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Influence of Porous Materials on Growing the Time of Hot Water Supply for the Solar Collector

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Abstract

The energy storage is the detention of energy at one time to utilize the for another time. The aim of this work is to enhance the storing time in a hot water storage tank as long period as possible by filling the tank with a suitable porous media and the best filling level of the packed bed material. This paper deals with the methods of thermal energy storage and its applications in the region of systems of solar water heating along with system of solar air heating and the substances used to preserve that thermal energy professionally. The experiments were conducted for normal household use for a family of five persons using a solar heater consisting of a storage tank of 120 liters and a solar collector of 20 vacuum tubes in addition to a tank for storing porous media with a capacity of 50 liters. The experiments were conducted without using porous media and using different levels of porous media (150, 300, 450 mm). The results showed that an increase in the level of porous media contributes to the supply of hot water at a useful temperature for domestic use (above 20 ^{o}C) throughout the day. Where 256 liters of hot water was consumed in the first experiment, 273 liters in the second experiment, 273 liters in the third experiment, 261 liters in the fourth experiment, and 207 liters in the fifth experiment.

Keywords: Porous media; latent heat storage; thermal energy storage; thermochemical energy storage; organization of PCM; applications of phase change material.

الخلاصة: تخزين الطاقة هو احتجاز الطاقة في وقت معين للاستفادة منها في وقت آخر. الهدف من هذا العمل هو تعزيز وقت التخزين في خزان تخزين الماء الساخن لأطول فترة ممكنة عن طريق ملء الخزان بوسائط مسامية مناسبة وأفضل مستوى تعبئة لمادة الطبقة المعبأة. تتناول هذه الورقة طرق تخزين الطاقة الحرارية وتطبيقاتها في مجال أنظمة تسخين المياه بالطاقة الشمسية ونظام تسخين الهواء الشمسي والمواد المستخدمة للحفاظ على تلك الطاقة الحرارية بشكل احترافي. أجريت التجارب للاستخدام المنزلي العادي لأسرة مكونة من خمسة أفراد باستخدام سخان شمسي مكون من خزان سعة ١٢٠ لترًا ومجمع شمسي مكون من ٢٠ أنبوبًا مفرغًا بالإضافة إلى خزان لتخزين الوسائط المسامية بسعة ٥٠ لترًا. أجريت التجارب بدون استخدام وسائط مسامية وباستخدام مستويات مختلفة من الوسائط المسامية (١٥٠، ٣٠٠، ٤٥٠ ملم). أظهرت النتائج أن زيادة مستوى الوسائط المسامية تساهم في تجهيز الماء الساخن عند درجة حرارة مفيدة للاستخدام المنزلي (فوق ٢٠ درجة مئوية) على مدار اليوم. حيث تم استهلاك ٢٥٦ لتر من الماء الساخن في التجربة الاولى و 273لتر في التجربة الثانية و 273 لتر في التجربة الثالثة و261 لتر في التجربة الرابعة و٢٠٧ لتر في التجربة الخامسة.

1. INTRODUCTION

The solar energy possesses a big influence upon the today's economy. The use of solar energy reduces the consumption of conventional fuels, leading to reduce the emissions**.** In order to limit these emissions, it's necessary going towards the energy improved usage, and increasing the renewables penetrations into the mixture of energy, like the solar energy (SE). The local hot water manufacture is one the highly attractive usage of SE, particularly into residential buildings described via a significant and a consistent requirement of hot water, during all the year [1]. One of the most important applications that used in almost of the world for the solar benefit in the domestic application is a Solar Water Heater (SWH), which is used in many applications, such as for washing, bathing, home central heating, etc. The solar collector and the storage tank as a considered the main parts of the solar thermal system; the first one captures the heat from the solar energy into the working fluid within the collector, whereas the second one being a storage tank (ST), which store an available energy where it is needed to offset a thermal load. Other parts include circulation pumps, piping, mains supply and the load. The circulation pumps system that moves a fluid of heat transfer between collectors as well as ST is available in most of the solar thermal system. A simple diagram of a system of solar heating is depicted in figure (1). Auxiliary heating may be required if the fluid temperature when the fluid leaving the tank is below the temperature set point required by the load.

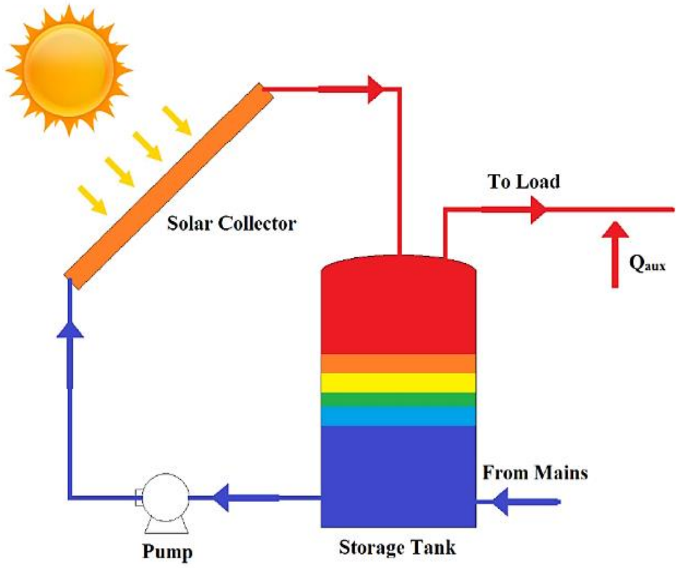

Figure 1 A schematic of the solar thermal system [2].

