PERFORMANCE ANALYSIS OF A COMPACT SOLAR WATER HEATER WITH PARAFFIN WAX STORAGE UNIT

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Abstract: The present work experimentally studies the thermal performance of a solar collector integrated with a thermal storage unit to form a compact solar water heater. The storage capacity is further enhanced by attaching a phase-change storage unit containing phase change material (PCM) which is paraffin wax. The two units (tanks) take the form of two shallow rectangular boxes (compartments) tilted at 45° to the horizon and are firmly attached to ensure complete mutual heat transfer between them. Water and PCM fill the top and bottom tanks respectively. Measurements were carried out from 8 a.m. to 4 p.m. where the temperatures at various locations in the system were measured along with ambient temperature and solar radiation intensity. Results show that the temperature of both compartments increases continuously during the simulated period with the upper tank having the higher temperatures. The PCM average temperature did not reach melting range ($55^oC – 60^oC$) which requires either decreasing the amount of PCM or using a PCM with a lower melting point. The maximum temperatures reached are 82^oC for water and 47^oC for PCM which are measured at 4 p.m. and the maximum overall system efficiency of the system was 74% at 11:30 a.m.

Keywords: *Compact Solar Heater, Solar Collector, Phase-Change Material, Paraffin Wax*

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تحليل اداء سخان ماء شمسي مدمج مزود بوحدة خزن من شمع البارافين

الخلاصة: يتناول البحث الحالي دراسة تجريبية للاداء الحراري لمجمع شمسي من النوع المدمج حيث يتولى المجمع الشمسي مهمة تجميع الطاقة الشمسية وخزنها في نفس الوقت. ولزيادة كفاءة الخزن لهذا المجمع المدمج تم في هذا الدراسة الحاق وحدة خزن كامن متغيرة الطور الى وحدة الخزن المحسوس بالمجمع حاوية على شمع البارافين. تم دمج وحدتي الخزن (المحسوس والكامن) ليشكلا خزانا مستطيلا واحدا قليل العمق ذو حجرتين ويميل عن الافق ٤٥ درجة. تحتوي الحجرة العلوية على الماء لغرض تجميع الطاقة الشمسية وخزنها بشكل محسوس فيما تحتوي الحجرة السفلية على شمع البارافين لغرض الخزن الكامن. تم تسجيل قراءات درجات الحرارة في مواقع مختلفة من المنظومة وللفترة من الساعة الثامنة صباحا وحتى الرابعة عصرا. كما تم قياس شدة الاشعاع الشمسي ودرجة حرارة الجو خلال الفترة اعلاه. اظهرت النتائج ان درجات الحرارة في كلتي الحجرتين تتزايدان بأستمرار خلال فترة التجربة وأن الخزان العلوي ذو درجات الحرارة الاعلى. لوحظ عدم بلوغ متوسط درجة الحرارة للشمع مدى الانصهار (٥٥ – ٦٠ درجة مئوية) مما يتطلب اما تقليل كمية الشمع المستخدمة او استخدام مادة متغيرة الطور ذات درجة انصهار اوطأ. وقد بلغت اعلى درجة حرارة خلال فترة المحاكاة ٨٢ درجة مئوية للخزان العلوي (للماء) و ٤٧ درجة مئوية للخزان السفلي (لشمع البارافين) كما سجلت الكفاءة الحرارية الاجمالية للمنظومة اعلى قيمة لها لتكون ٧٤ بالمائة عند الحادية عشر والنصف صباحا.

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1. Introduction

The use of solar energy to provide hot water is proved to be a feasible way to solve energy shortage problems. A solar hot water system SHWS consists of a solar collector, a storage tank and the connecting pipes. To reduce the cost of the SHWS and increase its efficiency; the solar collector and the storage tank can be merged to be a single unit. In such a case the collection of the solar radiation is carried out directly by the storage medium (water). The system where the collection and the storage units are the same is called compact solar heater or compact solar collector CSC. Compact systems have no connecting pipes or circulation pumps and take smaller space.

