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PII: S2451-9049(18)30641-3
DOI: <https://doi.org/10.1016/j.tsep.2019.02.010>
Reference: TSEP 314

To appear in: *Thermal Science and Engineering Progress*

Received Date: 18 November 2018
Revised Date: 26 February 2019
Accepted Date: 28 February 2019

Please cite this article as: M.S. Mahdi, H.B. Mahood, A.A. Khadom, A.N. Campbell, M. Hasan, A.O. Sharif, Experimental Investigation of the Thermal Performance of a Helical Coil Latent Heat Thermal Energy Storage for Solar Energy Applications, *Thermal Science and Engineering Progress* (2019), doi: <https://doi.org/10.1016/j.tsep.2019.02.010>

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Experimental Investigation of the Thermal Performance of a Helical Coil Latent Heat Thermal Energy Storage for Solar Energy Applications

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Abstract

Thermal performance of a Latent Heat helical coil Thermal Energy Storage (LHTS) was investigated experimentally for both phases; melting and solidification processes. Paraffin wax (type P56-58) and tap water were used as a Phase Change Material (PCM), and a Heat Transfer Fluid (HTF), respectively. The paraffin wax (PCM) thermos-physical properties were determined experimentally. To simulate the solar energy conditions, three different initial temperatures (70 °C, 75 °C and 80 °C) and flow rates (1 L/min, 3 L/min and 5 L/min) of the HTF were tested throughout the PCM melting experiments, while the temperature of HTF was only 30 °C with the same flow rates for solidification process. The storage was completely insulated to reduce the heat losses. The PCM temperature during the melting and solidification processes was measured with time using 16 K-type calibrated thermocouples distributed along the PCM axially and radially. The experimental results showed that contrary to the solidification process, the melting was a superior in the helical coil LHTS under different operational conditions. Axial and radial melting fronts were noticed during the PCM melting process which considerably shortened the melting time under the effect of convection and a shape like a pyramid is formed at the core of the storage. Initial temperature of heat transfer fluid (HTF) was significantly affected the melting process and the increased of it from 70 °C to 75 °C and from 75 °C to 80 °C resulted in shortening the total melting time by about 34.5% and 27.2% respectively. An optimum HTF flow rate was observed during the melting process and it was found to be 3 L/min under the operational conditions of the

present experiments. Contrary, the flow rate of HTF was insignificant during the solidification process. The initial temperature of HTF was slightly affected the effectiveness of the melting process. In spite of the efficiency of the melting process, enhancement of the solidification in the coiled LHTS is necessary in order to use the process in the thermal applications of solar energy.

Keywords: Thermal energy storage, LHTS, PCM, experimental technique, helical coil, thermal performance

1. Introduction

Global energy demand and the consequent emission of greenhouse gases such as CO₂, has become a high-priority issue that must be tackled. Renewable energy sources are currently in the position to be making such a solution possible. Among the various alternative energy resources that could be exploited, solar energy which has received more attention in recent years. A substantial amount of radiant energy (about 174 PW) reaches the earth from the sun [1]. Almost a half, about 51% (89 PW) of this energy reaches the land while other portion (about 49%) is attenuated at the surface of the earth [1]. There is clearly still a very significant quantity of solar energy that is available and it therefore could be utilized if collected and stored efficiently. Collection and storage are required to overcome the low-density of the energy, and its time dependent nature. To be able to exploit the stored energy effectively requires an efficient thermal energy storage system, which is designed specifically to meet the particular energy demand, especially during peak periods. Thus, thermal energy storage becomes an essential component in thermal solar applications. To illustrate the potential benefit of this technology, the case of domestic heating in Europe can be considered. Over a quarter of the energy consumed in Europe (about 26%) is supplied to household thermal energy systems. The vast majority, about 80%, of this energy is consumed for heating [2]. It is therefore clear that utilizing solar thermal energy storage to displace some or all of this heating requirement has the potential to reduce the demand on the national energy network.