Numerical simulations of convection heat transfer in porous media are usually founded on two various models for the energy equation, i.e. the local thermal equilibrium, and non-equilibrium model. In latest years, the model of local thermal non-equilibrium has been utilized more regularly in theoretical and numerical study of convection heat transfer in porous media to extra correctly model the convection heat transfer procedures in porous media [3]. Some studies exposed a mathematical model of double duct solar air collector with fins attached to the backside of the heat absorbing plate (solar cell) to augment the transfer of heat to the flowing air for developing the presentation of the hybrid collector [4]. This collector didn't state the potential problematic of irregular distribution of flow in the different riser tubes of the header and riser design, nonetheless serpentine collectors can't work efficiently in thermo siphon mode (natural circulation) and want a pump to mix the transfer of heat of fluid [5]. submitted an experimental evaluation of the addition of the cylindrical encapsulated Paraffin wax to the water storage tank as a Thermal Storage Material. Tests were performed in India on sunny days. A Flat Plate Solar Collector having a (2 m^2) surface area was used by authors for supplying a 47L cylindrical tank with hot water. For storing the latent heat. Four aluminum cylindrical encapsulated Paraffin wax layers having around (60°C) melting temperature were put into the tank. The outputs of discharge demonstrated that the influence of the heat storage of the PCM continued for a period of (100 min). It was inferred that Paraffin wax provided a big improvement in the SWH thermal storage for a long time through a consistent rate of charge and discharge.
[6]. performed several outdoor experiments for investigating the influence of the rate of mass flow of HTS upon the efficiency of a TES water tank (48 L) containing aluminum cylindrical capsules including Paraffin wax having a melting temperature of (60°C). Three various charging HTF rates of volume flow (2, 4, and 6 L/min) were studied, also the outputs manifested that the rise into the rate of flow as well as the inlet temperature caused an increase in stored energy and a decrease in the charging time[7]. Most of the previous research focused on improving the performance of the solar collector or improving the latent thermal storage. In this study, porous media was used to improve the sensible heat storage and thus increase the time of supplying hot water to the solar water heater.

Table 1: Nomenclature

Symbol	Description	Units
T_1	The temperature of the water entering the storage tank	^oC
T_2	The temperature of the water leaving the storage tank	^oC
T_3	The temperature of the water leaving the storage tank	^oC
T_4	Water temperature at the bottom of the storage tank	^oC
T_5	Water temperature under the porous media tank	^oC
T_6	Water temperature at high 150 mm for porous media tank	^oC
T_7	Water temperature at high 300 mm for porous media tank	^oC
T_8	Water temperature at high 450 mm for porous media tank	^oC
Q_{useful}	Hourly useful heat gained from the system	kW
$\dot{m}$	Water mass flow rate	kg/s
C_{pw}	Water specific heat	kJ/kg. K
C_{ppm}	Porous media specific heat	kJ/kg. K
ΔT	Temperature difference	°C
m_s	Mass of water in storage tank	kg
$m_{pm.}$	Mass of porous media	kg
Time	Time of starting time increment	hr
Δt	Time step	hr

Table 2 : Abbreviations

Symbol	Description
SE	solar energy
SWH	Solar Water Heater
ST	Storage Tank
PM	Porous Media
TES	Thermal Energy Storage
LHS	Latent Heat Storage
PCM	Phase Change Material
HTF	Heat Transfer Fluid

2. STORAGE TANK MODES

In the domestic thermal application for a hot water storage tank, there are several modes in the storage tank. They can be classified as a water behavior into the ST depending on the collector as well as the load. When the water being hot flows from collector to tank, the tank can be considered as in a charging mode. Also, when the water being hot is drained from tank to load, it's called a discharging mode. The two mentioned dynamic modes may operate separately once and may operate together in the storage tank. If there is no charge or discharge mode, the tank can be considered as in a static mode state. Figure (2) shows three modes in a simple sketch. The significant and easier way for storing hot water in the tank, as long time as possible, is by thermal insulation.

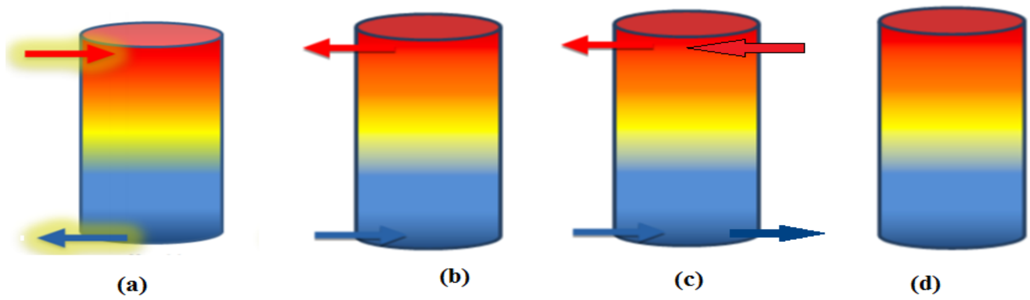

Figure 2 Three model types of solar storage tank from right: (a) The mode of charging (b) The mode of discharging (c) The mode of charging and discharging (d) The mode of standby (static) [5].

3. THE SOLAR ENERGY STORAGE IN WATER TANK SYSTEM

The thermal energy can be kept as variation in the material's internal energy as a latent heat, a sensible heat, or a thermo chemical or a combination of them. The sensible heat storage being owing to material's temperature variation, whereas the latent heat storage being owing to the phase transformation it's either solid-solid, solid-liquid or liquid-gas. Various kinds of the thermal energy storage of solar energy are displayed in the figure (3) [8].

