Evacuated Tube Solar Collectors Integrated with Phase Change Materials

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Abstract

This paper presents a novel method of integrating phase change materials (PCMs) within the evacuated solar tube collectors for solar water heaters (SWHs). In this method, the heat pipe is immersed inside the phase change material, where heat is effectively accumulated and stored for an extended period of time due to thermal insulation of evacuated tubes. The benefit of this method includes improved functionality by delayed release of heat, thus providing hot water during the hours of high demand or when solar intensity is insufficient. The proposed solar collector utilizes two distinct phase change materials (dual-PCM), namely Tritriacontane and Erythritol, with melting temperatures of 72°C and 118°C respectively. The operation of solar water heater with the proposed solar collector is investigated during both normal and on-demand operation. The feasibility of this technology is also tested via large scale commercial solar water heaters. Beyond the improved functionality for solar water heater systems, the results from this study show efficiency improvement of 26% for the normal operation and 66% for the stagnation mode, compared with standard solar water heaters that lack phase change materials.

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Nomenclature

A_c	Solar collectors surface area (m^2)
c_{pw}	Specific heat of water (kJ/kgK)
c_{pl}	Specific heat of PCM liquid phase (kJ/kgK)
c_{ps}	Specific heat of PCM solid phase (kJ/kgK)
G_t	Global radiation (W/m^2)
H	Latent heat of fusion (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
T_{Fin}	Fin temperature ($^{\circ}C$)
T_m	Melting temperature ($^{\circ}C$)
T_W	Water temperature ($^{\circ}C$)
T_{Wf}	Final water tank temperature ($^{\circ}C$)
T_{Wi}	Initial water tank temperature ($^{\circ}C$)
η_s	Efficiency of the solar water heater(%)
ρ_l	Density of PCM liquid phase(kg/m^3)
ρ_s	Density of PCM solid phase(kg/m^3)

1. Introduction

Solar collectors absorb the radiation from the sun and transform it to heat via a transfer medium. Two prevalent collector formats are Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC). One advantage of evacuated tube solar collectors is that they are relatively insensitive to the direction of sunlight, while flat plates can suffer from additional reflection if the direction of sunlight is not suitable. Evacuated tube collectors also have better thermal insulation in comparison with the flat plate collectors. Evacuated tubes consist of two concentric glass tubes that are sealed at the ends and the inner tube is coated with a solar selective coating. High vacuum is produced between the two tubes, thus eliminating convection loss and providing excellent thermal insulation. When the tube is exposed to the sun, the solar selective coating absorbs the solar energy and transfers it to a heat pipe that is located inside the inner tube. The heat pipe contains a heat

transfer fluid (typically water or ethylene glycol) that transfers the heat to the system's manifold. The liquid in the heat pipe has a low boiling point, so when it is heated, the liquid inside the pipe begins to vaporize and rapidly rises to the top of the heat pipe while carrying a large amount of energy to the manifold. As the heat is off-loaded to the manifold, the vapor condenses and liquid returns to the bottom of the heat pipe. An aluminum fin, held in the tube by a spring clip, facilitates heat transfer and mechanically supports the heat pipe in place. A schematic configuration of the evacuated tube solar collectors is shown in Figure 1.

This paper studies evacuated tube collectors, in particular, in the context of solar water heaters. A solar water heater system often needs a booster (storage unit) to provide heat whenever little or no solar energy is available. Efficient development of such storage devices have been widely studied (Cabeza et al., 2006; El Qarnia, 2009; Font et al., 1994; PBL, 2000; Prakash et al., 1985; Rabin et al., 1995; Sharma A, 2003; Tarhan et al., 2006; Tayeb, 1995; Tiwari et al., 1988; Mehling et al., 2003). Among various methods for heat storage, the use of solid-liquid phase change materials, has attracted considerable attention (Al-Jandal and Sayigh, 1994; Boy et al., 1987; Cabeza et al., 2006; El Qarnia, 2009; Ghoneim, 1989; Waschull et al.; Kürklü et al., 2002; Lee et al., 2006; Mettawee and Assassa, 2006; PBL, 2000; Rabin et al., 1995; Sharma et al., 2009; Tarhan et al., 2006; Tayeb, 1993; Tiwari et al., 1988; Talmatsky and Kribus, 2008; Mehling et al., 2003). There is a large variety of PCMs (e.g. water, salt hydrates, certain hydrocarbons, metal alloys, and paraffin) that melt and solidify at a wide range of temperatures, making them attractive for the purpose of energy conservation in a number of applications. PCMs have a high latent heat capacity, and by going through melting/solidification phase, can store 5 to 14 times more heat per unit volume than sensible storage materials while the absorption and release of heat happen at a nearly constant temperature (Sharma et al., 2009). Representative examples of work, based on the application of PCM in solar water heaters are discussed below, where typically the PCM is placed inside the water tank of SWH.