In some designs they do not even contain an absorbing metal sheet . To enhance the storage capability of the system whether its compact or not; a phase change material PCM may be integrated with the main storage material (water). PCM stores energy in the form of latent heat of fusion upon melting. The stored energy is released when the PCM re-solidifies.

Melting and solidification processes occur in approximately constant temperature called the melting point. However real phase change processes occur at a range of temperatures around the melting point.

2. Literature Review

The research in compact solar water heaters (CSWH) dates back to the mid seventies of the previous century. The system incorporated only water as a storage medium. Chauhan and Kadambi [1] studied a simple design of a Collector-Cum-Storage system. It included a rectangular storage tank whose upper face acts as the absorber surface to the system. The tank's dimensions was (140*90*5.5 cm) and was placed in a rectangular wooden box allowing an insulation layer of 10 cm of glass wool at the back and lateral sides. The performance was studied experimentally through four modes of operation, namely:- Forced circulation, Natural circulation, Water withdrawal and Continuous flow of cooling water past the absorber plate. The maximum water temperature measured was 86 ^{o}C at 3:30 p.m.

Garg and Rani [2] conducted a theoretical and experimental study on a compact solar heater. The theoretical part of the study included energy balance equations converted to Finite Difference form and solved via computer. The solar radiation and ambient temperature are represented by Fourier Series. The loss of collected energy during night or low insolation periods formed a problem in that system. The energy loss was mitigated through the use of insulation cover and an insulated baffle plate inside the tank adjacent to the absorber plate.

Sokolov and Vaxman [3] studied an integral compact solar water heater where two geometries were taken into account. They deduced that the efficiency of compact systems is larger than that of conventional systems.
The work on the subject continued in the nineties with the work of Kaptan and Kilic [4] who studied a novel built-in-storage solar water heater of 87 Liter capacity. The system comprised 5 pipes (1.8 m * 12 cm) with baffle plate inside each pipe. The theoretical part of the study was carried out indoor through the use of

artificial solar light coming from 27 lamps. A numerical technique via Finite Differences was used to solve energy balance equations. Good agreement was attained between theory and experiments.

Other studies appear later that incorporated integrated solar water heaters which are system without absorber plate. The storage water in these systems receives solar radiation directly after passing the transparent cover. Like the work of Smyth et al. [5], Chaurasia and Twidell [6] and Kumar and Rosen [7].

Some researchers worked on solar heaters equipped with a phase change material (PCM). The focus in research is to find the optimum PCM with minimum disadvantages such as; low thermal conductivity, subcooling and physical and chemical instability.

Bansal and Buddhi [8] studied analytically the performance of a collector cum phase change system. The collector they analyzed combines the working fluid pipes and the phase change material in one unit. So the collection and storage of solar energy is performed simultaneously. Results showed that placing the PCM within the collector unit has definite advantages over a system that has a separate collection and a separate storage unit. Stearic acid was used as a phase change material.

Rabin et al. [9] studied a similar system that incorporates the collection and storage in the same unit. The system consisted of a thermally insulated plastic container containing a layer of stationary heat transfer liquid (SHTL) consisting of an organic oil, floating over a layer of an immiscible salt hydrate PCM which is a eutectic mixture of calcium chloride. A finned heat exchanger located in the SHTL was used to heat cold water during the discharge process. The SHTL was covered with a metal plate coated with a selective absorbing film and with a transparent insulating lid. The paper analyzed the heat transfer process through the SHTL to the PCM, during the charging and discharging processes. The theoretical results were confirmed with measurements from a real system. The possible use of this system is limited to special applications, such as space and soil heating of greenhouses during winter.

Nallusamy et al. [10] conducted an experimental study to evaluate the thermal performance of a packed bed latent heat thermal energy storage unit integrated with a solar flat-plate collector. The storage unit contained paraffin as a phase change material filled in spherical capsules, which were packed in an insulated cylindrical storage tank. Water was used as a heat transfer fluid between the solar collector and storage tank. It also acts as a sensible heat storage material. It was concluded from the experimental results that the packed bed latent heat storage system reduces the size of the storage tank appreciably compared to conventional storage system.

