(j),a11(j),a12(j),a13(j),a14(j),a15(j),a16(j),
C
*a17(j),a18(j),a19(j),a20(j),a21(j),a22(j),a23(j),a24(j),a25(j),
```

```
C
*a26(j),a27(j),a28(j),a29(j),a30(j),a31(j),a32(j),a33(j),a34(j),
C      *a35(j),a36(j),a37(j),a38(j),a39(j),a40(j),a41(j)
      END DO
C
      DO  j=1,NC

WRITE(12,*)time(j),a1(j),a2(j),a3(j),a4(j),a5(j),a6(j),a7(j),

*a8(j),a9(j),a10(j),a11(j),a12(j),a13(j),a14(j),a15(j),a16(j),

*a17(j),a18(j),a19(j),a20(j),a21(j),a22(j),a23(j),a24(j),a25(j),

*a26(j),a27(j),a28(j),a29(j),a30(j),a31(j),a32(j),a33(j),a34(j),
     *a35(j),a36(j),a37(j),a38(j),a39(j),a40(j),a41(j)
      END DO
C
      TIN=31.10          !MIN. TEMP. IN TANK
      TMAX=49.10         !MAX. TEMP. IN TANK
      TIMED=12600         !TIME IN SECONDS TO HEAT THE TANK
      T2MT1=1/(TMAX-TIN)
C
      N=NR
      T(1)=A1(N)
      T(2)=A2(N)
      T(3)=A3(N)
      T(4)=A4(N)
      T(5)=A5(N)
      T(6)=A6(N)
      T(7)=A7(N)
      T(8)=A8(N)
      T(9)=A9(N)
      T(10)=A10(N)
      T(11)=A11(N)
      T(12)=A12(N)
      T(13)=A13(N)
      T(14)=A14(N)
      T(15)=A15(N)
      T(16)=A16(N)
      T(17)=A17(N)
      T(18)=A18(N)
      T(19)=A19(N)
      T(20)=A20(N)
      T(21)=A21(N)
      T(22)=A22(N)
      T(23)=A23(N)
      T(24)=A24(N)
      T(25)=A25(N)
      T(26)=A26(N)
      T(27)=A27(N)
      T(28)=A28(N)
      T(29)=A29(N)
      T(30)=A30(N)
      T(31)=A31(N)
      T(32)=A32(N)
      T(33)=A33(N)
      T(34)=A34(N)
      T(35)=A35(N)
```

```
      T(36)=A36(N)
      T(37)=A37(N)
      T(38)=A38(N)
      T(39)=A39(N)
      T(40)=A40(N)
      T(41)=A41(N)
C      T(42)=A42(N)
C   DIMENSIONLESS HIGHT OF THE TANK
      H=0.700
      HEL=H/NT
      SUM=0.0
      ONEOH=1.0/H
      DO j=1,NT
      SUM=SUM+HEL
      z(j)=sum
      Z(j)=Z(j)*ONEOH
      END DO
C
C DIMENSIONLESS TEMP. TS=TEMP OF STORE
C
      DO j=1,NT
      TS(j)=(T(j)-TIN)*T2MT1
      END DO
C----WRITING THE ABOVE DATA IN A FILE HEAT-STORAGE
C  dimensionless time  t^* versus dimensionless temperature theta
C
      DO i=1,NT
      WRITE(9,121)TS(i),Z(i)
      END DO
 121  FORMAT(36(F8.3,2X,F8.3))
C
C CALCULATE OF ENERGY STORE
C
C  THE CONTROL VOLUME ,CV, CALCULATION
      CP=4.182
      summ=0.0
      CVO=0.0
      cvh=0.0
      HE=0.7/NT   !ELEMENT HEIGHT
      W=0.5      !ELEMENT WIDTH
      DO j=1,NT
      summ=summ+HE
      x(j)=0.730-summ
      CV(j)=0.5*W*HE*(2*x(j)+HE)
      cvo=cvo+CV(j)
      CVOL(j)=CVO
      END DO
C  WRITE THE HEIGHT AND CONT VOL DATA INTO HEATCONT VOL DATA FILE
       DO j=1,NT
       WRITE(19,*)J,X(j),CV(j),cvol(j)
       END DO
C
C      print*,'j','T(j)','DEN','TIN'
      SUM=0.0
      DO j=1,NT
      DEN=1000.83-0.0723359*T(j)-0.00361826*T(j)*T(j)
      SUM=SUM+DEN*CP*CV(j)*ABS(T(J)-TIN)
C      print*,j,T(j),DEN,TIN
```