Prakash et al. (1985) studied a water heater system with a separate storage tank, which contained a layer of encapsulated PCMs at the bottom of the tank. Boy et al. (1987) proposed an integrated collector storage system based on a salt-hydrate PCM for providing hot water instantaneously, claiming that the thermal efficiency can be improved significantly by incorporating an appropriate PCM. However, the cost of the system was increased because

53 the salt-hydrate PCM was encapsulated in a special corrugated-fin heat ex-
 54 changer. Tiwari et al. (1988) analyzed a phase change component material
 55 storage system for water heaters by incorporating the effect of water flow
 56 through a parallel plate placed at the solid-liquid interface. Ghoneim (1989)
 57 compared the performance of PCMs by considering the heat conduction and
 58 heat loss from the storage unit for both air and water-based solar heating
 59 systems and investigated the required storage capacity. Bansal and Bud-
 60 dhi (1992) theoretically studied a cylindrical latent heat storage system for
 61 a domestic hot water system where during the charging mode of the phase
 62 change material, the cylindrical capsule is in the closed loop with a solar
 63 water heater, and during the discharging mode, the energy is extracted by
 64 a liquid flowing through the storage unit. Tayeb (1993, 1995) developed a
 65 system for domestic hot water using PCM in the storage media and com-
 66 pared its performance with a simulation model. This work demonstrated the
 67 optimum flow rate of the inlet water supply for maintaining constant water
 68 temperature at the outlet. Al-Jandal and Sayigh (1994) studied the combi-
 69 nation of solar collectors and PCM in one unit (similar to a heat exchanger)
 70 via both analytical and experimental analysis on a direct contact PCM solar
 71 storage system with water, using two vertical cylindrical concentric tubes
 72 with Stearic Acid PCM between them. Font et al. (1994) conducted a pre-
 73 liminary study for the design of a device for domestic water heater using a
 74 solid-solid PCM. In this work, water flows through the PCM in the restitu-
 75 tion period, in the same circuit as in the charge period. Kaygusuz (1995)
 76 studied the performance of the thermal energy storage materials, collectors
 77 and energy storage tank filled by the PCMs, for domestic heating.

78 Kürklü et al. (2002) developed a new type of solar flat panel collector
 79 consisting of two adjoining sections, one filled with water and the other with
 80 a paraffin wax PCM. Canbazoglu et al. (2005) investigated the energy storage
 81 duration of hot water, the produced hot water, and the total heat accumu-
 82 lated in the solar water storage tanks combined with PCM. Cabeza et al.
 83 (2006) constructed a water heater system by adding a PCM module at the
 84 top of the water tank, compensating heat loss from the top layers. They
 85 applied several cylinders at the top of the water tank and investigated the
 86 system performance with two, four and six PCM modules. Mettawee and
 87 Assassa (2006) investigated the thermal performance of a single unit PCM
 88 solar flat panel collector, where the absorber plate-container unit performs
 89 simultaneously as a solar energy absorber and PCM storage medium. Tarhan
 90 et al. (2006) experimentally evaluated three trapezoidal built-in storage solar

91 water heaters to study the effects of PCM types, the location of the PCM
 92 storage units, and the absorbing plates on the performance of the solar water
 93 heater. Lee et al. (2006) experimentally studied a latent heat storage unit
 94 in a two-phase thermosyphon solar water heater. Nallusamy et al. (2007) in-
 95 vestigated experimentally the thermal behavior of a packed bed of combined
 96 sensible and latent heat thermal energy storage unit for a solar water heater.
 97 Hassan and Beliveau (2008) proposed a solar energy collection system that
 98 consists of an integrated flat-plate collector and a PCM storage tank in one
 99 functional unit. Browne et al. (2015) investigated experimentally the perfor-
 100 mance of a photovoltaics/thermal phase change material system where the
 101 stainless steel container of water pipe network is filled with PCM.