Despite the endeavors of the previous researchers, there are still many aspects not taken into account regarding the optimum design of compact solar heaters and the optimum incorporation of PCM in them.

3. Aim of the Work

The aim of the present work is to study experimentally the thermal performance of a compact solar collector where the collector and the storage unit is the same part. The storage unit is enhanced by a phase change storage unit containing paraffin wax. A test

rig of the compact solar collector is manufactured and tested in real outdoor conditions in order to estimate the efficiency of the simultaneous collection and storage.

4. System Description

The system under consideration consists of a rectangular metal tank made of galvanized steel. The tank is divided into two equal-sized compartments; upper and lower (Fig. 1). The upper compartment faces the incident solar radiation and is filled with water while the other compartment lies directly below the upper one and is filled with PCM (paraffin wax).

The tank is thermally insulated on the back and lateral sides via layers of glass wool of 5 cm thickness. A glass sheet covers the upper side of the tank over a 2 cm air gap. The tank, insulation and glass sheet are all put in an Aluminum encasement tilted 45° to the horizon. Table (1) lists the specifications of the system under consideration.

Water and PCM temperatures are measured at 5 nodes equally spaced along the lateral longer side of each compartment. Each 5 readings are averaged to a single representative mean temperature for the water T_{wm} and PCM T_{pcm}. K-type thermocouples are used to measure temperatures and a thermometer is used to record the ambient temperature.

The solar radiation intensity in W/m^2 is measured via a solar digital meter. The compact collector is fed with water from another replacement tank. The replacement tank compensates any drainage from the compact collector if water is withdrawn from the collector for daily use.
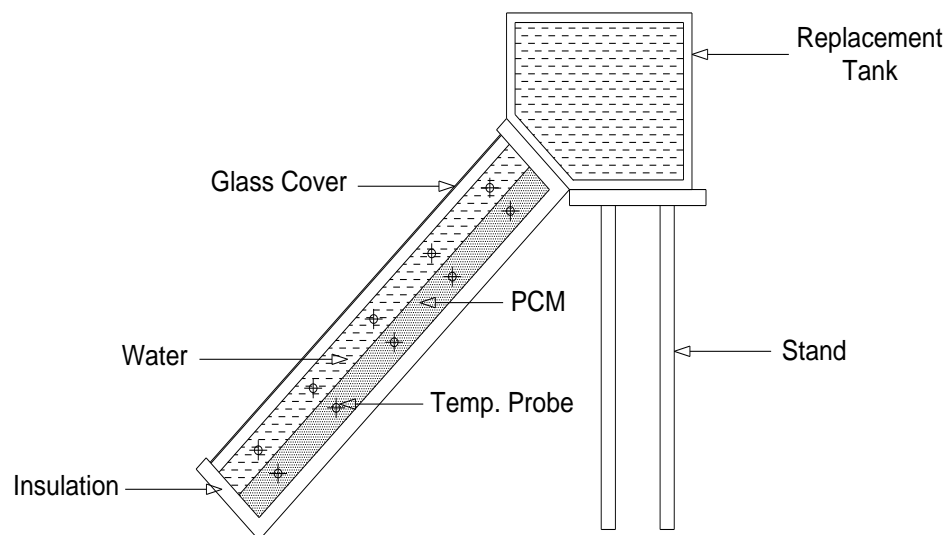

Figure (1): Schematic View of the compact solar water heater.

Table (1): Specifications of the system under consideration.

No.	Item	Dimension	Units
1	Collector Aperture Area	1.05	m^2
2	Water Tank Volume	0.052	m^3
3	Water Tank Dimensions	1.5*0.7*0.05	m
4	PCM Volume	0.052	m^3
5	PCM Melting Point (Paraffin Wax)	58	^{o}C
6	PCM Latent Heat of Fusion	140	kJ/kg
7	Air Gap Depth	4	cm
8	Water Tank Depth	5	cm
9	PCM Tank Depth	5	cm

5. Experimental Procedure

At the start of the experiments the water and PCM compartments are filled with water and paraffin wax respectively. Care should be taken to avoid filling the PCM tank completely. A gap of about 10% of the PCM compartment should be left without PCM because melting causes an expansion of PCM volume which must be taken into account. The system is then mounted to face the south at a tilt angle of 45°C above the horizon. The 10 temperature probes (Thermocouples) are fixed at their respective points (5 for water and 5 for PCM) and connected to a digital reader. The solar radiation meter sensor is put aligned with the collector glass cover to measure the amount of solar radiation intensity (irradiance) falling perpendicular to the solar collector in W/m^2. A separate digital thermometer is used to measure ambient temperature.

