Experimental analysis of Shape-Stabilized PCM applied to a Direct-Absorption evacuated tube solar collector exploiting sodium acetate trihydrate and graphite

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ARTICLE INFO

Keywords:
Solar energy
Direct-absorption solar collectors
Shape-stabilized phase change materials
Heat storage
Energy efficiency

ABSTRACT

A problematic issue with the solar water heaters is the storage tank requirement, which takes considerable space and makes the piping and installation more difficult. This study is the first report on experimentally applying a shape-stabilized PCM to a tankless direct-absorption evacuated tube solar collector to address this challenge and directly store solar energy. The proposed salt hydrate PCM was synthesized at various concentrations of related components and after detecting the optimum compound, it was tested under several cycles to ensure its sustainable heat storage capability. Furthermore, after charging the solar system in the stagnation mode (without water flow), it was discharged at 10, 27, and 40 L per hour (LPH) flow rates. It was revealed that the thermal efficiency in the stagnation mode was improved from 66 % to 82 % using this collector-storage system. In addition, it was concluded that changing the flow rate from 10 to 27 LPH does not considerably reduce the heat gain of collector; however, using the flow rate of 40 LPH plunges the discharge efficiency. Ultimately, cost and carbon footprint analyses of the proposed system were conducted and a payback period of 6 years and annual reduction of 5.4 tons of CO₂ emissions were reported.

1. Introduction

Growing global population leads to boosting the need for energy, which requires more production along with greater energy losses and increase of the hazardous emissions [1]. This can also disrupt the proportion between the peak demand and the highest production times that intensifies the energy loss. Thereby, the technology of energy storage can curb this inconsistency and store the excessive energy for consumption at less productive times [2]. Solar energy is the most abundant renewable energy on the earth and a suitable source for providing the required thermal energy in both domestic and industrial applications by means of solar thermal collectors [3]. Nonetheless, the peak demand–supply inconsistency and the intermittent nature of sun behoove the need for storing heat when sun is up [4].

Solar thermal collectors are mechanical systems for the conversion of solar energy to heat using an absorber plate, a heat exchanger, and a cover for creating a greenhouse effect [5]. However, the higher temperature of the absorber leads to improving the radiative heat losses from the collector. Hence, a thermal energy storage (TES) unit can retain the excessive heat during high sunshine times for being retrieved during the low-radiation periods [6]. Regarding the domestic thermal applications, solar collectors are comprised of flat plate and evacuated tube types so that the literature indicates a better thermal performance for the latter case [7]. It is because the evacuated tube solar collectors (ETSCs) exploit vacuum to reduce convective losses, possess selective absorbers to minimize the radiative losses, and the circular absorber causes the sunshine to always radiate perpendicular to the collector surface [7]. There have also been some research working on evacuated flat plate solar collectors; however, they are under development and have not still been commercialized widely [8]. Therefore, this paper continues with the ETSCs research background and how TES units have been integrated with them to decrease the heat losses and increase their overall efficiency.

In many studies, ETSCs have been integrated with nanofluids to improve their thermal conductivity for a faster heat absorption process and they have improved the heat absorption of solar collectors around 5
to 10 % [9]. Moreover, in recent years phase change materials (PCMs) have been introduced for integration with ETSCs to not only avoiding excessive heat losses during solar radiation input times but also providing heat over nights [10]. According to the literature, compact integration of PCM with solar collectors (as a single unit) not only avoids unnecessary space occupation, but also leads to less thermal losses and a better performance of the solar thermal system [11].

In 2016, Papadimitratos et al. [12] applied erythritol (C\textsubscript{4}H\textsubscript{8}O\textsubscript{4}) as the PCM to a heat pipe evacuated tube solar collector (HP-ETSC). They also utilized silicone inside the tubes for a stirring purpose and more uniform PCM melting process. The results showed that with using the PCM the hot water production rose from 7:00pm to 4:00 a.m. at 45 L per hour (LPH) water flow rate due to the high heat capacity and melting point of the PCM. Also, the collector efficiency was improved by 66 % during the charging process (stagnation mode) and was improved by 26 % during the discharge process considering the water circulation. Felinski and Sekret [13] utilized paraffin wax inside an HP-ETSC, containing seven tubes and each tube was filled with 1.98 kg of the PCM. The experiments were conducted in the laboratory under 900 W/m\textsuperscript{2} radiation intensity for four hours at 72 LPH flow rate during charging. The mean outlet water temperature was 45 °C and it was deduced that the heat losses decreased by 30 % since the outlet temperature and the ambient temperature difference was compromised using the TEUS unit. In addition, it was concluded that using the PCM increases the useful heat by around 45 % because of high latent heat capacity of the PCM. In 2017, Abokersh et al. [14] comparatively investigated the thermal characteristics of two ETSCs with U-pipe heat exchanger filled with paraffin and one of them was equipped with fins for accelerating the heat transfer rate. They concluded that using fins leads to more heat dissipation over the discharge process, so that the daily efficiency values of the ETSCs with and without fins were 33 % and 26 %, respectively. In 2018, Li et al. [15] considered a tankless ETSC with 10 tubes and erythritol with 3 wt% expanded graphite (EG) as the additive-PCM using copper U-pipes for water passage. The outdoor experiments were undertaken under 700 W/m\textsuperscript{2} average sun radiation and around 40 °C surroundings temperature. Considering 1.7 kg of the additive PCM in each tube (17 kg in total), the results demonstrated that 15.23 MJ/m\textsuperscript{2} input heat is needed to charge the PCM. Also, it was indicated that increasing the inlet flow rate and reduction of the inlet water temperature bring about shorter discharging times. As an example, the discharge periods at 50 and 70 LPH flow rates were reported as 2.45 and 2 h, successively.