Depending on the material utilized as the storage medium, thermal energy storage can be classified into two main types: sensible and latent heat. In contrast to sensible heat systems, the material used in latent heat thermal energy storage undergoes a phase change, usually melting and solidification, during the charging and discharging phases. Accordingly, the temperature of the phase change material (PCM) remains approximately constant during the phase change process. The heat of fusion, associated with this phase change, is one of the

key parameters governing selection of the specific PCM. The additional selection criteria are primarily concerned with the thermos-physical properties of the material, such as the melting point, heat capacity, thermal conductivity, and density of the PCM [3]. There is no single material can fulfill the criteria for all of the important properties; thus, no single PCM could be used for all applications. The selection of a PCM for a specific application therefore needs careful consideration. Paraffin has often been investigated as a PCM because it has a high latent heat, is non-corrosive, highly chemically stable and non-toxic. Nonetheless, the low thermal conductivity of the wax remains the main obstacle to its use as a PCM in latent heat thermal energy storage (LHTS). Many current studies have thus concentrated on improving the heat exchange process in the PCM, utilizing different techniques. These techniques have included adding fines to shell and tube storage [5-11] to increase the heat transfer area and adding nano-materials [12-19] to the PCM to improve the thermal conductivity.

The helical coiled tube is a design that can be implemented in LHTS to enhance the thermal performance during the charging and discharging processes. This design has many advantages over conventional designs; e.g., it is simple in design and construction, it offers a high heat transfer area within a small volume and the secondary vortices induced by the helical flow increase fluid mixing across the tube and consequently improve heat transfer. Despite these apparent advantages, and in contrast to shell and tube thermal energy storage [20-27], little attention has been paid in the literature to these devices. There is a particular dearth of experimental measurements, therefore the thermal performance of the coiled tube LHTS has not been fully characterised.

However, Zong-He et al. [28] simulated the charging and discharging process of internally melted ice-on-coil energy storage. Their simulation investigated the influence of different parameters, such as tube material and diameter, on the thermal performance of the ice thermal storage. They showed that an increase in the coiled tube diameter resulted in an enhancement of the thermal efficiency. Testing of two different configurations of coiled tube LHTS under various flow rates of heat transfer fluid (HTF) was carried out experimentally by Castell et al. [29]. They showed that the effectiveness of the storage was invariant with time but was increased by increasing the heat transfer area and decreasing working fluid flow rate. On the other hand, Tay et al. [30] observed experimentally, and simulated numerically using CFD, that the efficiency of the LHTS is high only when the temperature difference in the PCM was low. Focusing on the solar thermal applications, Ziyi Ling et al. [31] selected mannitol (melting temperature of 167°C, and latent heat of 323 kJ/kg) as a PCM for use with a coiled tube thermal energy storage systems, to be applied as a solar water heater. Their experimental

results showed that mannitol was an effective storage medium and its thermal performance was significantly affected by both the inlet flow rate and the temperature of the HTF. Quantitatively, they found that 14 kg of PCM can provide approximately 100 L of warm water with temperature of 55°C. Korti and Tlemsani [32] tested three different types of paraffin as a PCM in a helical coil thermal energy storage system under different HTF flow rates and temperatures. By analysing the temperature of the PCM and the HTF, the solid fraction in the PCM and the thermal effectiveness, they observed that the HTF flow rate has a more significant effect on the charging process than it does on the discharging process. Also, the HTF inlet temperature had significant impact on the LHTS performance. They showed that the charging and discharging processes could be improved by 42.4% and 66%, respectively, when a coiled tube was added to the paraffin. Using a composite PCM, Chen et al. [33] simulated the thermal performance of a coiled tube LHTS, which used a paraffin wax/expanded graphite composite as the PCM. They found that the performance of the energy storage was greatly influenced by the temperature difference between PCM and HTF, but there was no impact changing the Reynolds number of the HTF. Recently, Dinker et al. [34] performed a detailed set of experiments examining the thermal performance of a horizontal helical tube thermal energy storage system which used beeswax as a PCM in a rectangular shell. The thermal characteristics during the charging process under different flow rates of HTF (0.25 to 1 L/min) and temperatures (60°C, 70°C and 80°C) were tested. The efficiency and heat transfer coefficient of the LHTS were examined. They observed that both the HTF flow rate and temperature affected the charging time and efficiency of the storage. An increase in the flow rate was seen to result in a decrease in both the charging time and the efficiency of the storage. The charging time was increased by an increase of the initial temperature of working fluid. The maximum charging efficiency was obtained with HTF temperature and flow rate of 80°C and 0.5 L/min respectively. Dinker et al. concluded that the performance of natural beeswax as a PCM was better than other conventional PCM choices that are used in low temperature ranges. To improve the thermal performance of LHTS Delgado et al. [35] measured the heat transfer coefficient and volumetric energy density of an agitated heated tank containing a PCM. They postulated that the mixing would improve the thermal performance of the LHTS. The heat transfer coefficient, based on the impeller Reynolds number, between the helical coil and the agitated PCM was determined by solving the time dependent enthalpy balance using the measured temperature profiles. It was shown that when the stirring rate was 290 – 600 rpm, the overall heat transfer coefficient was higher