Experiments are carried out outdoor for several hours in the selected two days (15 and 16 of March) starting from 8 a.m. till 4 p.m. The period is divided into smaller intervals of 30 minutes. The measured data are recorded at the end of each interval. The measured data include the amount of solar radiation incident on the collector, the ambient temperature and the temperature at ten locations; five for water and five for the PCM. The water mean temperature is calculated as the average of the three readings. Same averaging is done for the PCM.

6. Estimation of System Efficiency

The overall system efficiency can be defined as the ratio of the useful heat stored in both water and PCM compartments to the amount of falling solar radiation over a specified time interval all in kilojoules. The length of time interval is 30 minutes where the efficiency is calculated at the end of the interval using the following equation:-

$$\eta_o = \frac{Q_{SW} + Q_{SPCM} + Q_{LPCM} - Q_{Loss}}{H_T} \qquad (1)$$

Where Q_{SW} and Q_{SPCM} are the sensible heats stored in water and PCM respectively, Q_{LPCM} is the latent heat stored in PCM after melting during 30 minutes and Q_{Loss} is the heat lost to the environment. H_T is the total amount of received solar energy in 30 minutes. So that:

$$Q_{SW} = M_W C_{PW}(T_{start} - T_{end})_W \qquad (2)$$

$$Q_{SPCM} = M_{PCM} C_{PPCM}(T_{start} - T_{end})_{PCM} \qquad (3)$$

$$Q_{LPCM} = \alpha M_{PCM} h_{fu} \qquad (4)$$

$$Q_{Loss} = U_L A_c(T_w - T_a) \qquad (5)$$

h_{fu} is the latent heat of fusion of the PCM (paraffin wax). α is the melting ratio of the PCM. The melting ratio is approximated to be within 5 values corresponding to the 5 temperature readings of the PCM lower compartment. This means that if only one of the thermocouple probes registers a temperature equal or greater than the melting temperature then 20% or 1/5 of the compartment is melted and the melting ratio is taken as 0.2. If all of the 5 probes reach melting point then the melting ratio is considered one.

7. Results and Discussion

The experiments were carried out during two days: 15th and 16th of March. At each day the test period spanned from 8 a.m. to 4 p.m. and was divided into smaller intervals of 15 minutes. At the end of each interval the water temperature (5 locations), the PCM temperature (5 locations), the ambient temperature and the solar radiation intensity (irradiance) were all measured. Fig. 2 and Fig. 3 show the variation of irradiance in the two days under consideration.

The weather was clear in the two days and the irradiance curves take a symmetrical shape around the solar noon. Fig.4 and Fig. 5 show the variation of the averaged water and the averaged PCM temperatures along with ambient temperature during the test period. It can be seen that water temperature had the higher value because water tank directly receives solar radiation and delivers part of it to the PCM tank bellow it. The poor PCM thermal conductivity and its indirect contact with solar radiation made a gap of temperature between water and PCM. The averaged PCM temperature did not reach melting range (55°C – 60°C) however the two top temperature probes of the PCM recorded temperatures in the melting range in the late afternoon indicating the commencement of melting. The close monitoring of the PCM temperatures showed that the melting ratio (liquid volume/total volume) did not exceeded 25% in the two days. This result suggests that in the future studies the PCM volume should be decreased or a PCM with lower melting point is used to ensure complete melting and complete utilization of the latent heat storage.