```
      END DO
      QS=SUM
C
C
      WRITE(11,16)QS
  16  FORMAT('QST=',F10.2)
C
C DIMENSIONLESS TEMP. IN THE TANK
      DO J=1,NT
      A1(j)=ABS(A1(j)-TIN)*T2MT1
      A2(j)=ABS(A2(j)-TIN)*T2MT1
      A3(j)=ABS(A3(j)-TIN)*T2MT1
      A4(j)=ABS(A4(j)-TIN)*T2MT1
      A5(j)=ABS(A5(j)-TIN)*T2MT1
      A6(j)=ABS(A6(j)-TIN)*T2MT1
      A7(j)=ABS(A7(j)-TIN)*T2MT1
      A8(j)=ABS(A8(j)-TIN)*T2MT1
      A9(j)=ABS(A9(j)-TIN)*T2MT1
      A10(j)=ABS(A10(j)-TIN)*T2MT1
      A11(j)=ABS(A11(j)-TIN)*T2MT1
      A12(j)=ABS(A12(j)-TIN)*T2MT1
      A13(j)=ABS(A13(j)-TIN)*T2MT1
      A14(j)=ABS(A14(j)-TIN)*T2MT1
      A15(j)=ABS(A15(j)-TIN)*T2MT1
      A16(j)=ABS(A16(j)-TIN)*T2MT1
      A17(j)=ABS(A17(j)-TIN)*T2MT1
      A18(j)=ABS(A18(j)-TIN)*T2MT1
      A19(j)=ABS(A19(j)-TIN)*T2MT1
      A20(j)=ABS(A20(j)-TIN)*T2MT1
      A21(j)=ABS(A21(j)-TIN)*T2MT1
      A22(j)=ABS(A22(j)-TIN)*T2MT1
      A23(j)=ABS(A23(j)-TIN)*T2MT1
      A24(j)=ABS(A24(j)-TIN)*T2MT1
      A25(j)=ABS(A25(j)-TIN)*T2MT1
      A26(j)=ABS(A26(j)-TIN)*T2MT1
      A27(j)=ABS(A27(j)-TIN)*T2MT1
      A28(j)=ABS(A28(j)-TIN)*T2MT1
      A29(j)=ABS(A29(j)-TIN)*T2MT1
      A30(j)=ABS(A30(j)-TIN)*T2MT1
      A31(j)=ABS(A31(j)-TIN)*T2MT1
      A32(j)=ABS(A32(j)-TIN)*T2MT1
      A33(j)=ABS(A33(j)-TIN)*T2MT1
C      A34(j)=ABS(A34(j)-TIN)*T2MT1
C      A35(j)=ABS(A35(j)-TIN)*T2MT1
C      A36(j)=ABS(A36(j)-TIN)*T2MT1
      END DO
C
C----write the above into the file heat-tp
C
      ONEOTD=1/TIMED
      DO j=1,NT
      TIM(j)=time(j)*ONEOTD