than in an unstirred system by 3.5 – 5.5 times. The thermal storage efficiency was improved from 77% to 100% under a low stirring rate. More recently, Kabbaraa et al. [36] measured the thermal characteristics of a coiled tube thermal energy storage using dodecanoic acid as a PCM. The results indicated that the natural convection and conduction control the heat transfer during charging and discharging processes. Also, the inlet temperature of the HTF was had a more substantial effect on the performance of the storage than did the HTF flow rate.

For assessing the applicability of coiled type LHTS in the thermal solar application, in this paper, experimental measurements of the thermal performance of a vertical coiled tube LHTS unit, which used paraffin as the PCM and tap water as HTF, are reported. Results for different operational conditions, such as HTF flow rate and initial temperature, are presented. The experiments considered both the PCM melting and solidification processes and the temperature and liquid fraction of the PCM were measured axially and radially.

2. Experimental work

2.1 Experimental apparatus and materials

In this work, an experimental investigation was carried out on a custom built coiled LHTS unit. A 7 m copper pipe was wound in to a 16 turn coil, with 12.5 cm centreline diameter. The coil was embedded in a 17.5 cm diameter acrylic shell. The shell side was filled with 10 kg of P56-58 paraffin wax. The outside surface of the shell was well insulated by using a 4 cm thick layer of glass wool with a laminated surface. The specifications of the LHTS unit appear in [Table 1](#). The experimental set-up that was fabricated for is shown in [Figure 1](#).

This set-up was used for evaluating the heat transfer characteristics during both the melting and solidification processes. The LHTS unit was mounted vertically. The experimental set-up comprised the LHTS unit (shell and coil), 22 K-type thermocouples (± 1.5 °C uncertainties) connected to a data logger and PC, a 500 L electrically heated water bath, a pump, ball valves, and LZM rotameter flow meter (± 0.05 L/min uncertainties). Tap water was used as the HTF for both the melting and solidification processes, while P56-58 paraffin wax was used as a PCM.

Table 1 Specifications of LHTS unit constructed for this work. Details of both the shell and the coil appear separately.

Equipment		Unit
Coiled LHTS Unit	Shell	Construction material
		Acrylic
		Length
		50 cm
		Inner diameter
	Coil	17.5 cm
		Shell thickness
		0.5 cm
		Lagging
		4 cm thick layer of glass wool with a laminated surface
		Construction material
		Copper
		Height
		44 cm
		Diameter (centerline diameter)
		12.5 cm
		Number of turns
		16
		Pitch length
		3 cm
		Pipe diameter
		0.953 cm
		Pipe thickness
		0.07 cm
		Pipe length
		700 cm

2.2 Selection and characterization of paraffin wax

Paraffin wax is a chemically stable non-corrosive material, which has a high latent heat and a melting temperature below the temperature of the water heated by solar water heater [37]. Paraffin of P56-58 which supplied from Zhengzhou Allis Chemical Co., Ltd was used as a PCM for the present study. Paraffin waxes are separated from crude oil during the production of lubricating oils. These waxes are categorized by oil content and the degree of refinement. The proposed paraffin wax is fully refined (~ 99% purity) and contains less than 0.5% oil. To determine the physical and thermal properties of the P56-58 paraffin wax used in the experiments, several characterisation techniques were applied.

Figure.1 Schematic diagram of the experimental work

A differential scanning calorimeter (DSC, LINSEIS, STA PT – 1000, Germany) was used to measure the latent heat and the melting temperature range of the PCM (see Figure 2). The analyses were performed on a sample of 22 mg of paraffin wax over a range of temperatures of 30 °C to 130 °C, with a heating rate of 5 °C/min. A constant volumetric flow rate of argon gas was supplied. The estimated errors in the temperature and the latent heat were ± 0.3 °C and $\pm 5\%$ respectively. Figure 2 shows the DSC result for the paraffin wax used in the experiments. The melting temperature range of the paraffin wax is about 48.3 - 62 °C, and its melting enthalpy is about 114.5 kJ/kg.