Fig.6 and Fig.7 show the variation of the overall system efficiency (defined by equation (1)) during the test periods of the two days. It can be seen that the efficiency kept a high value (above 70%) between 10 a.m. and 1 p.m. after which the efficiency steeply declined till the end of test at 4 p.m. This trend is similar to what is known in conventional flat-plate solar collectors, however the decline of efficiency in the second group (flat-plate type) starts earlier (around 10 a.m.). The reason behind this improvement in efficiency is due to the presence of the PCM layer behind the water

tank. The PCM layer works not just as a complementary storage unit, but also as an insulating layer absorbing a considerable amount of heat which would be otherwise lost to the environment. The system with just water would reach higher temperatures causing higher thermal losses. So, the PCM also keeps the system at a relatively lower temperature with higher efficiency. The amount of heat stored in the PCM is included in the calculation of the overall system efficiency which contributes to its high values.
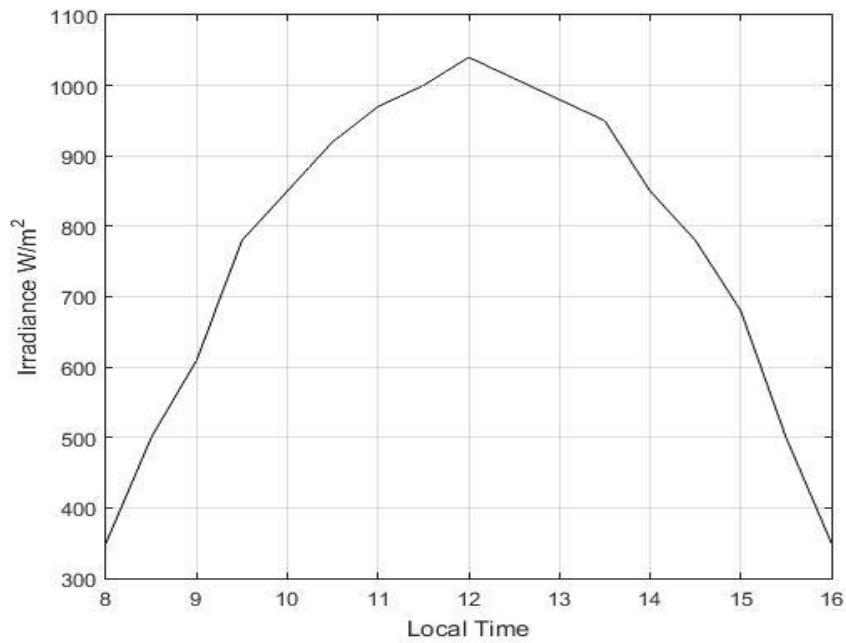