In 2020, Chopra et al. [16] used SA-67 as the TES unit inside an HP-ETSC and surveyed the impacts of using PCM and inlet water flow rate on the performance of the system. They concluded that using the PCM can increase the overall efficiency of the collector by around 30 % at 8 LPH flow rate over the discharge time. They also reported the reduction of discharge efficiency with increasing the flow rate above 20 LPH. Moreover, Essa et al. [17] investigated the impact of using different fin configurations around the evaporator part of heat pipe in a PCM-contained HP-ETSC. They compared a conventional aluminum fin with a helical fin around the heat pipe and found that using helical fin leads to 15 % higher daily efficiency of the collector. It can be attributed to this fact that in conventional HP-ETSCs, the fin is attached to the inner tube which facilitates the heat dissipation; whereas, the helical fin was only twisted around the heat pipe contributing to the heat transfer rate within the system. In 2021, Manirathnam et al. [18] used paraffin with CMC dispersion as a thickening agent to not have a leakage problem over the liquid state of the PCM in solar water heaters. The novelty of this work lies in experimental application of an SSPCM in a tankless direct-absorption ETSC (DA-ETSC) to not only avoid the leakage problem in solar collectors, but also directly absorb the input radiation. Hence, heat can be absorbed and stored directly without any thermal barrier implying a faster charging process for the SSPCM. Furthermore, the performance of the proposed SSPCM-DA-ETSC with one tube was generalized to a multi-tube DA-ETSC supplying the heat demand of a four-people family and the related techno-economic analysis has been presented.

2. Shape-stabilized phase change material

In order to store the excessive heat of the solar collector, an SSPCM was utilized to not only have a considerable amount of H\textsubscript{2} but also avoid the leakage problem while the solar system operating. The proposed SSPCM in this research is comprised of four elements, namely sodium acetate trihydrate (SAT), sodium phosphate monohydrate (SPM), carboxymethylcellulose (CMC), and expandable graphite. All the materials were provided by VWR Corporation in Germany and SAT is the main PCM; SPM was used as a nucleating agent, and CMC was employed as a thickening agent. Also, the expandable graphite was adopted to give not only a shape-stability property but also to increase the thermal conductivity of the SSPCM, as well as its black colour leads to improving the absorptivity of the material. In the following, related explanations about the SSPCM preparation and optimum processes have been given.

2.1. Material preparation

The SAT was placed inside an Erlenmeyer and it was placed inside a water-contained beaker to make sure the heat reaches the circumferential surface of the SAT. Then, the beaker was placed on a hot plate (electric heater) to melt the SAT as illustrated in Fig. 1(a), and then it was stirred by the magnetic stirrer. Afterwards, 2 wt% of SPM was added as the nucleating agent. After 20 min of magnetic stirring, 1 wt% of CMC was slowly added to the previous solution for the thickening agent while the stirrer was working to avoid the solution agglomeration. Next, the solution was again stirred to come up with a homogeneous solution and then the solution was kept inside the fridge for two days to become solid. On the other hand, as presented in Fig. 1(b), expandable graphite was employed to not only increase the thermal conductivity of the PCM but also offer a shape-stability property to it. Also, in order to enhance the surface contact of the expandable graphite, it was placed inside a furnace at 900 °C for 30 s to be converted into expanded graphite (EG) carried by a crucible container to withstand the furnace high temperature as demonstrated in Fig. 1(c).

At the next stage, the solid SAT-SPM-CMC was crushed in a grinder to turn into a powder so that it can be mixed with 4 wt%, and then the powdery mixture was similarly placed into a water-contained beaker heated on the hot plate. After that, when some part of the mixture was melted it was manually stirred to speed up the SSPCM melting process and contribute to placing the SAT-SPM-CMC inside the EG pores. After three times of stirring and ensuring well mixing of the SAT-SPM-CMC-EG (SSCCE), the proposed SSPCM was placed inside plastic bags and
kept at an atmospheric temperature. The following day, the solid SSPCM was crushed and ground to provide a powdery SSPCM for being used inside the solar collector.

2.2. Material optimization process

After development of the proposed SSPCM, the same process was conducted for 2 wt% and 3 wt% of CMC as well as 8 wt% of the EG to see the effect of different concentrations of CMC and EG on the thermal characteristics of the material. Since only the concentrations of CMC and EG are variable within the samples, the materials are indicated by SSCE (a, b) so that “a” represents the wt% of EG and “b” shows the wt% of CMC. As a whole, the six investigated SSPCMs are listed and clarified in Table 1.

Fig. 2 illustrates the SSPCMs compounds at 1, 2, and 3 wt% of the CMC as well as at 4 and 8 wt% of the EG.