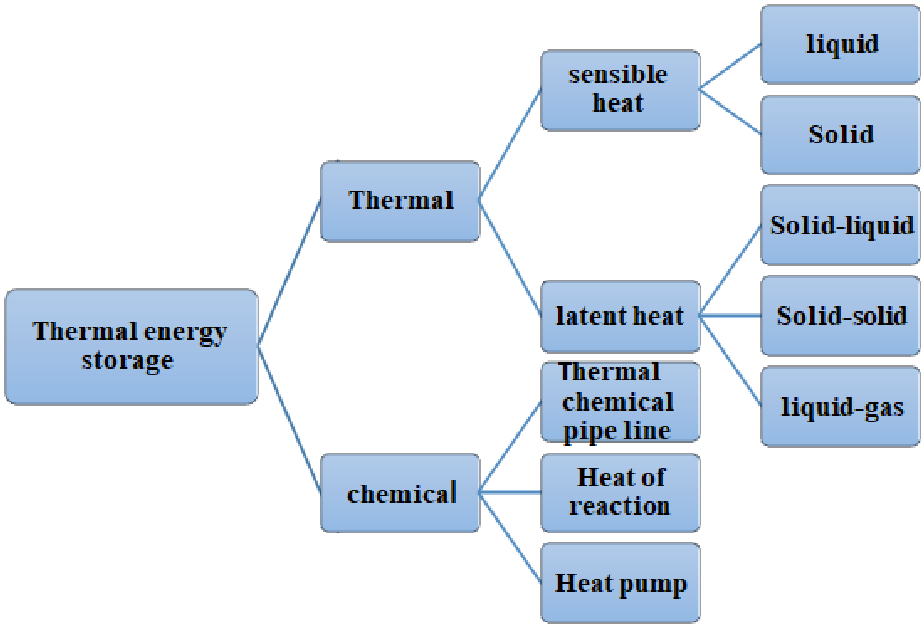

Figure 3 Various kinds of the thermal storage of solar energy [8].

4. LATENT STORAGE MATERIAL

Latent heat storage system (LHS) is gaining much attention due to its ability to store and release heat isothermally. In a typical solid–liquid PCM, heat storage system heat is absorbed by the PCM during charging where it gains its latent heat of melting. During the discharging process, the stored heat is released back to the surrounding (or working fluid) that is at temperature below the freezing point of the PCM material. The energy released during its discharge can be used for applications such as building heating, heat pumps, drying applications in agriculture and industries, and several other applications [9]. Common phase change materials are salt hydrates, metallic, paraffin's and non-paraffin organic materials, and eutectics. The desirable properties of any PCM includes: (1) high latent heat of fusion, (2) high thermal conductivity, (3) moderate melting point, (4) stability at different temperatures, (5) high specific heat, Cp (6) ability to undergo repeated cycles of melting and solidification without significant change in its properties, and (7) non-toxicity and non-flammability [10]. Latent heat of melting dictates on the amount of heat a given mass of PCM can store. Therefore, it is desirable to have a high latent heat of melting to provide high energy storage density. Large latent heat values of PCMs make them an attractive means for thermal energy storage [11]. Successful implementation of LHS is highly dependent on configuration of energy storage device and properties of PCMs such as thermal conductivity, specific volume, heat of fusion etc. Challenges associated with system and PCMs need to be addressed systematically to get high performing LHS systems [12]. Due to their properties, molten salts have become very popular in heat storage systems in recent years. The advantages of molten salts include a wide range of phase transition temperatures; good thermal conductivity; high density of stored heat; no undesired exothermic chemical reaction; good thermal stability at high temperatures; non-toxicity; and low price [13]. Geometric, operational and design parameters should be taken into account in assessing the energy performance of TES latent heat. The energy and exergy performance for latent thermal energy storage with various influence factors including the HTF mass flow rate, HTF inlet temperature, PCM melting temperature and number, additives for PCMs, reference temperature, storage unit dimension, heat exchanger surface enhancement, and sensible heating and sub-cooling [14].

5. EXPERIMENTAL WORK

This part involves the experimental setup, the steps for assembling, installing and testing a solar water heater with a capacity of 120 liters are described with the addition tank full with a porous media have a capacity of 50 liters, which was installed and tested in the home of a family of 5 people in the city of Kut, Iraq (32.5 latitude and 45.82 longitude). The usual home use experiments were performed in addition to the laboratory experiments in the case of using porous media and without porous media, and the results were compared. As shown in figure (4) and (5).

Figure 4 Solar water heater, Porous media tank, Measuring device

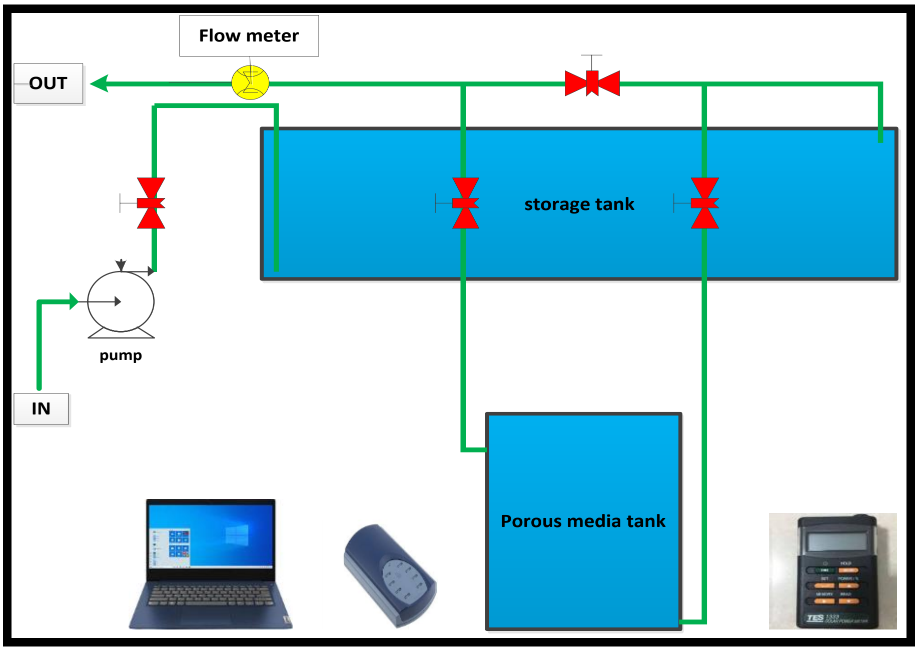

Figure 5 Show the schematic diagram for the experimental rig.