Figure (2): Variation of Solar Radiation Intensity (Irradiance) for the day 15th of March.
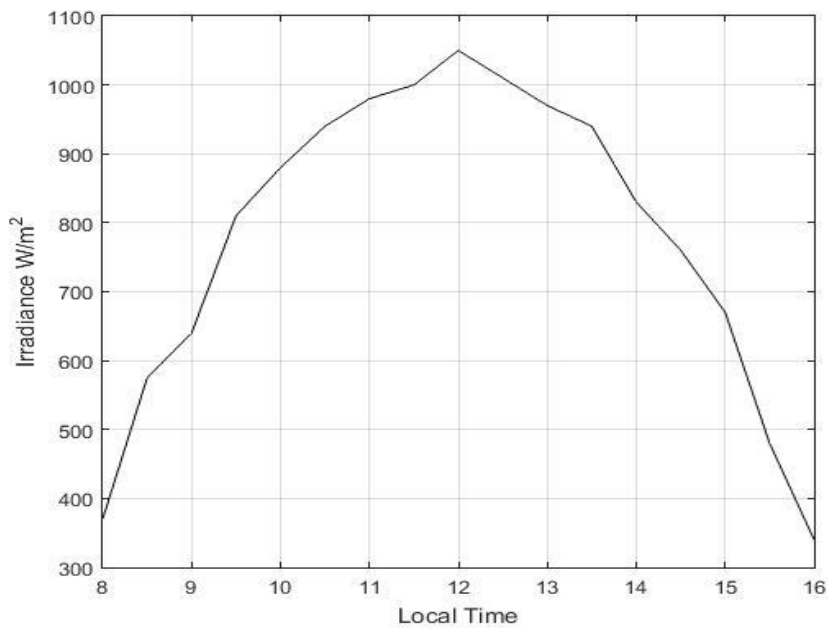
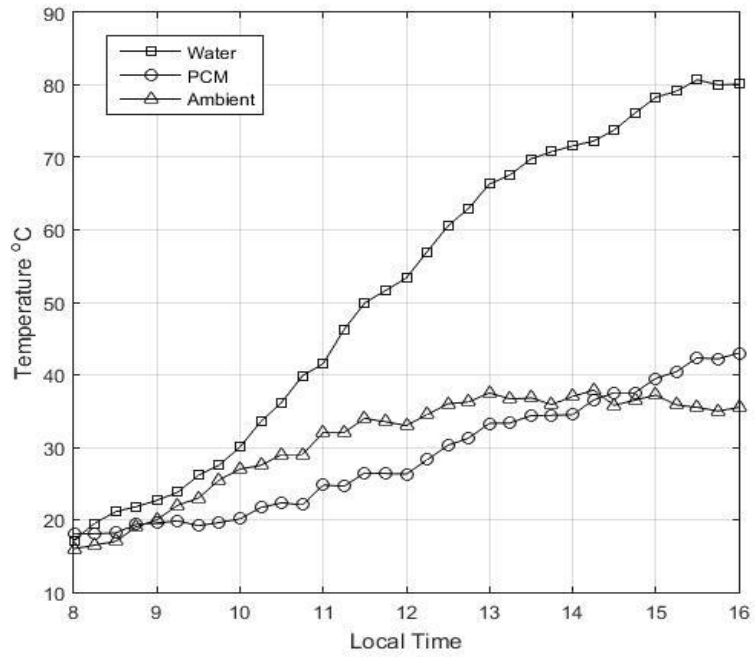Figure (3): Variation of Solar Radiation Intensity (Irradiance) for the day 16th of March.

Figure (4): Variation of Water, PCM and ambient temperatures during the test period for the day 15th of March.
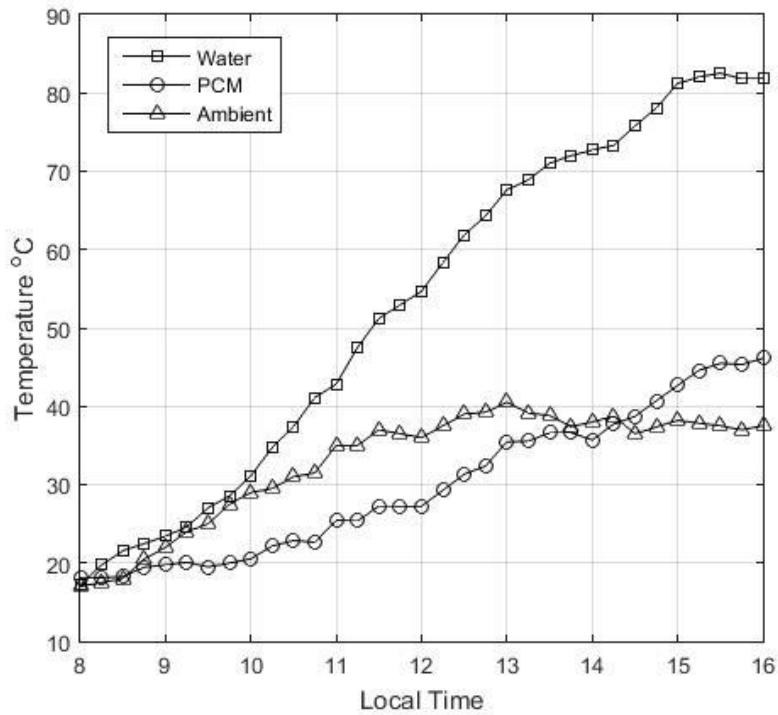