WRITE(10,20)TIM(j),a1(j),a2(j),a3(j),a4(j),a5(j),a6(j),a7(j),

*a8(j),a9(j),a10(j),a11(j),a12(j),a13(j),a14(j),a15(j),a16(j),

*a17(j),a18(j),a19(j),a20(j),a21(j),a22(j),a23(j),a24(j),a25(j),
```

```
     *a26(j),a27(j),a28(j),a29(j),a30(j),a31(j),a32(j),a33(j)
      END DO
 20   FORMAT(33(F6.3,2X))
C
  44   FORMAT(F6.3,1X,400(F6.3,1X))
C
C     WRITE THE ABOVE DATA INTO FILE  HEATPRO
C
      WRITE(8,44)Z(1),(A1(i),i=1,NT)
      WRITE(8,44)Z(2),(A2(i),i=1,NT)
      WRITE(8,44)Z(3),(A3(i),i=1,NT)
      WRITE(8,44)Z(4),(A4(i),i=1,NT)
      WRITE(8,44)Z(5),(A5(i),i=1,NT)
      WRITE(8,44)Z(6),(A6(i),i=1,NT)
      WRITE(8,44)Z(7),(A7(i),i=1,NT)
      WRITE(8,44)Z(8),(A8(i),i=1,NT)
      WRITE(8,44)Z(9),(A9(i),i=1,NT)
      WRITE(8,44)Z(10),(A10(i),i=1,NT)
      WRITE(8,44)Z(11),(A11(i),i=1,NT)
      WRITE(8,44)Z(12),(A12(i),i=1,NT)
      WRITE(8,44)Z(13),(A13(i),i=1,NT)
      WRITE(8,44)Z(14),(A14(i),i=1,NT)
      WRITE(8,44)Z(15),(A15(i),i=1,NT)
      WRITE(8,44)Z(16),(A16(i),i=1,NT)
      WRITE(8,44)Z(17),(A17(i),i=1,NT)
      WRITE(8,44)Z(18),(A18(i),i=1,NT)
      WRITE(8,44)Z(19),(A19(i),i=1,NT)
      WRITE(8,44)Z(20),(A20(i),i=1,NT)
      WRITE(8,44)Z(21),(A21(i),i=1,NT)
      WRITE(8,44)Z(22),(A22(i),i=1,NT)
      WRITE(8,44)Z(23),(A23(i),i=1,NT)
      WRITE(8,44)Z(24),(A24(i),i=1,NT)
      WRITE(8,44)Z(25),(A25(i),i=1,NT)
      WRITE(8,44)Z(26),(A26(i),i=1,NT)
      WRITE(8,44)Z(27),(A27(i),i=1,NT)
      WRITE(8,44)Z(28),(A28(i),i=1,NT)
      WRITE(8,44)Z(29),(A29(i),i=1,NT)
      WRITE(8,44)Z(30),(A30(i),i=1,NT)
      WRITE(8,44)Z(31),(A31(i),i=1,NT)
      WRITE(8,44)Z(32),(A32(i),i=1,NT)
      WRITE(8,44)Z(33),(A33(i),i=1,NT)
C      WRITE(8,44)Z(34),(A34(i),i=1,NT)
C      WRITE(8,44)Z(35),(A35(i),i=1,NT)
C      WRITE(8,44)Z(36),(A36(i),i=1,NT)
C
      STOP
      END
```

Appendix C: Sample Data File for Discharge Case

```
0       34.60 35.80 36.30 36.70 37.30 38.10 38.30 39.30 38.50 39.00
        39.20 40.20 40.80 41.10 42.30 42.40 42.70 42.90 44.30 43.90
        45.10 45.20 45.80 46.60 46.20 47.20 48.20 48.10 48.60 48.80
        49.20 49.90 47.40 39.00 39.60 39.70 46.40 46.20 45.70 39.43
        46.10
0       34.90 36.20 36.20 36.90 37.70 37.90 38.50 38.90 38.40 38.90
        39.10 40.20 40.40 41.50 42.00 42.70 42.70 43.40 43.80 44.40
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250 36.00 36.60 36.90 36.50 36.80 37.10 37.10 36.80 36.40 36.40
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265 36.40 36.50 37.00 36.70 36.40 37.20 37.30 37.20 36.60 36.40
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37.00 36.50 36.60 37.20 36.90 37.10 37.20 37.50 40.10 40.30
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43.03
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42.90
310 36.20 36.10 36.90 36.80 37.10 37.20 36.90 36.90 36.80 36.10
36.30 36.80 36.60 36.40 37.00 36.80 36.90 37.30 39.40 39.60
40.80 41.00 40.80 41.30 41.10 42.10 42.30 42.90 41.70 42.80
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42.83
315 36.50 36.60 36.90 37.10 36.70 36.80 37.00 37.10 36.20 36.20
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40.80 41.00 41.00 41.00 41.00 41.70 42.10 42.80 41.60 42.50
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325 36.10 36.70 37.00 36.90 36.70 36.40 36.90 37.10 36.70 36.60
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36.70 37.00 36.90 37.10 36.80 37.00 36.80 36.60 36.80 39.60
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42.50 42.10 42.40 36.60 36.50 36.10 42.60 42.80 42.20 36.40
42.53
335 36.70 36.90 36.40 36.70 36.40 37.10 36.90 37.20 37.00 36.80
36.70 36.60 36.80 36.80 36.80 36.80 36.50 36.80 36.90 38.80
40.90 40.30 40.60 40.40 40.70 41.50 42.20 42.70 42.30 42.00
42.20 42.80 41.80 36.80 36.60 37.10 42.60 42.00 42.20 36.83
42.27