102 Seeniraj and Narasimhan (2008) studied numerically the performance of a
 103 latent heat thermal system unit with both finned-tube and multiple PCM em-
 104 ploying an enthalpy-based model with application in solar energy. The shell
 105 side contains five different PCMs and the tube side (though unevacuated-
 106 conventional tube) has an arrangement of radial fins with uniform thick-
 107 nesses that carry the fluid. Sharma et al. (2009) compared the performance
 108 of PCM, water, and rock based storage system. El Qarnia (2009) studied a
 109 theoretical model to predict the thermal behavior and performance of a solar
 110 latent heat storage unit that consists of a series of identical tubes embedded
 111 in the PCM. In their experiment, a heat transfer fluid from the solar collector
 112 passes through the tubes and transfers the absorbed solar radiation energy
 113 to the PCM inside the storage tank.

114 Until now, the PCM-based storage unit has been designed either as a
 115 separate medium away from the solar collectors or directly applied inside the
 116 flat panel collectors. This paper proposes a new system that combines the
 117 heat collection and the PCM-storage system both in a single unit, inside the
 118 evacuated tube solar collectors (Figure 2). To the best of the authors' knowl-
 119 edge, this is the first study of the integration of PCM inside the evacuated
 120 solar tubes. This paper describes the addition of phase change materials
 121 inside typical evacuated tube solar collectors to improve their functionality
 122 by storing energy in the system during on-demand operation. This concept
 123 can be applied to provide delayed heat to a system when solar energy is
 124 insufficient or unavailable at night and on cloudy days.

125 In general, water heater demand (in kW) in a household varies during the
 126 season and also during the day. On a daily basis, the demand peaks in the
 127 morning and late evening hours can be seen in (Figure 3). The motivation for
 128 our technology of PCM within evacuated tube solar collectors, is to address

129 the evening peak demand with energy storage in PCM, independently of
130 weather conditions and time.

131 2. Experimental Study

132 The experimental study in this paper has three phases:

- 133 • Phase-I: Selecting the proper phase change material for the application
134 of evacuated tube solar collectors.
- 135 • Phase-II: Testing the performance of the PCM integrated solar water
136 heater system in both normal and on-demand operations.
- 137 • Phase-III: Optimization of the PCM integrated water heater system
138 based on the obtained results from the previous phases.

139 The details of each phase and its related approaches and results are out-
140 lined below:

141 2.1. Phase-I: Selection of Proper Phase Change Materials

142 PCMs can be divided into two broad categories of high melting tempera-
143 ture (above 100 °C) and low melting temperature (below 100 °C). Among
144 the low melting temperature PCMs, paraffins with chemical formulation
145 (C_nH_{2n+2}) have stable physical/chemical properties, no toxicity and no fire
146 hazard, low cost and high availability. These characteristics make them at-
147 tractive for the application of heat storage in solar collectors. Paraffins have
148 a large spectrum of latent heat capacities (220-270 kJ/kg) and melting tem-
149 peratures (5.5-80 °C) based on their number of carbons (n). Therefore, for
150 heat storage purposes, proper paraffins can be selected based on their melt-
151 ing/solidification temperature and also the system's operating temperature.

152 Although paraffins with low melting temperature are good candidates
153 for solar storage applications (as a separate tank), not all paraffins are suit-
154 able for the inside of the evacuated tube collectors. The reason is that the
155 temperature inside the evacuated tubes may reach up to 180 °C due to the
156 vacuum layer. Therefore, selection of PCM with appropriate melting tem-
157 perature and stability is challenging for the heat storage functionality inside
158 the collector tubes.

159 Phase change materials with high melting temperature (above 100 °C)
160 usually have high cost, subcooling, and poor stability during the tempera-
161 ture cycling. Therefore, the number of suitable phase change materials with

high melting temperature is limited (Waschull et al.). Among the proposed PCMs in literature (Table 1), we have chosen Erythritol in the current study. Erythritol is a widely available sugar alcohol with the melting point of 118 °C and latent heat capacity of 340 kJ/kg . Clinical studies confirm that Erythritol is a non-toxic and safe material; its level of non-toxicity can be highlighted by the fact that it is used in the food industry as sweetener (Munro et al., 1998). Compared with other sugar substitutes, Erythritol does not caramelize when heating up. The thermophysical properties of Erythritol are shown in Table 2.