Figure (5): Variation of Water, PCM and ambient temperatures during the test period for the day 16th of March.
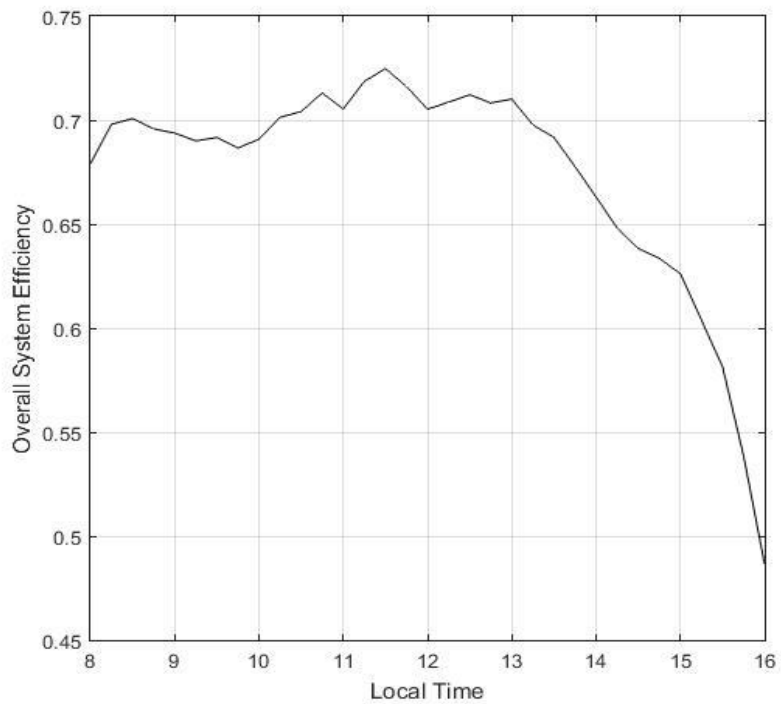
Figure (6): Variation of Overall System Efficiency during test period for the day 15th of March.
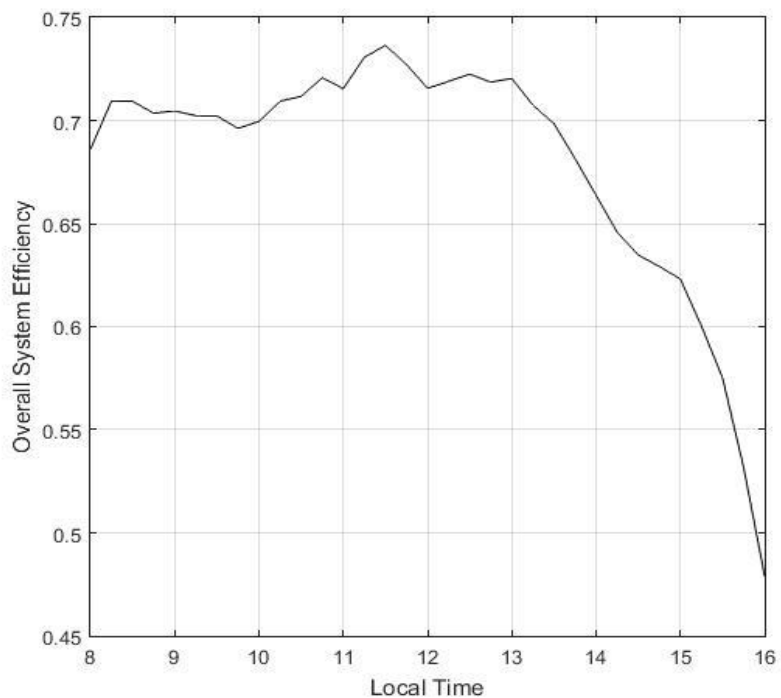

Figure (7): Variation of Overall System Efficiency during test period for the day 16th of March.

8. Conclusions and Recommendations

A new design of compact solar water heater is studied with the incorporation of latent heat storage via PCM (paraffin wax). The system showed high collection efficiency and reasonable water temperature for domestic applications. The melting of PCM and hence the start of latent heat storage was late in the present system. This

suggests either decreasing the amount of PCM or using a PCM with lower melting point. Further future studies are required to find the optimum PCM/water ratio.

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