340	36.40	37.00	36.80	37.20	36.70	36.80	37.00	37.10	36.70	36.60
	36.30	37.10	36.80	36.90	36.70	37.00	37.00	37.20	36.80	37.60
	40.00	40.50	40.40	40.60	40.90	41.30	41.90	42.00	41.70	41.60
	42.00	42.40	41.80	36.30	37.10	36.90	42.30	42.30	42.10	36.77
	42.23									
345	36.40	36.40	36.80	36.90	36.80	37.00	37.20	37.00	36.40	36.60
	36.90	37.20	36.80	37.20	36.90	37.10	36.50	37.00	36.40	38.90
	40.10	39.70	40.60	40.50	41.00	41.60	41.70	41.90	41.50	42.10
	42.20	41.90	41.90	36.30	37.10	36.70	42.30	42.20	42.10	36.70
	42.20									
350	36.60	37.00	36.70	36.70	36.70	36.80	37.00	37.10	36.40	36.40
	36.70	36.90	36.80	36.50	37.10	37.00	36.60	36.90	36.80	38.80
	40.10	40.40	40.30	40.70	40.70	41.30	41.60	42.20	41.60	42.10
	42.20	42.20	41.60	36.80	36.60	36.40	42.10	42.10	42.10	36.60
	42.10									
355	36.30	36.30	36.90	36.70	36.50	36.70	36.90	37.30	36.40	36.30
	36.40	36.80	36.70	37.20	36.70	36.80	36.40	37.10	36.50	37.30
	39.50	40.10	40.70	40.10	40.50	41.30	41.60	41.50	41.00	41.90
	42.70	42.20	41.80	36.70	36.90	36.50	42.00	41.90	42.40	36.70
	42.10									
360	36.30	36.70	36.80	37.00	36.80	37.00	37.00	37.10	36.40	36.30
	36.40	36.20	36.60	36.80	37.20	36.60	37.10	37.00	36.70	37.60
	40.10	40.40	40.50	40.00	40.40	41.30	42.00	41.90	41.60	41.70
	42.60	42.20	41.90	36.60	36.90	37.00	41.90	41.60	41.80	36.83
	41.77									
365	35.90	36.50	36.40	36.60	36.70	36.70	37.00	36.70	36.50	36.50
	36.30	36.70	36.50	37.00	37.00	36.70	36.60	36.90	36.80	38.00
	39.50	39.50	40.30	40.30	40.30	41.40	41.40	42.00	41.60	41.70
	42.00	42.00	41.80	36.60	36.40	36.80	41.50	42.10	41.80	36.60
	41.80									
370	36.60	36.80	36.50	36.80	36.70	36.70	36.80	37.00	36.60	36.60
	36.80	36.50	36.90	36.60	36.90	36.80	36.70	36.60	36.50	37.70
	39.20	40.10	40.00	40.10	40.70	41.20	41.60	42.00	41.30	41.60
	41.80	41.90	42.00	36.80	37.00	37.10	41.80	41.60	41.90	36.97
	41.77									
375	36.30	36.80	36.90	36.80	36.90	36.70	36.90	37.40	36.30	36.60
	36.80	36.70	36.40	37.00	36.90	36.70	36.60	36.70	36.70	37.00
	38.90	40.00	40.10	40.70	40.10	40.70	41.10	41.80	41.50	41.80
	41.80	42.20	41.50	36.40	36.80	36.90	41.90	41.80	41.60	36.70
	41.77									
380	36.50	36.50	36.70	36.90	36.70	36.50	37.10	37.20	36.80	36.20
	36.80	36.50	36.40	36.70	36.70	36.90	36.60	36.30	36.50	36.80
	38.60	39.60	40.00	39.80	40.00	41.20	41.50	42.10	41.50	41.70
	42.00	41.50	41.20	36.40	36.90	36.70	41.50	41.70	41.60	36.67
	41.60									
385	36.90	36.70	36.60	36.70	37.10	36.90	37.10	37.00	36.80	36.50
	36.30	36.50	36.70	36.80	36.70	36.50	37.00	36.70	36.70	37.40
	38.50	39.20	39.80	40.40	40.20	41.30	41.60	41.90	41.10	41.70
	42.00	42.30	41.30	36.80	37.20	36.80	41.20	41.30	41.20	36.93
	41.23									
390	36.30	36.70	36.90	37.50	36.60	36.60	37.00	37.00	36.60	36.50
	36.40	37.10	36.60	37.00	36.70	36.90	36.60	37.00	36.80	37.00
	38.50	39.00	39.90	39.70	39.90	41.10	41.50	41.60	41.20	41.20
	41.80	41.80	41.20	36.70	36.90	36.80	41.40	41.40	41.00	36.80
	41.27									
395	36.80	36.30	37.00	37.10	36.70	36.90	36.90	37.10	36.70	36.30
	36.70	36.80	36.80	36.40	37.00	36.60	36.60	36.60	36.60	37.10
	37.80	38.80	39.80	39.80	39.90	40.70	41.00	41.10	41.10	41.30