For comparative purposes, we also study two types of paraffins for application in evacuated tubes. These paraffins are Hexacosane and Trtriacontane, with melting temperature of 56 °C and 72 °C respectively. The chemical formulas and physical properties of these PCMs are shown in Table 2 (Himran et al. (1994); Zalba et al. (2003); Kakiuchi et al. (1998); Takahashi (2013)).

A bench-top (small size) Apricus evacuated solar water heater system (Model# 513) is chosen for the phase-I of the study (Figure 4). In this experiment, the inner space of three individual tubes are filled with Hexacosane, Trtriacontane, and Erythritol PCMs while the aluminum fins are in place. After capping the tubes, they are placed under sunlight for several hours to make sure the PCMs are fully melted. Once the tubes are removed from the sunlight and moved indoor, the heat pipes attached to a 600 ml water tank, (with initial temperature of 25 °C) are inserted into the tubes (Figure 5). The temperature inside the evacuated tubes attached to the aluminum fins (T_{Fin}) and the water tank (T_W) are recorded for two hours, during which the system settles into a steady condition. The latent heat inside the PCMs are released during the solidification process and initiates the temperature reduction inside the tube (Figure 6a). At the same time, heat pipes transfer heat from the PCM to the tank, therefore the temperature of water inside the tank increases (Figure 6b). A temperature rise of 9°C in the water tank is recorded for Hexacosane material, and 18°C for Trtriacontane paraffin. For the Erythritol which has higher melting temperature and latent heat capacity, the temperature increase is around 36°C.

Erythritol provided the most desirable (highest) temperature rise, however, immediately after heat pipe insertion, Erythritol rapidly solidified inside the tubes. This sudden spot heating/cooling causes non-uniform Erythritol volume expansion/contraction. We observed as high as 13% volume expansion for the Erythritol during heating cycles which can result in the cracking of the glass tube. Therefore, despite the promising fundamentals of the pre-

liminary results, a solution was needed for practical usage of Erythritol in evacuated collectors. This problem is solved by placing Erythritol inside small aluminum bags (Figure 7) while leaving some space for the expansion of that during the melting process. To avoid sudden spot heating/cooling around the bags, Silicon oil is injected in the tubes between the void spaces between the bags. Silicon oil increases convective heat transfer (stirring effect) which leads to a uniform melting inside the Erythritol bags and prevents tube breakage or malfunction. Two thermocouples are installed on top (facing sunlight) and bottom (facing the ground) of the Erythritol bags (Figure 7) to monitor the melting process of Erythritol during different hours of the day.

2.2. Phase-II: Normal vs. Stagnation Operation

In the second phase of the experiment, a standard Apricus collector is used to facilitate the comparison of the performance of identical commercial evacuated tubes simultaneously with and without phase change materials. The commercial Apricus solar collector has 10 evacuated tubes which four tubes are left untouched (no PCM), three tubes are filled with Tritriacontane paraffin (2 kg per tube), and three tubes with Erythritol baggies (1.4 kg per tube) and silicon oil. Total latent heat capacity of PCM integrated tubes are almost equal due to the higher latent heat capacity of the Erythritol compared with paraffin. Each setup includes an immersion pump inside the storage tanks with 40L capacity to circulate the water in the system and a flow meter that controls the water flow-rate entering the manifold.

Several thermometers record the temperature inside each evacuate tube (T_{Fin}) which are attached to the aluminum fin, and water tank (T_W) during the test (Figure 8). The thermocouple readings are recorded with an OMEGA HH309A thermometer with accuracy $\pm 0.2\%$. The repeatability and accuracy of measurements are examined by monitoring the solar irradiation using a SP-Lite2 Pyranometer (directional error (up to 80° with 1000 W/m^2 beam) less than 10 W/m^2) during the consecutive days of experiment. A sample of recorded data has been plotted in Figure 9.

Among the efficient phase change materials tested in phase-I, Tritriacontane paraffin and Erythritol are chosen for the second phase of the experiment to study their effect on the storage capacity in both normal and on-demand operation by keeping the collectors initially stagnated for an extended period of time before water flow circulation. In “normal operation”, water is continuously circulating through the manifold during the day. “On-demand operation” (stagnation mode) is unique to our SWH systems with PCM.