6. MEASURING DEVICES AND EQUIPMENT

In order to measure the temperatures for different points of the system, the amount of water flow, and the intensity of sunlight, in the experimental work, many measuring devices and equipment were used as shown below;

1. Thermocouples: Type K thermocouples were used to measure the temperatures. They were fixed in the plastic pipe by making holes until (1mm) and material was put to prevent leakage (Epo putty two-part type adhesive), and the calibration of these entire thermocouples is shown in Appendix A. There were eight thermocouples, and their distribution was as follows: One of them was used to measure the temperature of the water entering the system, the second to measure the temperature inside the storage tank, the third to measure the temperature of the water coming out of the storage tank, and the fourth to measure the temperature of the water prepared for the load. The rest from the fifth to the eighth were used to measure the temperature distribution inside a porous media tank starting from the base tank. A distance of 150 mm between the measurement point and another was left, as shown in figure (6).

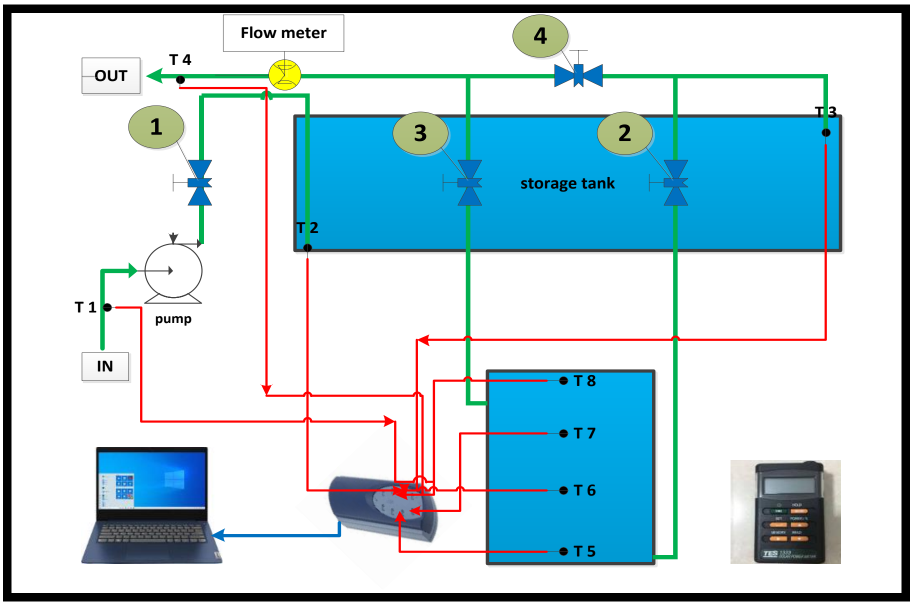

Figure 6 Temperature measurement points.

2. Data logger: (MODEL: PP222 USB TC-08), 8-channels was employed. The data logger was equipped with (PICOLOG 6) Manager Software which can visualize the data in the form of tables and graphs.
3. Solar Power Meter: A light meter type TES (1333) was used to measure the solar irradiation in W/m². Besides dealing with high power (up to 2000W/m²) it also handles a very wide spectrum, from UV (400nm) to IR (1000nm). This sensor is a photovoltaic silicon sensor, which ensures stable and accurate measurements over a long time. and the devices are placed perpendicular to the solar collector to measure the intensity of the solar radiation falling on it.
4. Flow meter: The YF-S201 turbine electronic flow meter was used to measure the flow rate of the water prepared for the load, turbine flow meter is attached to the Arduino, which gives an electrical digital signal. It measures flow rate up to (60L/min) and maximum current (5mA).

7. HABITUAL HOME USE EXPERIMENTS

Experiments of habitual home use were conducted for a family of (5) people

1 - The first experiment was with a solar heater without the additional tank and an entire day during which the readings of temperature, flow rate and solar radiation rate were recorded.

2 - The second experiment was using an additional tank with a solar heater, without using porous materials. The experiment was also carried out during a whole day during which all readings were recorded.

3 - The third experiment was using (150 mm) porous materials for a whole day and all readings were recorded.

4 - The fourth experiment was using (300 mm) porous materials for a whole day and all readings were recorded

5 - The fifth experiment was using (450 mm) porous materials for a whole day and all readings were recorded

6 - The sixth experiment was using (450 mm) porous materials and day (partially cloudy) and all readings were recorded. Thus, the sum of practical experiments is (6) the experience of normal home use.

8. RESULTS AND DISCUSSION (NORMAL HOME USE EXPERIENCES)

Five experiments were conducted for normal domestic use in the house of a family consisting of five persons in the city of Kut. Through it, it can be observed the period of time during which the water is hot at a useful temperature higher than the temperature of the source water, as shown below:

1. Experiment in 30 Jan, 2021 lasted 13 hours and 30 minutes from 8:22 AM to 21:52 PM. This experiment was conducted without the use of a porous media tank, and the temperatures, water flow rate and amount of water used were recorded every ten minutes. Where the temperature of the source water was T_1 at 13.351°C and the temperature of the exit water T_4 at 13.597°C at the beginning of the experiment, then the temperature of the exit water T_4 rose to 21.523 °C at 8:52 AM, which can be considered a useful temperature for domestic use, and the first use of water was at 8:52 AM with temperature of 21.523 °C and flow rate (4 liters / min), and the use of hot water continued at different intervals and flow rates throughout the experiment. It is noted that the highest temperature of the outside water T_4 was 41.65 °C at 12:52 AM. The water was at temperatures useful for domestic use for 10 hours from 8:52 AM to 18:52 PM, when the temperature became 19.871 °C. It should also be noted that the useful amount of water used is 256 liters. As shown in figure (7)
2. Experiment in 31 Jan, 2021 lasted 12 hours and 20 minutes from 9:38 AM to 21:58 PM. In this experiment, the porous media tank was used without placing the porous media in it, which means that it was filled with water only. and the temperatures, water flow rate and amount of water used were recorded every ten minutes. Where the temperature of the source water was T_1 at 14.255°C and the temperature of the exit water T_4 at 22.241°C Water exit temperature from porous media tank T_8 at 24.308 °C at the beginning of the experiment, then the temperature of the exit water T_4 rose to 22.241°C at 9:38 AM, which can be considered a useful temperature for domestic use, and the first use of water was at 9:38 AM with Temperature of 22.241 °C and flow rate (4 liters / min), and the use of hot water continued at different intervals and flow rates throughout the experiment. It is noted that the highest temperature of the outside water T_4 was 46.003 °C at 12:58 AM. The water was at temperatures useful for domestic use for 11 hours and 10 minutes from 9:38 AM to 20:48 PM, when the temperature became 19.43 °C. It should also be noted that the useful amount of water used is 273 liters. As shown in figure (8).
3. Experiment in 1 Feb, 2021 lasted 14 hours and 10 minutes from 8:49 AM to 22:59 PM. Porous media was used in this experiment with a height h = 150 mm. And the temperatures, water flow rate and amount of water used were recorded every ten minutes. Where the temperature of the source water was T_1 at 10.705 °C and the temperature of the exit water T_4 at 17.362 °C Water exit temperature from porous media tank T_8 at 10.878 °C at the beginning of the experiment, then the temperature of the exit water T_4 rose to 21.332 °C at 9:09 AM, which can be considered a useful temperature for domestic use, and the first use of water was at 9:09 AM with Temperature of 21.332 °C and flow rate (4 liters / min), and the use of hot water continued at

different intervals and flow rates throughout the experiment. It is noted that the highest temperature of the outside water T_4 was 45.473 °C at 11:39 AM. The water was at temperatures useful for domestic use for 12 hours and 20 minutes from 9:09 AM to 21:49 PM, when the temperature became 19.261 °C If the periods in which the temperature of the water outside T_4 is less than 20° C. are excluded. It should also be noted that the useful amount of water used is 273 liters. As shown in figure (9)

4. Experiment in 2 Feb, 2021 lasted 12 hours and 40 minutes from 9:38 AM to 22:18 PM. Porous media was used in this experiment with a height h = 300 mm. And the temperatures, water flow rate and amount of water used were recorded every ten minutes. Where the temperature of the source water was T_1 at 14.183 °C and the temperature of the exit water T_4 at 28.567 °C Water exit temperature from porous media tank T_8 at 20.965 °C at the beginning of the experiment, and the first use of water was at 9:58 AM with Temperature of 31.344 °C and flow rate (4 liters / min), and the use of hot water continued at different intervals and flow rates throughout the experiment. It is noted that the highest temperature of the outside water T_4 was 45.722 °C at 12:48 AM. The water was at temperatures useful for domestic use for 11 hours and 50 minutes from 9:58 AM to 22:18 PM, when the temperature became 18.612 °C If the periods in which the temperature of the water outside T_4 is less than 20° C. are excluded. It should also be noted that the useful amount of water used is 261 liters. As shown in figure (10).
5. Experiment in 3 Feb, 2021 lasted 11 hours and 50 minutes from 8:34 AM to 20:24 PM. Porous media was used in this experiment with a height h = 450 mm. And the temperatures, water flow rate and amount of water used were recorded every ten minutes. Where the temperature of the source water was T_1 at 14.725 °C and the temperature of the exit water T_4 at 20.835 °C Water exit temperature from porous media tank T_8 at 15.35 °C at the beginning of the experiment, and the first use of water was at 8:34 AM with Temperature of 20.835 °C and flow rate (5 liters / min), and the use of hot water continued at different intervals and flow rates throughout the experiment. It is noted that the highest temperature of the outside water T_4 was 38.753°C at 12:45 AM. The water was at temperatures useful for domestic use for 11 hours and 50 minutes from 8:34 AM to 20:24 PM, when the temperature became 20.145 °C If the periods in which the temperature of the water outside T_4 is less than 20° C. are excluded. It should also be noted that the useful amount of water used is 207 liters. As shown in figure (11).

9. THE TOTAL EFFICIENCY OF THE SOLAR COLLECTOR

The total efficiency of the collector (η), is simply the ratio of the received heat to the total incoming solar energy [15].

The daily efficiency of the evacuated solar collector system for 150 mm height level of the porous media and flow rate 2 L/min, calculation is:

$$\eta_{daily} = \frac{Q_{usful}}{Q_{solar}} \quad (1)$$

$$Q_{useful} = \left[\dot{m} \times Cp_w \times \left(\frac{\Delta T_{time} + \Delta T_{time+\Delta t}}{2}\right)\right] + \left[\frac{m_{storge} \times Cp_w \times (Ts_{time} - Ts_{time+\Delta t})}{\Delta t \times 3600}\right] + \left[\frac{m_{pm} \times Cp_{pm} \times (Tpm_{time} - Tpm_{time+\Delta t})}{\Delta t \times 3600}\right] + \left[\frac{m_{spm} \times Cp_w \times (Tspm_{time} - Tspm_{time+\Delta t})}{\Delta t \times 3600}\right] \quad (2)$$

$$Q_{solar} = \frac{(I_{time} + I_{time+\Delta t})}{2} \times Ac \quad (3)$$

$$Ac = (\pi \times D_{in_{ev.tube}} \times L_{ev.tube} \times N_{ev.tube})/2 \quad (4)$$