3. Experimental setup

In this section, the construction process and the configurations of the tested solar thermal collector have been explained. Moreover, the implementation of the experiments and the related testing conditions have been clarified.

3.1. Setup description

The DAET was manufactured from borosilicate glass with a 2.5 mm thickness by ROOS Company [22]. Furthermore, a novel design of the stainless-steel heat exchanger (HEX) was regarded for the water flow passage as two U-pipes crossing each other (double U-pipe HEX) inside a borosilicate double-glazed DAET as illustrated in Fig. 3(a and b). Meanwhile, a PMMA-made cap was used to minimize the heat losses during the operation of the system. the SSPCM was well pressed during filling the tubes to ensure the contact between the material and the thermocouples. Fig. 3 (c) shows the contact of SSPCM with the HEX inside the DA-ETSC. Additionally, the polyethylene foam was utilized to insulate the pipes and the water hose in order to minimize the heat losses over the operation of the solar thermal system. Furthermore, two built-together ball valves were considered to regulate the water flow rate supplied by a thermal bath. Lastly, the collectors were positioned under a solar simulator at 45° angle. Table 2 gives the physical characteristics of the current experimental setup.

3.2. Implementation of experiments

Fig. 4 demonstrates the experimental setup of the tested DA-ETSC equipped with the developed SSPCM as a single-unit. The DA-ETSC was tested under the solar simulator in Kleinhorst Laboratory at the University of Twente. For this purpose, 850 gr of the SSPCM was placed inside the DAET over multiple melting PCM and refilling the tube to ensure the tube is well filled with the SSPCM and the thermocouples are acceptably attached to the material for the temperature measurement. The water hose and the pipes were well insulated by an elastomeric material and aluminum tape was wrapped over the insulation to reflect the incoming light. This contributed to maintaining the apparatus accessories at lower operational temperatures.

To test the thermal performance of the proposed DA-ETSC, six K-type thermocouples were employed to register the temperatures of the solar system components. Three thermocouples were positioned at the top, middle, and bottom parts of the tube to measure the SSPCM temperature, and they were placed at 30 cm distance from the opening of the DAET. It should be mentioned that the position of the thermocouples inside the SSPCM has been also illustrated in temperature-profile charts in the Results Section. In addition, two thermocouples were used for the inlet and outlet water temperatures measurement, and one thermocouple was used for recording the ambient temperature throughout the course of the experiments. Moreover, during the experiments, the connector parts of the thermocouples were well insulated to avoid being affected by the temperature rise. The experiments were conducted at 10, 27, and 40 LPH to investigate the effect of changing volume flow rate on the heat extraction from the SSPCM, and for adjusting the flow rate, a graded container and a stopwatch were employed.

4. Techno-economic correlations

In this section, the thermodynamic equations which are required for analyzing the solar collectors are given, and the formulas for doing a cost and carbon-footprint analyses of the proposed DA-ETSC have been elaborated.
4.1. Thermal energy analysis

Three different efficiencies have been defined for analyzing the charging and discharging processes of the proposed solar collector-storage system, namely heat absorption efficiency, heat storage efficiency, and discharging efficiency of the solar collector. The heat ab-
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where \(Q_s\) and \(Q_u\) are the extracted heat from the SSPCM and the stored energy in the SSPCM, successively. The heat extraction value can be obtained from the initial time of discharge to the final time of discharge using [25]:

\[
Q_s = \bar{m} c_p \int_{t_{\text{ini}}\text{dis}}^{t_{\text{dis}}} (T_{\text{ini}} - T_\text{amb}) \, dt
\]

(5)

in which \(\bar{m}\), \(c_p\), \(T_{\text{ini}}\), \(T_\text{amb}\), \(t_{\text{ini}}\text{dis}\) and \(t_{\text{dis}}\) are mass flow rate, specific heat of water, inlet temperature, outlet temperature, initial time of discharge process, and final time of discharge process, successively. Finally, the discharging efficiency of the proposed solar collector has been acquired by:

\[
\eta_s = \frac{Q_s}{Q_{\text{in}}} + \frac{Q_{\text{loss}}}{Q_{\text{in}}}
\]

(6)

Furthermore, the energy content of the DA-ETSC can be written as [26]:

\[
Q_{\text{in}} = Q_s + Q_{\text{loss}}
\]

(7)

where \(Q_{\text{loss}}\) is presenting the heat loss value as [26]:

\[
Q_{\text{loss}} = U_L A_s (T_\text{amb} - T_\text{ini})
\]

(8)

in which \(U_L\), \(T_\text{ini}\), and \(T_\text{amb}\) are the heat loss coefficient, the absorber temperature (i.e., which is the PCM temperature in this study), and the ambient temperature, respectively. After obtaining the \(U_L\) for both charging and discharging processes from the aforementioned correlation, the overall \(U_L\) has been obtained by:

\[
U_L = \frac{U_L \text{ch} \times t_{\text{ch}} + U_L \text{dis} \times t_{\text{dis}}}{t_{\text{ch}} + t_{\text{dis}}}
\]

(9)