237 The PCM inside the evacuated tube collector acts as a storage medium for
238 releasing heat at a later time for providing hot water in a specific time of
239 the day once the water flow restarts. In this experiment, the SWH system
240 is kept in stagnation mode with no water circulation while the collectors ab-
241 sorb the solar radiation continuously, which results in trapping the heat in
242 the tubes (maximum energy storage). Temperature variation inside the evac-
243 uated tubes are shown in Figure 10 for both normal and stagnation operation
244 mode.

245 Under normal operation (Figure 10a), the temperature inside the tubes
246 increases, eventually stabilizing at a maximum value. The results show that
247 standard tubes are heated up to 140°C , while the PCM integrated tubes after
248 similar exposure to sunlight to reach to the temperature around $90 \pm 10^{\circ}\text{C}$.
249 The rate of cooling in a typical tube with no PCM is very fast, with the
250 temperature falling within a few minutes. In the case of PCM filled tubes, the
251 cooling process is significantly slower and the heat pipe can operate for several
252 hours. The paraffin filled tube temperature shows a higher latent heat release
253 compared with the Erythritol filled tubes, where the heat release happens
254 around 75°C . The reason is that, due to higher melting temperature of
255 Erythritol compared to paraffin, Erythritol does not fully melt and shows less
256 latent heat release. In summary, paraffin filled tubes show better performance
257 in normal operation mode compared with Erythritol filled tubes.

258 Figure 10b presents the inner tube temperatures recorded during the
259 cooling process after the stagnation mode. To mimic the stagnation mode
260 on the second system, no water flow is initiated through the manifold for
261 an extended time until the PCMs in the tubes completely melt, then the
262 system (collectors) were covered completely from sun and water circulation
263 starts by switching the pump on. It is observed that the initial temperature
264 inside the standard tubes reach 200°C , for paraffin tubes temperature is
265 around 155°C and for Erythritol tubes around 130°C . The PCM tubes initial
266 temperatures are above their related melting point, therefore phase change
267 (melting) process has occurred for the majority of the paraffin and Erythritol
268 material. After switching the pump on, energy transfers to the water through
269 the heat pipe and the manifold. The paraffin tube temperature curve shows
270 a plateau around 70°C , and Erythritol tube shows a plateau around the
271 transition temperature of 100°C .

272 As observed, during stagnation operation (on-demand), Erythritol filled
273 tubes show an improved performance with higher storage capacity compared
274 with paraffin filled tubes. It can be seen that, as in the stagnation operation

the temperature inside the tubes can reach to a higher value compare to the normal operation, so it allows the Erythritol to be fully melted this time, so the Erythritol would have higher rate of heat storage capacity and consequently results in the slower cooling rate inside the tubes. The delayed cooling of PCM collectors can extend operation of SWH systems when solar radiation is not enough (after sunset).

2.3. Phase-III: Dual-PCM Solar Water Heater

In the third phase of the experiment, two standard Apricus large scale evacuated tube collectors are used to demonstrate the feasibility of the proposed approach in commercially available solar water heaters. The experimental setup is designed to facilitate the comparison of the performance of identical commercial evacuated tube solar collector arrays simultaneously with and without phase change materials.

The effect of PCM on the solar water heater operation is even more pronounced when comparing the recorded water temperatures in the storage tanks. Based on the results from Phase-II, a dual-PCM solar water heater system is proposed with improved performance in both normal and on-demand operation. The dual-PCM system includes a large scale Apricus solar collector with five tubes filled with paraffin and five tubes filled with Erythritol. A standard (No PCM) and dual systems work simultaneously under similar situation as seen in Figures 11 and 12.

The results for the water temperature in the storage tanks of both standard and dual-PCM are shown in Figure 13 in normal and stagnation operation. While water temperature in storage tanks of both systems are almost 50°C around 5:00 PM, the dual PCM system has a longer delayed cooling period and keeps water in higher temperature compared with standard system during the evening and at night when solar radiation is not available (Figure 13a). The hatched area is a representative of the improved heat storage capacity for the dual-PCM system compared with the standard one during the normal operation.

For the stagnation mode testing, the PCMs inside the dual-PCM system are fully melted before the water circulation initiates. Figure 13b shows the recorded temperature of both systems during the cooling process after the stagnation mode. Fast cooling in standard system and delayed cooling of dual-PCM system are observed. While both systems are stagnated, the majority of absorbed energy is accumulated in the PCMs and once the water flow is started, the energy can be transferred to water through the heat pipe

and the manifold assembly. Therefore, the dual-PCM solar water heater system allow the operation of the system for a longer period of time when sunlight is not available. The hatched area in Figure 13b represents the improved heat storage capacity of the dual-PCM solar water heater system in the stagnation mode compared with the standard one with no PCM.