42.00 41.40 41.30 36.50 36.90 36.70 40.80 41.30 41.30 36.70
41.13
400 36.40 37.40 36.70 36.80 36.80 37.10 37.00 36.90 36.40 36.40
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38.00 38.50 39.40 39.80 39.80 40.60 40.80 41.10 41.20 41.20
41.70 41.20 41.40 36.60 36.90 37.00 41.00 40.90 41.20 36.83
41.03
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41.40 41.80 41.30 36.30 36.40 37.10 40.90 41.20 40.70 36.60
40.93
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37.00 36.10 36.40 37.00 37.20 36.70 36.60 36.70 36.70 36.70
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41.50 41.70 41.00 36.20 36.50 37.30 40.90 41.20 40.80 36.67
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415 36.30 36.70 37.00 37.10 37.10 37.00 37.00 36.90 36.50 37.10
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41.80 41.60 40.90 36.80 36.30 37.00 40.80 41.20 40.80 36.70
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420 36.10 36.50 37.10 37.40 36.60 37.20 37.20 37.10 36.60 37.10
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37.70 37.20 39.10 39.70 39.10 40.90 41.00 41.40 40.90 41.30
41.50 41.20 41.00 37.10 36.90 36.70 40.40 40.70 40.50 36.90
40.53
425 36.30 36.70 36.70 36.90 36.90 36.70 37.10 37.10 36.50 36.90
37.00 36.60 37.10 36.70 36.70 36.70 36.60 36.70 36.30 36.90
37.50 36.80 38.70 39.50 39.70 40.40 41.00 41.10 40.80 41.20
41.60 41.10 40.60 36.80 36.80 36.70 40.60 40.50 40.90 36.77
40.67
430 36.70 36.50 36.70 36.80 36.70 37.00 37.30 37.40 36.50 36.10
36.60 36.40 36.60 36.70 36.80 36.60 36.50 36.80 36.30 36.60
37.00 37.40 38.30 39.10 39.50 40.20 40.90 41.40 41.20 41.10
41.40 41.70 40.50 36.90 37.10 37.00 39.80 40.50 40.50 37.00
40.27
435 36.50 36.40 36.60 36.60 36.80 36.50 36.90 37.30 37.10 36.70
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40.60 41.20 40.40 36.70 36.50 36.60 40.40 40.30 40.80 36.60
40.50
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41.70 41.40 40.70 36.50 37.00 36.50 40.50 40.30 40.60 36.67
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40.13

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40.80 41.00 40.90 36.70 36.80 37.10 39.90 40.10 40.40 36.87
40.13

460 36.20 36.80 36.90 37.40 36.90 36.50 36.90 37.20 37.10 36.60
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40.23