On the other hand, in order to generalize the performance of a single-tube collector to the multiple-tube solar collector, the heat removal factor is defined as [27]:

\[
F_R = \frac{\bar{m} c_p \int_{t_{\text{ini}}\text{dis}}^{t_{\text{dis}}} (T_{\text{ini}} - T_\text{amb}) \, dt}{A_s (I \times t_{\text{ini}} \alpha_{\text{PCM}} - U_L (T_\text{ini} - T_\text{amb})}
\]

(10)

Hence, the useful heat gain of next similar tubes can be obtained

\[
\eta_{\text{dis}} = \frac{Q_s}{Q_{\text{in}}}
\]

(4)

\[
\eta_{\text{dis}} = \frac{Q_s}{Q_{\text{in}}}
\]

Table 2

| Characteristic                  | Unit   | Dimension and substance |
|---------------------------------|--------|-------------------------|
| Length of the DAET              | m      | 0.5                     |
| Inner diameter of the DAET      | m      | 0.048                   |
| Outer diameter of the DAET      | m      | 0.075                   |
| Number of the DAETs             | -      | 1                       |
| Aperture area of the DA-ETSC    | m²     | 0.0375                  |
| Length of the double U-pipe HEX | m      | 2.2                     |
| Inner diameter of the U-pipe HEX| m      | 0.004                   |
| Outer diameter of the U-pipe HEX| m      | 0.006                   |
| Tilted angle of the collector   | Degree | 45                      |
| Working temperature range       | Degree C (°) | 20-80                  |
| Material of double U-pipe HEX   | -      | Stainless steel         |
| Material of glass               | -      | Borosilicate            |
| Material of frame               | -      | Aluminum                |
| Material of insulation          | -      | Polyethylene foam       |

\[\eta_\text{abs} = \frac{Q_u}{Q_\text{in}} \] (1)

in which \(Q_u\) and \(Q_\text{in}\) are stored energy in the SSPCM and the input energy, respectively estimated from [24]:

\[Q_u = M c_p,\text{pcm} (T_{\text{ini}} - T_{\text{pcm}}) + M c_p,\text{film} (T_{\text{film}} - T_{\text{ini}}) + M c_p,\text{film} (T_{\text{film}} - T_{\text{ini}})\]

(2)

\[Q_{\text{in}} = A_s \times I \times t_{\text{ch}}\]

(3)

where \(M\), \(c_p,\text{pcm}\), \(c_p,\text{film}\), \(H_p\), \(T_{\text{pcm}}\), \(T_{\text{ini}}\), and \(T_{\text{film}}\) are the mass, the specific heat in the solid-state, the specific heat in the melted-state, heat of fusion, initial temperature, melting temperature, and final temperature of the developed SSPCM, successively. Also, \(A_s\), \(I\), and \(t_{\text{ch}}\) are the collector surface area, the radiation intensity, and the charging period, respectively. Moreover, the heat storage efficiency has been defined by:

\[
\eta_\text{abs} = \frac{Q_u}{Q_\text{in}}
\] (4)

Fig. 4. Experimental setup of the SSPCM-DA-ETSC tested under the solar simulator in the laboratory.
from having the data from the previous tube which has been experimented. Thereafter, the performance of the solar collector with N number of tubes included will be [26]:

\[ F_{k}U_{t,\text{therm}} = F_{b}U_{t} \left[ \frac{1 - (1 - K)^{N}}{NK} \right] \]  \hspace{1cm} (11)

in which K is the correction factor as [26]:

\[ K = \frac{A_{e}F_{k}U_{t}}{\eta_{\text{heater}}} \]  \hspace{1cm} (12)

In other words, the correction factor describes how much the efficiency has been reduced using the next tubes as the result of an increase in the overall heat loss of the collector.

4.2. Cost and carbon-footprint investigations

The guidelines for the cost analysis of the constructed DA-ETSC have been presented in this section. It is assumed that every day 300 L of hot water is required for an average four-person family and over 100 days in a year the hot water will be supplied by an electric water heater due to the cloudy weather conditions. It is assumed that the electric water heater employs water as the working fluid and the proposed solar system uses the SSPCM as the working fluid to meet the hot water demand. The total annual cost (TAC) of the proposed solar collector-storage system can be defined as [28]:

\[ TAC = AC_{f} - SFF \times SV + IC_{\text{sys}} \times CRF + AO\&MC \]  \hspace{1cm} (13)

where \( AC_{f} \), SFF, SV, IC\(_{\text{sys}}\), CRF, and AO\&MC are the annual cost of fuel, sinking fund factor, salvage value of the system, the initial cost of the proposed system, capital recovery factor, and annual operation and maintenance cost. The annual cost of fuel \( (AC_{f}) \) can be calculated through [29]:

\[ AC_{f} = \frac{n_{s} \times E_{\text{HW}} \times EC}{\eta_{\text{heater}}} \]  \hspace{1cm} (14)

where, \( n_{s} \), \( E_{\text{HW}} \), \( EC \), and \( \eta_{\text{heater}} \) are the number of days in a year when hot water is supplied by the electric heater (i.e., cloudy days), the required energy to heat up the water from 20 °C to 56 °C in terms of kWh/day on cloudy days, the electricity cost per kWh, and the efficiency of the electric water heater (i.e., geyser). In addition, the sinking funding factor (SFF) is estimated by [28]:

\[ SFF = \frac{i}{(1 + i)^{N} - 1} \]  \hspace{1cm} (15)

in which \( i \) and \( N \) are the annual bank interest rate and the lifetime of the system in years, which is usually considered 20 years. Moreover, the capital recovery factor (CRF) is calculated from [28]:

\[ CRF = \frac{(1 + i)^{N} \times i}{(1 + i)^{N} - 1} \]  \hspace{1cm} (16)