Based on the latent heat storage of each PCM, the total energy storage can be calculated as multiplying the mass by latent heat of each PCMs and it can be written as following:

$$Q = m_{Tritriacontane}H_{Tritriacontane} + m_{Erythritol}H_{Erythritol} \quad (1)$$

where m is the mass of Tritriacontane and Erythritol in kg (2kg of Tritriacontane and 1.4 kg Erythritol per tube), and H is the latent heat capacity of Tritriacontane and Erythritol in kJ/kg. The total amount will be:

$$Q = (5)(2kg)(256kJ/kg) + (5)(1.4kg)(339.8kJ/kg) = 4938.6kJ \quad (2)$$

This value represents the energy storage capacity of PCMs in the current configuration.

The gray area (Evening Peak Zone) presents an overall perceptive of maximum average hourly energy demand (kW) for the residential solar water heaters during the summer and winter times (Carlos J.Colon, 2010). As shown, an improved performance and functionality of the dual-PCM solar water heater during this peak zone is achieved. In this regard, the system efficiency can be obtained from the following equation, based on the maximum temperature gradient in the storage tank during the normal and stagnation operation of the system (Sukhatme and Sukhatme, 1996):

$$\eta_s = \frac{\dot{m}c_{pw}(T_{w,f} - T_{w,i})}{A_c G_t} \quad (3)$$

where $\dot{m}$ is the water mass flow-rate which in our experiment is around 0.0126 kg/s, c_{pw} is the specific heat capacity of water which is 4.186 kJ/kg.k, and $T_{w,i}$ and $T_{w,f}$ are initial and final water temperatures in the storage tank. A_c is the collector gross area which is 1.6 m² (AP-10 gross area), and G_t is the total global radiation on the surface of the collectors which is measured by the SP-Lite2 Pyranometer and shows the maximum amount of 947 w/m² on the selected days (Figure 9).

The recorded temperatures show a maximum temperature gradient between the standard and Dual-PCM systems as $\Delta T_{max} = 8^\circ C$ in normal

operation and $\Delta T_{max} = 15^{\circ}C$ in stagnation mode. Based on this calculation, the efficiency of the Dual-PCM solar water heater system has increased 26% compared with standard system in normal operation and 66% in stagnation mode.

3. Conclusion

This paper presents the performance of a solar water heater with evacuated tubes integrated with phase change materials. The results show that phase change material integrated inside the inner tubes of evacuated tube solar collectors can effectively store energy (in the form of latent heat) next to the heat pipes and enable a delayed cooling after sunset or late evening. The proposed solar collector utilizes two distinct phase change materials (dual-PCM), namely Tritriacontane and Erythritol with melting temperature $72^{\circ}C$ and $118^{\circ}C$ respectively. The operation of solar water heater with the proposed solar collector is investigated during both normal and on-demand operation. The feasibility of this technology is tested via large scale commercial solar water heaters. This study shows a significant efficiency improvement of dual-PCM solar water heaters for both normal and stagnation operation, compared with standard solar water heaters that lack phase change materials.

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372		et al. (1998); Takahashi (2013)	15

Table 1: Phase change materials with high melting temperature

Substance	Melting Temperature (°C)	Latent Heat (kJ/kg)
Erythritol	119	332-340
Pentaerythritol	186-187	287-298
Azelais acid	98-108	174
Sebacic acid	130-134	228
Dimethyl Terephthalate	142	170
P-Toluic acid	180	167
Octadecanamide	106	211
Urea	133-135	170-258

Table 2: Thermophysical properties of Hexacosane, Tritriacontane and Erythritol Himran et al. (1994); Zalba et al. (2003); Kakiuchi et al. (1998); Takahashi (2013)

Properties	Hexacosane	Tritriacontane	Erythritol	Silicon Oil
Chemical Formula	$C_{26}H_{54}$	$C_{33}H_{68}$	$C_4H_{10}O_4$	-
T_m ($^{\circ}C$)	56	72	119	-
H (kJ/kg)	250	256	339.8	-
c_{pl} (kJ/kgK)	0.87	1.11	2.76	-
c_{ps} (kJ/kgK)	0.68	0.87	1.38	-
ρ_l (kg/m^3)	765	782	1300	960
ρ_s (kg/m^3)	800	810	1480	960
$FiringPoint$ ($^{\circ}C$)	-	-	-	318