Lee's Disc method was used to determine the thermal conductivity of paraffin wax [38]. The thermal conductivity of solid phase paraffin wax as a function of temperature is shown in Fig. 3. The thermal conductivity accuracy was $\pm 5\%$. Figure 3 shows the thermal conductivity of the paraffin wax at the solid phase between 25 °C and 45 °C. The thermal conductivity decreases linearly with the temperature increasing from 25 °C to 45 °C. Correlation between the thermal conductivity K and the temperature T is fitted as follows:

$$K = -0.0002 T + 0.1274 \quad (25^{\circ}\text{C} \leq T \leq 45^{\circ}\text{C}) \quad (1)$$

Figure 2: DSC curve for the paraffin wax used in the experiments.

Figure 3: Thermal conductivity of the paraffin wax used in the experiment.

The viscosity of the proposed paraffin wax was measured using a Brookfield digital viscometer (Model: RVDV-II+ Pro). The liquid paraffin wax sample was contained in a glass beaker that was immersed in a thermostatically controlled water bath to maintain a constant temperature during the measurement. The viscosity measurement was carried out at a temperature range between 52 °C to 61 °C and at rpm level of 100. For getting an accurate reading on the display of the viscometer, the spindle namely RV-2 was used. The viscosity of the paraffin wax as a function of temperature is shown in Figure 4 with an estimated error of $\pm 1\%$. Figure 4 shows that the viscosity decreases with the increase of temperature. Correlation between the viscosity μ and the temperature T is fitted as follows:

$$\mu = -0.0008 T + 0.0815 \quad (51^\circ\text{C} \leq T \leq 62^\circ\text{C}) \quad (2)$$

Figure 4: Viscosity of the paraffin wax used in the experiment.

The classical physics method of density measurement was used to estimate the density of liquid and solid phase paraffin wax with an estimated error of $\pm 5\%$. Average values of 780 kg/m³ for liquid and 860 kg/m³ for solid respectively were measured. The measured thermophysical properties of paraffin wax are agreed well with the available literature values [39-41].

2.3 Thermocouple locations

Sixteen thermocouples were used to measure the temperature profile in both the axial and radial directions of the PCM. The 16 thermocouples were mounted at 4 levels in the axial

direction: levels A, B, C and D at distances of 2.5, 13.5, 25 and 36.5 cm from the bottom of the LHTS unit, respectively. In each of these four levels there were four thermocouples in the radial direction at distances of 0, 2.5, 5 and 7.5 cm from the centreline of the shell. An additional four thermocouples ($T_1 - T_4$) were used to measure the surface temperature of the HTF coil at four locations, as shown in Figure 6. Two more thermocouples were mounted in the HTF pipe to record the inlet and outlet temperatures of the HTF. All of the 22 thermocouples were of k-type with a measurement uncertainty of $\pm 1.5^\circ\text{C}$. Two thermocouple input modules, NI 9213 (16-channel thermocouples input), were used to record the temperatures; these modules were inserted in to a NI Compact DAQ 4-Slot USB Chassis (NI cDAQ-9174) that connected to a PC. The data was analysed using Lab VIEW Software.

Figure 5 Locations of the thermocouples.

2.4 Operating conditions and experimental procedure

To study the effect of the temperature and flow rate of the HTF on the thermal behaviour of the PCM in the LHTS unit, multiple HTF temperatures and flow rates were examined. To

imitate the real operational conditions of a domestic solar water heater, where temperatures can reach 80 °C [37], and to avoid the evaporation of water, three temperatures were selected for the melting process i.e. 70 °C, 75 °C and 80 °C. For the solidification process tap water at 30 °C was used. For both the melting and solidification stages, multiple HTF flow rates were investigated. Specifically, values of 1, 3 and 5 L/min were tested [37]. The PCM temperature was initially 30 °C for all of the experimental runs. Experimental work was carried out in the system shown in Fig. 1. During the melting process (i.e. charging), hot water from the water bath was pumped to the bottom of the LHTS unit. The charging experiment ended when the reading on all of the thermocouples was above the melting temperature of the PCM, thus it could be reasonably inferred that the solid PCM had been completely converted to the liquid phase. The solidification process of paraffin wax was then started, by switching over the valves to allow cold water to enter the LHTS unit from the bottom. A digital camera was set to capture an image every 10 minutes during the melting and solidification processes as the insulator was modified to facilitate the covering and uncovering of coil LHTS unit during image capturing. The temperatures during the melting and solidification processes were recorded every minute.