$Ac = \frac{\pi \times 0.037 \times 1.5 \times 20}{2} = 1.744\ m^2$

$Q_{solar} = \frac{(680.3+674.6)}{2} \times 1.744 = 1181.47\ W$

$Q_{useful} = \left[0.0333 \times 4184 \times \left(\frac{(21.781-45.236)+(21.242-26.738)}{2}\right)\right] + \left[\frac{120 \times 4184 \times (45.107-26.631)}{1 \times 3600}\right] + \left[\frac{2500 \times 0.015 \times 837 \times (45.087-45.009)}{1 \times 3600}\right] + \left[\frac{35 \times 4184 \times (45.087-45.009)}{1 \times 3600}\right] = 563.8\ W$

$$\eta_{daily} = \frac{563.8}{1181.47} \times 100\% = 47.7\ \%$$

10. CONCLUSIONS

1. The addition of the porous media tank and the increase in the height of the porous media in it contributes to the supply of hot water useful for domestic uses at a temperature (more than 20 ^{o}C) throughout the day.
2. Although the specific heat capacity of water is 4184 J/kg.℃ and the specific heat capacity of glass is 837 J/kg.℃ it is possible to use the porous medium filled with water for the purpose of perceptible thermal storage for a longer period in order to prepare hot water during the day.
3. Since the thermal conductivity of water is 0.655 W⁄(m℃) and the thermal conductivity of the glass is 0.197 W⁄(m℃), this results in the porous medium retaining heat for a longer time when water passes through it.
4. The results of the daily efficiency of the solar collector showed that it increased with the increase in the level of the porous media and for all flow rates (2, 4, 6 and 8) L/min.

11. FUTURE WORK

1. Studying the effect of placing porous media in the upper half of the storage tank on increasing thermal storage
2. Adding a reflective surface for solar radiation under the tubes of the solar collector to increase the heat energy gained.

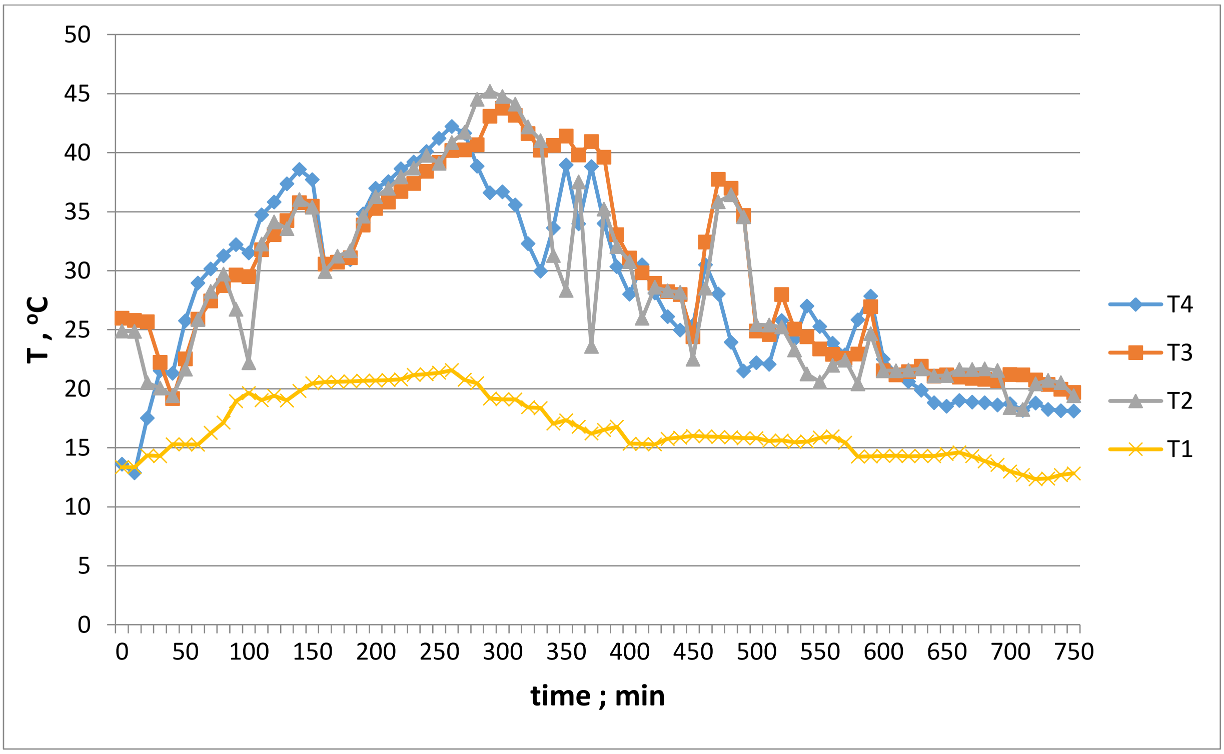

Figure 7 Temperature vs. time of thermal storage system, Regular home use Without porous media