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Figure 1: A schematic of evacuated tube solar collector and its cross-sectional view

Figure 2: Schematic of evacuated solar collector filled with PCM

Figure 3: Daily residential water heater demand (kW) in summer and winter (Carlos J.Colon, 2010)

Figure 4: Phase-I: Experimental apparatus

Figure 5: Phase-I: Schematic Configuration of Experimental setup

(a)

(b)

Figure 6: Phase-I: (top) Temperature inside the tubes, and (bottom) Temperature of the water tank

Figure 7: A schematic configuration of evacuated solar tubes filled with Erythritol baggies and silicone oil flow

Figure 8: Phase-II: Schematic Configuration of Experimental Setup

Figure 9: A sample of solar radiation recorded by Pyranometer

(a)

(b)

Figure 10: Phase II: Temperature inside the evacuated tubes, (top) Normal operation, and (bottom) Stagnation operation

Figure 11: Phase-III: Experimental apparatus

Figure 12: Phase-III: Schematic Configuration of Dual-PCM Experimental Setup

(a)

(b)

Figure 13: Phase III: Water temperature, (a) Normal operation, and (b) Stagnation operation

References

- Al-Jandal, S., Sayigh, A., 1994. Thermal performance characteristics of storage system with phase change storage. *Renewable Energy* 5, 390–399.
- Bansal, N., Buddhi, D., 1992. An analytical study of a latent heat storage system in a cylinder. *Energy conversion and management* 33, 235–242.
- Boy, E., Boss, R., Lutz, M., 1987. A collector storage module-with integrated phase change material. *Proc. ISES, Pergamon Press, Hamburg* , 3672–3680.
- Browne, M.C., Lawlor, K., Kelly, A., Norton, B., Mc Cormack, S.J., 2015. Indoor characterisation of a photovoltaic/thermal phase change material system. *Energy Procedia* 70, 163–171.
- Cabeza, L.F., Ibanez, M., Sole, C., Roca, J., Nogués, M., 2006. Experimentation with a water tank including a pcm module. *Solar Energy Materials and Solar Cells* 90, 1273–1282.
- Canbazoglu, S., Sahinaslan, A., Ekmekyapar, A., Aksoy, Y.G., Akarsu, F., 2005. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. *Energy and Buildings* 37, 235–242.
- Carlos J.Colon, D.S., 2010. Side-by-side Testing of Water Heating Systems: Results from the 2009-2010 Evaluation. Technical Report FSEC-CR-1856-10. Florida Solar Energy Center. 1679 Clearlake Road, Cocoa, Florida 32922, USA.
- El Qarnia, H., 2009. Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water. *Energy Conversion and Management* 50, 247–254.
- Font, J., Muntasell, J., Cardoner, F., 1994. Preliminary study of a heat storage unit using a solid-solid transition. *Solar energy materials and solar cells* 33, 169–176.
- Ghoneim, A., 1989. Comparison of theoretical models of phase-change and sensible heat storage for air and water-based solar heating systems. *Solar Energy* 42, 209–220.