2.5 Uncertainty analysis

Commonly, the accuracy of experimental data depends on the measuring tools and measuring techniques. The uncertainties due to some independent variables were evaluated using the following formula [42]:

$$\sigma_R = \left[\left(\frac{\partial R}{\partial X_1} \sigma_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} \sigma_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial X_n} \sigma_n \right)^2 \right]^{\frac{1}{2}} \quad (3)$$

R represents the derived or dependent variables, which are a function of many independent variables ($X_1, X_2, \dots, X_n$), and σ is the uncertainty. For the present work, the uncertainty in the effectiveness of the melting or solidification process (ϵ) can be evaluated as a function of temperature (T) can be calculated by Eq. 4 and the results shown in Table 2.

$$\sigma_R = \left[\left(\frac{\partial \epsilon}{\partial T_{in}} \sigma_{T_{in}} \right)^2 + \left(\frac{\partial \epsilon}{\partial T_{out}} \sigma_{T_{out}} \right)^2 + \left(\frac{\partial \epsilon}{\partial T_m} \sigma_{T_m} \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

Where ϵ , T_{in} , T_{out} and T_m represent the effectiveness, the HTF inlet temperature, the HTF outlet temperature and the PCM melting temperature respectively.

Table 2 Uncertainty parameters

Parameter	Unit	Uncertainty (%)
Thermocouples	°C	±1.5
NI cdaq-9174	°C	±0.075
Water volumetric flow rate	L/min	±0.25
Effectiveness of melting process, ε	-	±1.9
Effectiveness of solidification process, ε	-	±3.6

3. Results and discussion

3.1 Melting process

In this section, the experimental results of the PCM melting process in a vertical coiled type LHTS unit at different operational conditions are presented. Figure (6) illustrates the temperature of PCM during melting process for a constant HTF flow rate (3 L/min) and initial temperature (80°C) at each radial position (0, 1, 2, 3) and axial locations (A, B, C and D) along the storage, (as shown in Fig. (5) above). In general, the temperature of the PCM during melting process increases with time at all locations along the storage height taking variant behaviour depending on the position. In all cases, the temperature rises quickly at the beginning of the melting process, and then increases steadily until ending of the process. However, for a single axial location the behaviour of the temperature of melting PCM is varied depending on the radial position. Consistency, the higher the axial position, the higher the temperature of PCM is.

It is obvious from the figure that the temperature of PCM becomes higher with increasing height of storage from the bottom to the top. This clearly reflects on the duration of the local melting process and makes it shorter. However, the higher the location, the shorter the melting time was. Practically, the melted PCM over the entire volume of the storage ascends under the buoyant force forming PCM liquid layer at the top of the storage. Accordingly, convection earlier is being dominated at this layer than other parts of the storage which control by pure conduction. Consequently, the PCM temperature notably increases with time at the top of the storage and the melting front consistency moving slowly downward raising the local PCM temperature simultaneously. The variation of time duration for completing PCM melting at the different axial positions along the storage was about 186 min, 150 min, 120 min and 80 min for position A, B, C and D respectively. Consistence with this behaviour, the temperature of PCM is obviously being higher from the center outward. The highest PCM

temperature was at the location near to the coil surface (heat transfer surface) nearby the shell of the storage which results in forming radial melting fronts. This can be shown clearly by Fig. (7), which will discuss later on.

Surprisingly, the measured temperature of the PCM for the positions nearest the storage centre (for all axial positions) increase sharply when the others positions have completely melted (see Fig. (7)). This could be encountered by the strong convection accompanying by the axial and radial two melting fronts. The slight asymmetry of the coil turns at the axial locations B, C and D makes the coil turn in these locations closer to radial location 2 than location 3 which results in the irregularity in the measured PCM temperatures at the radial positions 2 and 3 that appearing in the subfigures B, C and D.

Fig. 6. Variation of temperature of PCM with time during melting process for different radial and axial locations along the vertical LHTS, and for initial temperature of HTF of 80 °C and flow rate of 3 L/min. Initial temperature of HTF is also appeared as blue points.