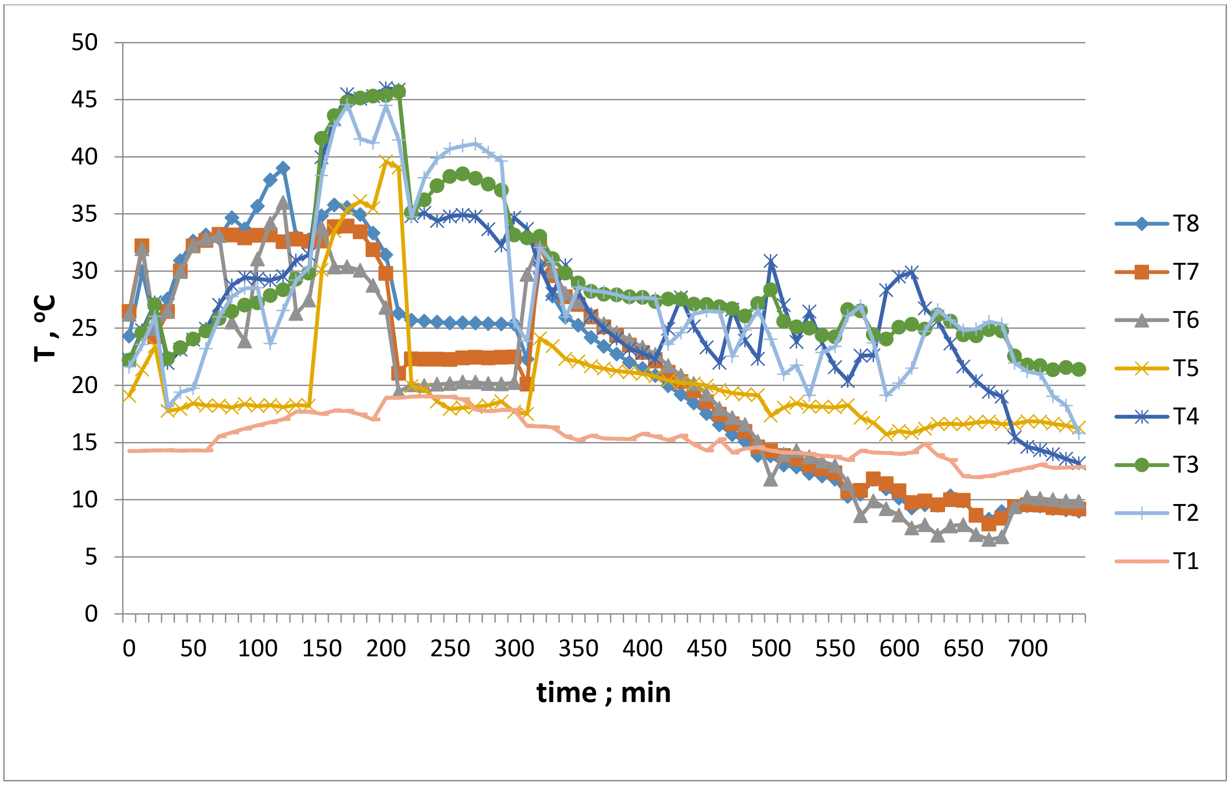

Figure 8 Temperature vs. time of thermal storage system, Regular home use Without porous media, h=0 mm

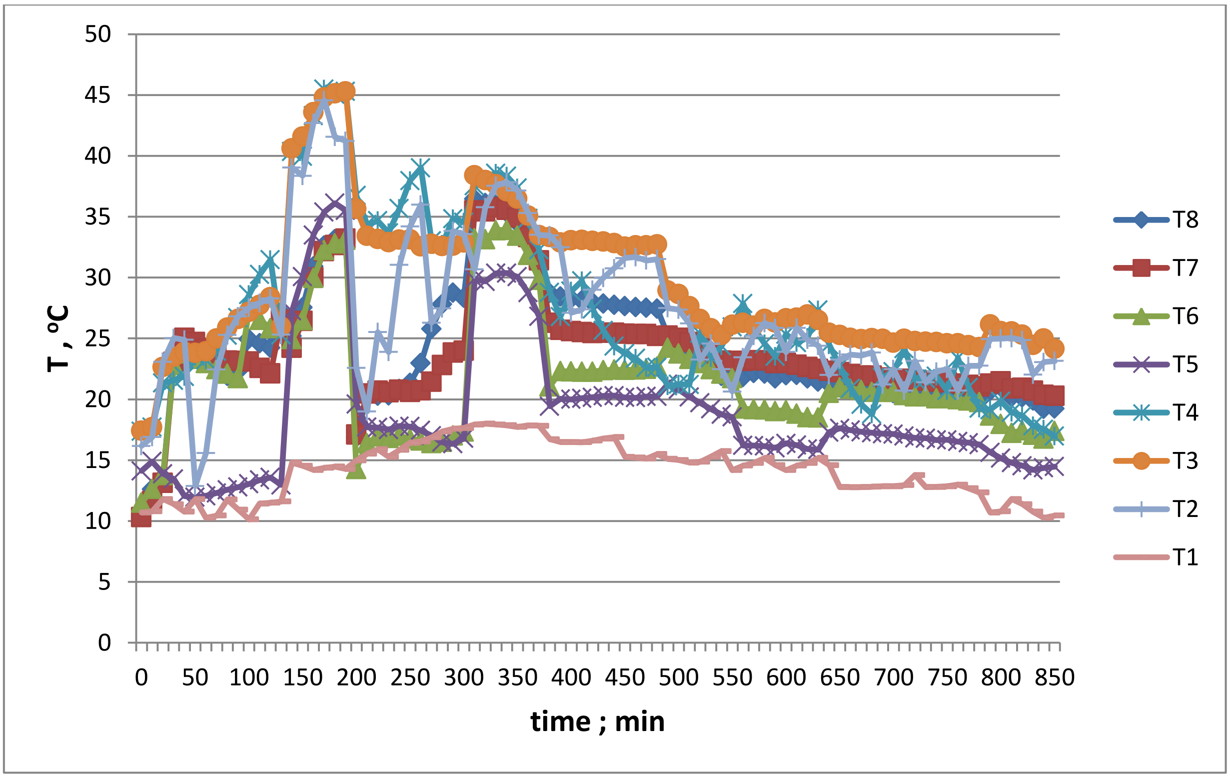

Figure 9 Temperature vs. time of thermal storage system, Regular home use with porous media, h=150 mm