- 425 Hassan, M.M., Beliveau, Y., 2008. Modeling of an integrated solar system.
426 Building and Environment 43, 804–810.
- 427 Himran, S., Suwono, A., Mansoori, G.A., 1994. Characterization of alkanes
428 and paraffin waxes for application as phase change energy storage medium.
429 Energy Sources 16, 117–128.
- 430 Kakiuchi, H., Yamazaki, M., Yabe, M., Chihara, S., Terunuma, Y., Sakata,
431 Y., Usami, T., 1998. A study of erythritol as phase change material. Iea
432 Annex 10, 11–13.
- 433 Kaygusuz, K., 1995. Experimental and theoretical investigation of latent
434 heat storage for water based solar heating systems. Energy conversion and
435 management 36, 315–323.
- 436 Kürklü, A., Özmerzi, A., Bilgin, S., 2002. Thermal performance of a water-
437 phase change material solar collector. Renewable Energy 26, 391–399.
- 438 Lee, W.S., Chen, B.R., Chen, S.L., 2006. Latent heat storage in a two-phase
439 thermosyphon solar water heater. Journal of solar energy engineering 128,
440 69–76.
- 441 Mehling, H., Cabeza, L., Hippeli, S., Hiebler, S., 2003. Pcm-module to
442 improve hot water heat stores with stratification. Renewable Energy 28,
443 699–711.
- 444 Mettawee, E.B.S., Assassa, G.M., 2006. Experimental study of a compact
445 pcm solar collector. Energy 31, 2958–2968.
- 446 Munro, I., Bernt, W., Borzelleca, J., Flamm, G., Lynch, B., Kennepohl,
447 E., Bär, E., Modderman, J., 1998. Erythritol: an interpretive summary of
448 biochemical, metabolic, toxicological and clinical data. Food and Chemical
449 Toxicology 36, 1139–1174.
- 450 Nallusamy, N., Sampath, S., Velraj, R., 2007. Experimental investigation
451 on a combined sensible and latent heat storage system integrated with
452 constant/varying (solar) heat sources. Renewable Energy 32, 1206–1227.
- 453 PBL, C., 2000. Phase change material in solar water heater storage system,
454 in: Proceedings of the 8th international conference on thermal energy stor-
455 age.

- 456 Prakash, J., Garg, H., Datta, G., 1985. A solar water heater with a built-in
457 latent heat storage. *Energy conversion and management* 25, 51–56.
- 458 Rabin, Y., Bar-Niv, I., Korin, E., Mikic, B., 1995. Integrated solar collec-
459 tor storage system based on a salt-hydrate phase-change material. *Solar*
460 *Energy* 55, 435–444.
- 461 Seeniraj, R., Narasimhan, N.L., 2008. Performance enhancement of a solar
462 dynamic lhts module having both fins and multiple pcms. *Solar Energy*
463 82, 535–542.
- 464 Sharma, A., Tyagi, V., Chen, C., Buddhi, D., 2009. Review on thermal
465 energy storage with phase change materials and applications. *Renewable*
466 *and Sustainable energy reviews* 13, 318–345.
- 467 Sharma A, Pradhan N, K.B., 2003. Performance evaluation of a solar wa-
468 ter heater having built in latent heat storage unit. Technical Report p.
469 10915. Advanced thermal energy storage through phase change materials
470 and chemical reactionsfeasibility studies and demonstration projects. 4th
471 workshop. Indore, India.
- 472 Sukhatme, K., Sukhatme, S.P., 1996. Solar energy: principles of thermal
473 collection and storage. Tata McGraw-Hill Education.
- 474 Takahashi, A.H.H.J.N.H.K., 2013. Direct contact latent heat storage system
475 using erythritol as a latent heat storage material. *Thermal Science and*
476 *Engineering*; ISSN:0918-9963 VOL.21, 83–93.
- 477 Talmatsky, E., Kribus, A., 2008. Pcm storage for solar dhw: An unfulfilled
478 promise? *Solar Energy* 82, 861–869.
- 479 Tarhan, S., Sari, A., Yardim, M.H., 2006. Temperature distributions in
480 trapezoidal built in storage solar water heaters with/without phase change
481 materials. *Energy conversion and management* 47, 2143–2154.
- 482 Tayeb, A.M., 1993. A simulation model for a phase-change energy storage
483 system: experimental and verification. *Energy conversion and management*
484 34, 243–250.
- 485 Tayeb, A.M., 1995. Organic-inorganic mixtures for solar energy storage sys-
486 tems. *Energy conversion and management* 36, 969–974.

- 487 Tiwari, G., Rai, S., Ram, S., Singh, M., 1988. Performance prediction of pcm
488 collection-cum-storage water heater: quasi-steady state solution. *Energy*
489 *conversion and management* 28, 219–223.
- 490 Waschull, J., Müller, R., Römer, S., . Investigation of Phase Change Materi-
491 als for Elevated Temperatures. Technical Report. Institute for Air Condi-
492 tioning and Refrigeration Dresden (ILK Dresden). Department of Applied
493 New Technologies, Bertolt-Brecht-Allee 20, 01309 Dresden, Germany.
- 494 Zalba, B., Marín, J.M., Cabeza, L.F., Mehling, H., 2003. Review on thermal
495 energy storage with phase change: materials, heat transfer analysis and
496 applications. *Applied thermal engineering* 23, 251–283.