The local temperature of the PCM at the end of melting process with the storage height can be shown in Fig. (7) for initial temperature of HTF of 80 °C and 3L/min flow rate. It is obvious that the temperature of the PCM is increased with height from the bottom of the storage towards its top. However, this raise of the temperature is significant at the bottom and then increase slowly. In addition to the temperature difference for different radial locations along the storage height seems more pronouncing at the bottom of the storage and then dismissed with increasing the storage height. Nevertheless, the behaviour of the PCM local temperature has the same trend for all radial locations.

Fig. 7. Local temperature of PCM at the end of melting process with storage height at HTF flow rate 3 L/min and initial temperature of 80 °C

Figure (8) illustrates as a contour the variation of the temperature of PCM melting with time with the pictures that captured during the experiments for HTF initial temperature of 80 °C and flow rate of 3 L/min. This figure was developed from the experimental data collected by the thermocouples immersed in the PCM, using the linear interpolated finite elements method (Tec Plot360, R2018 Software). It is obvious that the melting of the PCM takes nearly a pyramidal shape where melting has started up axially at the top of the storage and circumferentially near the coil surface producing two melting fronts. It is apparent from the figure that the circumferential melting front due to the convection current produces by the hot

heat transfer surface (coil) was more pronounced than the axial convection (axial melting front), which arises the pyramidal shape of the non melting PCM.

Fig. 8. Measured PCM temperature contour during melting process for a constant HTF flow rate (3L/min) and HTF initial temperature of 80 °C

The effect of the initial temperature (70 °C, 75 °C and 80 °C) of HTF on the time history of the PCM temperature during melting process is shown by Fig. (9) for a constant HTF flow rate (3 L/min). A significant effect of the initial HTF temperature on the PCM temperature is evident which is completely agreed with literature, for example see [31, 32, 34, 36]. However, the higher the initial HTF temperature, the higher the temperature of PCM was. This of course reflects positively on the charging process by shortening the PCM total melting time. Quantitatively, the average PCM melting time was measured and found to be about 308 min, 229 min and 180 min for HTF initial temperature of 70 °C, 75 °C and 80°C respectively.

However, the effect of initial HTF temperature on the time required for melting of the PCM at different axial (A, B, C and D) and radial (0, 1, 2 and 3) locations of the storage, can be illustrated by Fig. (10) which is plotted for the three initial temperatures of HTF (70 °C, 75 °C and 80 °C) and constant flow rate (3L/min). It is clear from the figure that the melting time is decreased with increasing of HTF initial temperature. The highest the initial HTF temperature, the lowest the time required for completing the PCM melting is. In addition to for a specific radial location (0, 1, 2 or 3) the melting time is obviously decreased significantly with increasing the storage height. This is confirmed our finding above regarding the convection becomes effective first the top of the storage.

Fig. 9. Variation of the average measured temperature of melting PCM with time for constant HTF flow rate (3 L/min) and three different HTF initial temperatures.

Fig. 10. Effect of HFT initial temperature on the time required for melting PCM at different radial location (0,1 and 2) and axial locations (A, B , C and D) for three different HTF initial temperatures ((70 °C, 75 °C and 80 °C) and constant flow rate (3 L/min).

The second important parameter that can be affected the entire thermal performance of the LHTS is the flow rate of HTF. However, the variation of the average temperature of PCM with time for three different HTF flow rates (1 L/min, 3 L/min and 5 L/min) and constant HTF initial temperature (80 °C) is shown by Fig. (11). In agreement with the energy balance, the higher flow rate is obviously resulted in a higher temperature of PCM. Surprisingly, this outcome has diminished at a specific value HTF flow rate, which indicates to an optimal value of the HTF flow rate. This is completely agreed with the finding of [32]. The reason for that could be understood according to the energy balance where at a specific PCM mass there is an amount of energy (HTF flow rate) at which the PCM melting process is. Thereafter, further increased of HTF mass flow rate (amount of energy) has no effect on the temperature of melted PCM because of the poor thermal conductivity of the PCM.

The same behaviour can be distinguished from Fig. (12), which demonstrates the effect of the HTF flow rate on the PCM local temperature at the end of melting process along the storage height (A, B, C and D) for a constant initial temperature of HTF (80 °C). At each axial location, the local temperature is clearly increased when the HTF flow rate raise from 1 L/min to 3 L/min while a very slight increased in the PCM temperature could be associated with the further increased of HTF flow rate (from 3 L/min to 5 L/min, in the present case). This is completely in agreement with the finding of Fig. (11). Again, the figure confirms our above finding that the PCM temperature is increased with the storage height.