Then, the fixed annual cost of the system will be obtained by means of [28]:

\[ FAC_{\text{sys}} = IC_{\text{sys}} \times CRF \]  \hspace{1cm} (17)

Then, the parameter AO\&MC can be obtained from [30]:

\[ AO\&MC = 0.15 \times FAC_{\text{sys}} \]  \hspace{1cm} (18)

Moreover, the parameter SV will be defined as [29]:

\[ SV = IC_{\text{sys}} \times \left( 1 - \frac{N}{N_{\text{max}}} \right) \]  \hspace{1cm} (19)

Then, the TAC of the solar system considering all the financial parameters will be acquired. Ultimately, the payback period of the system will be defined as [30]:

\[ PB = \frac{\ln \left( \frac{CF}{CF - (IC_{\text{sys}})} \right)}{\ln(1 + i)} \]  \hspace{1cm} (20)

where \( CF \) is the amount of money that should have been paid for electricity to meet all the annual hot water demand without using the solar system. Considering 300 L of daily hot ware demand for a four-person family, the parameter \( CF \) can be calculated from:

\[ CF = \frac{365 \times E_{\text{HW}} \times EC}{\eta_{\text{heater}}} \]  \hspace{1cm} (21)

Furthermore, the CO\(_{2}\) emission mitigation of running the proposed solar collector-storage system can be obtained by [31]:

\[ R_{CO_{2}} = \frac{(E_{\text{out,year}} \times n) - E_{\text{em}}}{1000} \times 2 \]  \hspace{1cm} (22)

in which \( R_{CO_{2}} \), \( E_{\text{out,year}} \), and \( E_{\text{em}} \) are respectively the reduction of the CO\(_{2}\) emission in tons throughout the longevity of the system, annual output of the proposed solar system (kWh), and the embodied energy (kWh).

4.3. Uncertainty analysis

In this part, the uncertainty of the experimental devices has been explored to make sure about the trustworthiness of the acquired results. The standard uncertainty value for each component has been obtained from [23]:

\[ u = \frac{\text{Measurement accuracy value}}{1.73} \]  \hspace{1cm} (23)

In addition, the energy efficiency value uncertainty of the DA-ETSC was acquired by [23]:

\[ \Delta \eta = \left[ \left( \frac{\partial \eta}{\partial \rho} \Delta \rho \right)^{2} + \left( \frac{\partial \eta}{\partial \Delta T} \Delta \eta \right)^{2} + \left( \frac{\partial \eta}{\partial \eta_{\text{heater}}} \Delta \eta \right)^{2} \right]^{1/2} \]  \hspace{1cm} (24)

where \( \rho \) is the density of the working fluid, which is water at this study.

Table 3 shows the uncertainty values of different components utilized in this research.

5. Results and discussions

In this section, the findings of the present study have been presented for the synthesized SSPCM and the performance analysis of the direct-absorption solar collector-storage system. Regarding the solar collector discussions; first, the performance of the DAET was elaborated, and then the current design has been generalized to a large system to meet the whole heat demand of a family. Lastly, the cost analysis and the prospective reduction of the carbon-footprint have been given.

5.1. Material characterisation

After synthesizing the SSPCM, it needs to be ensured that the prepared material has an acceptable heat capacity. For this purpose, the
5.2. Results of the proposed solar collector

The DAET was filled with the SSPCM and tested according to the conditions presented in Table 5 to assess its thermal performance as the DA-ETSC under 1 kW/m² radiation intensity as the standard solar testing conditions. In addition, each measurement was conducted at least twice under the same environmental conditions to make sure about the reliability of the data so that the temperature values and the temperature variation trends agree with each other.

5.2.1. Temperature variations of the direct-absorption evacuated tube

Fig. 8(a) illustrates the charging process of the SSPCM inside the DA-ETSC without any flow rate in the U-pipe HEX to let the material become charged sooner. It can be witnessed that the temperature rise of the SSPCM at the bottom part is slightly greater than that of the middle part even though the middle part is closer to the light source. It is because the thermocouple positioned at the bottom part of the DAET is adjacent to the metallic stainless-steel U-pipe HEX, the high thermal conductivity of which leads to a faster charging process of the SSPCM at the bottom part. On the other hand, during the charging process, the inlet temperature is shown higher than the outlet temperature. Since there is not any water flow during the charging process of the SSPCM, the inlet-outlet thermocouples are merely indicating the temperatures of stagnant water, which has already been existed inside the pipe (HEX). After the system is wholly charged and the lamps went off, the water flow was started with adjusting the inlet water at 20 °C to discharge the SSPCM and produce hot water. In all the discharge experiments, the water passage inside the HEX has been illustrated so that the water enters the solar system from the top part (blue circle) and after extracting the heat from the SSPCM, it exits the system from the right-hand side (red circle). Fig. 8(b) shows the discharging process of the solar collector-storage system at a 10 LPH flow rate along with showing the positions of the thermocouples, which measured the SSPCM temperature change. As it can be seen, the discharging process is 41 min without any input energy (i.e., the solar simulator is off) and the average inlet-outlet water temperature difference is 8.09 °C. In addition, it can be noticed that the temperatures of the SSPCM in the top and bottom parts of the tube have been dropped sooner than that of the middle part. This is due to the fact that they are closer to the stainless-steel U-pipe and therefore at those locations the heat transfer from PCM to the heat transfer fluid is faster and consequently discharging of PCM is faster.