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40.30

470 36.20 36.30 36.60 36.90 36.80 37.00 36.90 37.10 36.80 36.40
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37.00 36.70 37.10 38.50 39.60 40.40 40.30 41.00 40.20 41.00
41.20 40.80 39.90 36.60 36.80 36.60 40.10 40.20 40.50 36.67
40.27

Appendix D: Sample Data File for Heating Case

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0       31.20 31.20 34.60 31.60 30.00 30.30 31.70 31.20 30.30 31.30
        30.70 30.30 31.20 30.70 30.30 31.30 31.50 30.80 29.40 31.60
        31.20 32.90 32.60 31.30 34.60 35.40 34.20 35.80 34.30 34.40
        35.00 36.50 35.60 33.50 35.00 33.10 34.20 34.80 35.00 33.87
        34.67
1800    31.30 31.50 34.10 31.00 31.60 31.70 31.40 31.00 31.90 31.70
        31.10 30.70 32.10 31.50 32.30 32.80 32.00 32.20 31.00 33.20
        32.70 32.30 32.90 34.10 34.50 35.20 34.90 35.30 34.80 35.40
        35.90 34.80 35.50 34.70 34.30 34.20 34.00 33.90 34.40 34.40
        34.10
3600    31.20 31.00 34.60 31.90 31.20 32.60 32.30 31.60 31.60 32.00
        32.80 32.20 31.50 33.10 33.20 33.10 32.60 33.70 32.60 33.50
        33.80 34.50 34.00 34.20 36.20 36.90 36.30 37.10 37.80 37.20
        36.80 37.70 37.60 35.00 34.50 35.20 36.10 36.20 35.50 34.90
        35.93
5400    31.00 30.40 33.20 32.40 31.80 31.30 31.50 32.50 33.20 32.50
        31.00 32.10 33.30 34.00 33.40 33.20 33.20 34.50 35.70 34.90
        34.20 34.90 35.40 36.80 39.20 38.30 38.10 38.90 39.70 39.40
        40.30 39.20 39.00 35.20 36.10 36.20 38.30 37.90 38.20 35.83
        38.13
7200    31.90 32.00 33.40 32.90 32.80 32.80 33.40 33.00 33.40 34.00
        34.20 34.10 34.40 35.10 35.60 36.20 35.80 36.00 36.50 37.10
        37.10 37.70 38.10 38.20 40.30 40.30 41.20 41.30 41.20 41.20
        41.50 42.00 41.80 35.70 36.00 36.70 40.10 40.10 39.70 36.13
        39.97
9000    32.50 32.40 34.30 33.50 33.50 34.50 34.30 34.40 34.10 34.00
        34.80 35.30 35.30 35.60 36.20 36.80 36.80 37.00 37.60 38.30
        38.40 38.20 39.40 40.20 41.30 42.00 42.80 43.20 43.90 43.50
        43.40 44.00 43.60 37.00 37.60 37.30 41.50 41.30 40.90 37.30
        41.23
10800 33.10 32.20 35.50 34.00 33.10 35.10 34.90 34.50 35.10 35.50
        34.50 36.80 36.20 36.70 38.30 38.40 37.00 38.90 38.90 39.30
        40.30 40.00 40.70 41.90 43.00 44.30 45.40 43.60 44.80 45.40
        44.70 46.40 45.80 38.30 40.00 39.10 42.30 43.80 42.30 39.13
        42.80
12600 33.20 33.30 35.40 34.20 34.60 35.50 35.50 35.90 35.70 36.20
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        41.10 41.50 42.40 42.70 45.00 45.40 45.90 46.90 46.30 46.60
        47.00 47.20 47.30 40.60 41.90 41.80 44.80 44.70 44.30 41.43
        44.60
14400 35.40 35.70 35.80 36.30 37.10 38.40 38.20 39.20 38.30 39.40
        39.90 40.80 40.50 41.50 42.00 42.70 42.10 43.80 43.20 44.10
        44.40 45.40 45.40 45.80 46.20 47.20 47.80 48.60 48.10 48.60
        48.30 48.50 48.70 39.90 39.50 40.00 45.90 45.80 45.30 39.80
        45.67
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