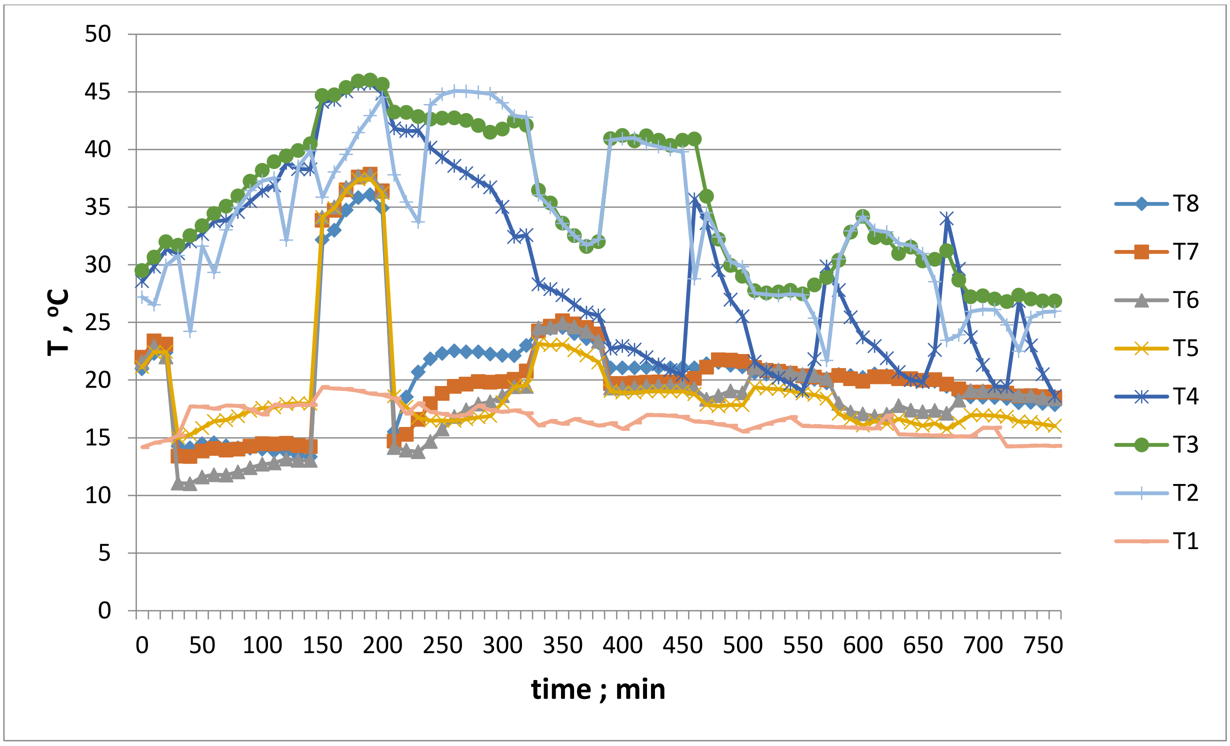

Figure 10 Temperature vs. time of thermal storage system, Regular home use, With porous media, h=300 mm.

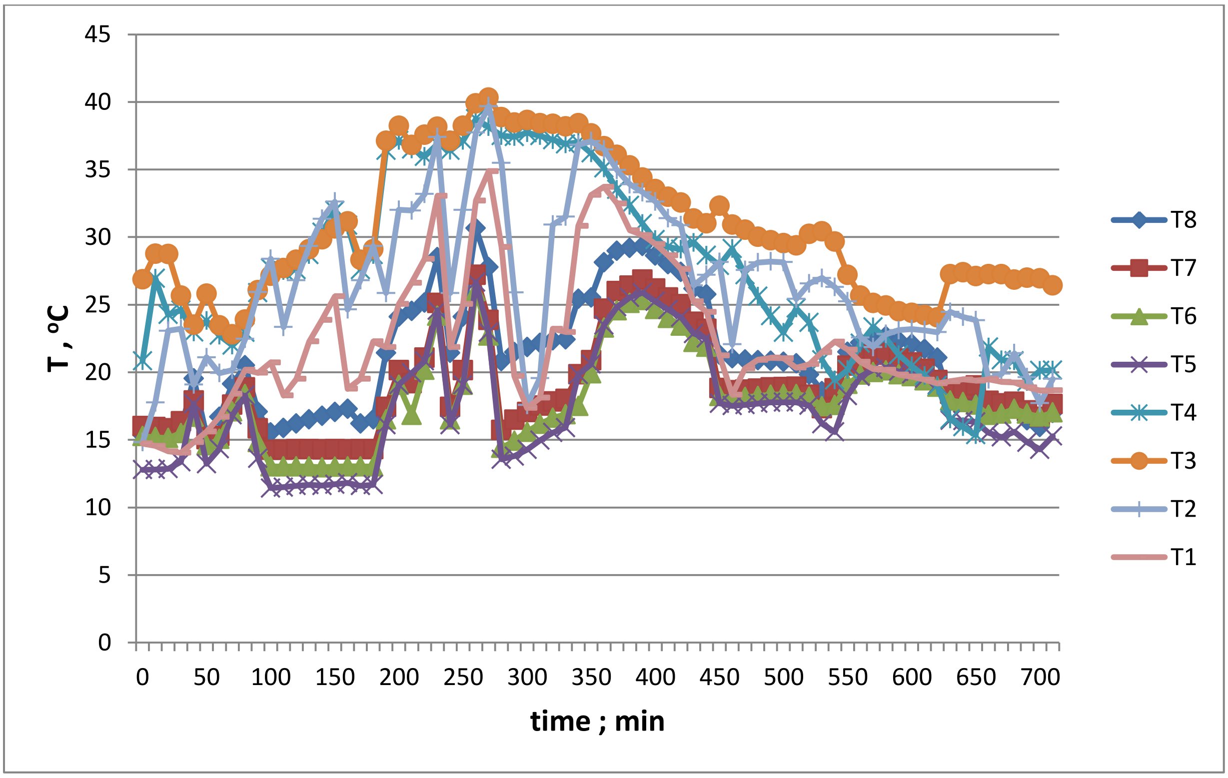

Figure 11 Temperature vs. time of thermal storage system, Regular home use with porous media, h=450

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