Also, Fig. 8(c) shows the discharging of the solar collector at 27 LPH. It can be seen that the discharging time has decreased to 26 min with a 4.7 °C average temperature difference. Similarly, Fig. 8(d) illustrates the discharging process of the collector at a 40 LPH flow rate amount. In this case, the discharging time has decreased to 21 min with an average temperature difference of 3.3 °C.

5.2.2. Performance analysis at different flow rates

Table 6 presents the performance data for the manufactured DA-ETSC storage system. Considering no-flow condition during charging under radiation intensity of 1 kW/m², the discharging times of the SSPCM at 10, 27, and 40 LPH flow rates have lasted 2462 s (41 min), 1550 s (26 min), and 1206 s (20 min), respectively. In addition, it is shown that the heat extraction values at the corresponding flow rates have been 232, 229, and 187 kJ so the heat extraction decreases with increasing the flow rate since the water inside the HEX has less time to extract heat from the material. Subsequently, the corresponding heat loss values are 63, 68 and 108 kJ regarding the investigated water flow rates, which shows the considerable difference between the lowest and the highest flow rates. Moreover, the efficiency of the solar collectors
has been acquired as 82%, which is around 15% more than that of traditional water-based ETSCs [34]. It is due to the direct absorption of the radiation without any thermal barrier, high energy density value and the higher thermal conductivity of the utilized SSPCM compared to the water as the heat storage media. Meanwhile, the solar collector discharge efficiencies at the corresponding flow rates are 64, 63, and 51%, respectively.

As a whole, it can be concluded that increasing the flow rate from 10 to 27 LPH has not affected the collector’s performance considerably; however, raising the flow rate to 40 LPH has diminished the discharging performance tangibly. Hence, it can be derived that the 27 LPH flow rate must be applied to the solar collector-storage system because using a 10 LPH flow rate is highly susceptible to flow disruption as the result of pressure and friction losses.

Also, Fig. 9 indicates the useful heat of the proposed DA-ETSC throughout the discharging processes at 10, 27, and 40 flow rates. As it can be noticed, the useful heat gain of the solar collector is rather low at 10 LPH and at 40 LPH has diminished the discharging performance tangibly. Hence, it can be derived that the 27 LPH flow rate must be applied to the solar collector-storage system because using a 10 LPH flow rate is highly susceptible to flow disruption as the result of pressure and friction losses.

5.2.3. Design of solar collector for supplying the total heat demand

After analyzing the single-tube solar collector-storage system, the performance of the system has been generalized to a multi-tube solar water heater considering a 27 LPH flow rate during the discharging process as shown in Fig. 10(a). The aim of this part is to define the amount of SSPCM and the required number of DAETs to provide 300 L of hot water at 56°C on a daily basis. Therefore, by obtaining the heat removal factor for the first tube using Eq. (10), the performance of the next tubes is obtained by exploiting Eqs. (11 and 12). It is assumed that the maximum possible water temperature is 56°C (i.e., no more than the melting point of the SSPCM). Considering this, by using 25 similar PCM-contained DAETs, the hot water at 56°C can be supplied for 22 min.

Furthermore, assuming that each similar DAET is 0.5 m long with the same diameter as the tube in this study, each ET will contain 0.85 kg of SSPCM with 8 m length of the stainless-steel HEX. In order to supply 300

Table 4

| Material | $H_f$ (kJ/kg) | $C_p,l$ (kJ/kg.K) | $C_p,s$ (kJ/kg.K) |
|----------|---------------|------------------|------------------|
| SSCE (41) | 189.04 | 2.74 | 2.53 |
| SSCE (42) | 194.54 | 2.86 | 2.24 |
| SSCE (43) | 160.98 | 2.86 | 2.17 |
| SSCE (81) | 144.49 | 2.59 | 2.04 |
| SSCE (82) | 148.81 | 2.57 | 1.96 |
| SSCE (83) | 188.66 | 2.39 | 1.85 |

$T_m$ range = 55 – 57°C
L of hot water, the required energy is:

\[ Q_w = mC_p\Delta T = 300 \times 10^{-3} \times 997.8 \times 4.18 \times (56 - 20) = 45MJ \]  

(25)

Hence, the required amount of SSPCM which can store this amount of energy can be obtained from Eq. (2); therefore, 140 kg of the SSPCM is required to store the heat inside 164 DAETs placed on the rooftop (6.15 m² collector area). Fig. 10(b) illustrates the discharge heat loss coefficient and collector heat removal factor values in terms of the number of tubes. As it can be seen, the values of heat loss coefficients increase with the increase of the number of tubes up to 25 tubes and after that this trend reduces. It is because by adding more tubes the water remains at higher temperatures for longer times, which leads to enhancing the heat losses. Nonetheless, the increase of tubes brings about a higher heat absorption surface (input energy) that reduces the increased rate of heat loss coefficient values.

However, it can be noticed that the values of heat removal factors are consistently decreasing with adding to the tubes and it is because this factor is only dependent on the useful heat gain of the collector and considering the absorber at ambient temperature. By increasing the number of tubes, the useful heat gain decreases and the ambient temperature is constant; hence the heat removal factor is continuously reduced. The final design can be considered as 4 sets of 40-tube DA-ETSCs (one set will have 44 DAETs) and each set is working at 27 LPH flow rate so that the accumulated flow rate will be \( 4 \times 27 = 108 \) LPH which is an acceptable rate for domestic applications [36]. This design not only leads to raising the flow rate of hot water, but also creates a roughly uniform discharge rate for the tubes in all DA-ETSC sets.

Furthermore, the other advantage of this design is the fact that usually a 300 L tank is used as the water storage tank inside the house in addition to the solar collector on the rooftop. However, in this study, a tankless solar collector is proposed with around 140 kg of the heat storage medium without any need for a separate hot water tank at home occupying 2.14 times less space compared to using a water tank.

Table 7 shows the characteristics of the large-scale DA-ETSC which

**Table 5**

Environmental and operational conditions of the conducted experiments.

| Test   | Conditional parameter                  | Value | Unit |
|--------|----------------------------------------|-------|------|
| Test 1 | Mass flow rate during charging         | 0     | LPH  |
|        | Mass flow rate during discharging      | 10    | LPH  |
|        | Ambient temperature                    | 20    | °C   |
|        | Radiation intensity                    | 1     | kW/m²|
|        | Place of experiment                    | Laboratory |      |
| Test 2 | Mass flow rate during charging         | 0     | LPH  |
|        | Mass flow rate during discharging      | 27    | LPH  |
|        | Ambient temperature                    | 20    | °C   |
|        | Radiation intensity                    | 1     | kW/m²|
|        | Place of experiment                    | Laboratory |      |
| Test 3 | Mass flow rate during charging         | 0     | LPH  |
|        | Mass flow rate during discharging      | 40    | LPH  |
|        | Ambient temperature                    | 20    | °C   |
|        | Radiation intensity                    | 1     | kW/m²|
|        | Place of experiment                    | Laboratory |      |

Fig. 7. Heat of fusion and supercooling degree values for every cycle of the T-history test regarding SSCE (42) material for samples A, B, C, and D.
Fig. 8. Charts for temperature variation of SSPCM, inlet-outlet water, and ambient regarding a) charging process without flow rate, b) discharging process at 10 LPH flow rate, c) discharging process at 27 LPH flow rate, and d) discharging process at 40 LPH water flow rate.

**Table 6**

Thermal analysis of the DA-ETSC without any water flow during the charging process and three flow rates during the discharging process.

| No. | Parameter Description | Number of the employed Eq. | Flow rate during the discharging process (LPH) |
|-----|-----------------------|-----------------------------|-----------------------------------------------|
| 1.  | \( t_{ch} \) (s)     | –                           | 9650 9650 9650                                |
| 2.  | \( t_{dis} \) (s)     | 2                           | 2462 1550 1206                                |
| 3.  | \( Q_m \) (kJ)        | 3                           | 361.87 361.87 361.87                          |
| 4.  | \( T_{pre} \) (\(^{o}\)C) | –                           | 20 20 20                                      |
| 5.  | \( T_{ini, PCM} \) (\(^{o}\)C) | –                           | 63.86 64.37 64.54                             |
| 6.  | \( Q_a \) (kJ)        | 2                           | 295.41 297.23 296.79                          |
| 7.  | \( Q_{dis} \) (kJ)    | 5                           | 232.02 229.2 187.96                           |
| 8.  | \( Q_{loss, ch} \) (kJ) | 7                           | 66.46 64.63 65.07                             |
| 9.  | \( Q_{loss, dis} \) (kJ) | 7                           | 63.39 68.03 108.083                           |
| 10. | \( F_{in} \)          | 10                          | 0.79 0.78 0.64                                |
| 11. | \( U_{L, ch} \) (W/m\(^2\).K) | 8                           | 4.08 3.96 3.99                                |
| 12. | \( U_{L, dis} \) (W/m\(^2\).K) | 8                           | 15.25 26.01 53.47                             |
| 13. | \( U_{L} \) (W/m\(^2\).K) | 9                           | 6.35 7.01 9.49                                |
| 14. | \( \eta_{ab} \)       | 4                           | 0.78 0.77 0.63                                |
| 15. | \( \eta_{ab} \)       | 6                           | 0.64 0.63 0.51                                |
| 16. | \( \eta_{ab} \)       | 1                           | 0.82 0.82 0.82                                |
| 17. | \( \eta_{ab} \)       |                             | 0.82 0.82 0.82                                |

Fig. 9. \( Q_u \) values of the investigated DA-ETSC at 10, 27, and 40 LPH water flow rates over the discharge periods of experiments.

**Table 6**

Thermal analysis of the DA-ETSC without any water flow during the charging process and three flow rates during the discharging process.
can provide all the required hot water demand of a normal four-people family adopted from this study.

### 5.3. Cost analysis

Assuming that each similar DAET is 0.5 m long with the same diameter as the tube in this study, each ET contains 0.85 kg of SSPCM with an 2 m length of the stainless-steel HEX. In order to supply 300 L of hot water, it is estimated that 140 kg of the SSPCM is required to store the heat; hence, 164 DAETs are needed to be placed on the rooftop. The cost analysis has been conducted for considering the whole heat demand of a four-people family using 164 DAETs to supply 300 L of hot water per day and it is assumed that both DAETs and SSPCM are mass-produced so that the cost is fairly lower. The detailed calculation parameters of the cost analysis are presented in Appendix A. Table A.1 lists the components of the utilized SSPCM-based solar water heater along with their price values presenting the total price of 3752 € for the whole system as an initial cost. Moreover, Table A.2 illustrates the cost analysis parameters and their calculations regarding the European bank interest rate of 3 %, 10 years of the longevity of the solar system, assuming 100 days of cloudy days in a year, the geyser efficiency of 80 %, and the electricity cost of 0.12 €/kWh Europe [37]. The TAC of this solar system is 498 € obtained from Eq. (13); whereas, in the case of using electricity for meeting the whole hot water demand the annual cost of electricity will be:

\[ EC_{\text{non-solar}} = \text{Annualheatdemand(kWh)} \times EC = 6367.7 \times 0.12 = 764.12\text{€} \]  

which shows a monthly saving in the case of using this solar thermal system. Also, the PBP of the proposed system has been estimated as around 6 years, i.e., the last four years of the system’s longevity offers net profit without paying for the domestic hot water production-consumption process.

### 5.4. Carbon-footprint reduction and environmental aspects

The CO₂ emission mitigation evaluation of the proposed solar collector-storage system has been discussed in this part using the annual output of the system, the longevity of the system, and the total embodied energy. Table B in Appendix B illustrates the embodied energy values of all components used to construct the large-scale solar system to meet the whole heat demand demonstrating a 666-kWh embodied energy amount. Moreover, the annual energy out of the system is to produce 300 L of hot water with a 30 °C inlet-outlet temperature difference for 265 days (the heat demand of the other 100 days is supplied by the geyser); hence the parameter \( E_{\text{out, year}} \) will be acquired as follows:

\[ E_{\text{out, year}} = \frac{(300 \times 4.18 \times 30) \times 265}{5600} = 2769.25\text{kWh/year} \]  

Then, the parameter \( R_{\text{CO}_2} \) over the longevity of the proposed DA-ETSC (10 years) will be obtained using Eq. (22) as:

\[ R_{\text{CO}_2} = \frac{((2769.25 \times 10) - 666) \times 2}{1000} = 54.05\text{tons} \]  

Therefore, it can be stated that using this SSPCM-based solar collector can save around 54 tons of CO₂ emission to the atmosphere within 10 years of its longevity (i.e., 5.4 tons/year). This demonstrates how much environmentally effective it will be if this solar thermal system becomes commercialized and utilized widely.

### 6. Conclusion

In this work, a novel design of tankless ETSC-storage system has been presented employing a SSPCM as the thermal energy storage media and the system was performed on a lab scale for domestic hot water...
The proposed material was well stable over 12 melting-solidification cycles and the highest energy density of the SSPCM was achieved at 2 wt% of CMC and 4 wt% of EG presenting less than 4 °C supercooling degree.

The energy to fully melt (charge) the 850 gr-SSPCM inside the DA-ETSC was obtained as 2.68 kWh/m² and the discharging time of the material at 10, 27, and 40 LPH were 41, 26, and 21 min, respectively.

The average water temperature difference values during the discharging process at 10, 27, and 40 LPH flow rates were 8.09, 4.7, and 3.3 °C, respectively with the corresponding heat gains of 232, 229, and 187 kJ, successively.

The heat absorption efficiency of the proposed DA-ETSC is 82 %, which is around 15 % higher than water-based traditional ETSCs, which work the whole day long, and the storage efficiency at the investigated flow rates were 78, 77, and 61 %, respectively.

Regarding the same charging conditions, the discharging efficiency values at 10, 27, and 40 LPH were 64, 63, and 51 %; hence, the optimum flow rate is 27 LPH since the discharging efficiency is close to that at 10 LPH and the risk of head loss is lower.

Considering supplying 300 L of daily hot water, 141 kg of the SSPCM and 164 DAETs are required without any need for a separate hot water tank storage.

The PBP of 6 years has been indicated for the proposed DA-ETSC with impedings 5.4 tons of annual CO₂ emission.

CRediT authorship contribution statement

Gholamabas Sadeghi: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing. Mohammad Mehrali: Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. Mina Shahi: Validation, Writing – review & editing, Supervision. Gerrit Brem: Supervision. Amirhoushang Mahmoudi: Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors want to appreciate the Thermal Engineering Laboratory at the University of Twente for allowing the development of the concept and helping with provision of required materials. Also, special thanks to TCO Company for assisting with the related challenges during the system construction.

Funding information

This research work has been supported and funded by the Netherlands’ TKI Urban Energy, Project Inno-DSS with project number 1621202.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.116176.
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