Finally, according to the finding of the experiments above, it is obvious that the PCM melting process with using helical coiled configuration seems efficient and suitable to implement in the solar thermal applications. About 10 kg of the PCM was melted during only 3 hours using HTF at 80 °C initial temperature and 3 L/min flow rate.

Fig. 11. Variation of the measured PCM temperature (average of 16 thermocouple) with time during melting process for constant HTF initial temperatures (75 °C) and three different HTF flow rates (1L/min, 3 L/min and 5 L/min).

Fig. 12. Local temperature of PCM at the end of melting with HTF flow rate at the four different axial locations of the storage (A, B, C and D) and the four radial locations (0, 1, 2 and 3) for constant HTF initial temperature 80 °C.

The analysis of heat transfer in the thermal energy storage is quite liked to that of a heat exchanger where the heat exchanges between HTF and PCM. Therefore, the effectiveness of the melting and solidification processes in the LHTS can be found as the ratio of the actual heat transfer to the maximum, as:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} = \frac{\sum \dot{m} \cdot C_p \cdot (T_{in} - T_{out}) \cdot \Delta t}{\sum \dot{m} \cdot C_p \cdot (T_{in} - T_m) \cdot \Delta t} = \frac{T_{in} - T_{out}}{T_{in} - T_m} \quad (5)$$

where Q_{actual} is the actual energy released from the LHTS unit during the phase, Q_{max} is the maximum energy released from the LHTS unit during the phase change, $\dot{m}$ is the mass flow rate of the HTF, C_p is the heat capacity of the HTF, T_{in} is the inlet temperature of the

HTF to the LHTS unit, T_{out} is the outlet temperature of the HTF from the LHTS unit, T_m is the melting temperature of the PCM and Δt is the time interval.

Figure (13) shows the variation of the storage unit effectiveness with time at three different HTF initial temperatures and the optimum HTF flow rate (3 L/min). It is obvious that at the beginning of the melting process, the effectiveness was at the maximum values and then declined quickly when the PCM melting is beginning. Thereafter, as the phase change transition, the effectiveness decreases slowly with time until reaches its minimum values and remains constant after about 180 min from the starting of the melting process. Due to the ability of the PCM to offer a nearly constant outlet fluid temperature during the melting process (phase change process), the effectiveness value after about 180 min seems constant. In general, no noticeable effect of the HTF initial temperature on the effectiveness can be seen within the range of the present experiments.

Fig. 13. Effectiveness evolution of the PCM storage tank during melting process for different HTF initial temperature and constant flow rate (3 L/min)

Similarly, Fig. (14) illustrates the effect of HTF flow rate (1 L/min, 3 L/min and 5 L/min) on the LHTS effectiveness at constant HTF initial temperature. Clearly, the low flow rate (1 L/min) results in a high effectiveness, while the others flow rates seem have nearly same values. This is in agreement with the finding above (Fig. (11)) where an optimal HTF flow rate was found. The finding of Fig. (14) can be justified, in addition to the aforementioned

above (Fig. (11)), by that the low HTF flow rate associates with a large HTF temperature difference because of a mutual heat transfer process due to the large HTF residence time of fluid.

Fig. 14. Effectiveness evolution of the PCM storage tank during melting process for different HTF flow rates (1 L/min, 3 L/min and 5 L/min) and constant initial temperature (80 °C).

3.2 Solidification process

Assessment of thermal energy storage requires the investigation of its viability during charging and discharging phases. In the present work, the discharging (solidification) process is investigated directly after the end of melting process using constant HTF temperature (30°C) and three different flow rates (1L/min, 3 L/min and 5 L/min). The same distribution and number of the thermocouples were exploited through this part of the experiments.

Figure (15) demonstrates the axial and radial variation of the measured temperature of PCM with time during solidification process under the operational condition of HTF temperature (30°C) and flow rates (3 L/min). Once the coolant has started flowing in the coiled tube, the temperature of the PCM began decreased along the storage. Obviously, the PCM temperatures along the axial and radial positions decreased sharply and equally at the beginning of the solidification process. Hence, at this short period convection is controlled the whole process. Thereafter, depending on the radial position of the thermocouple, the

variation of the temperatures becomes significant which indicates to the formation of PCM solid. Consequently, the heat transfer throughout the entire geometry has affected by the solidified PCM layer which adheres to the coil surface and impedes the heat exchange from the heat transfer surface to the PCM. Therefore, the solid-front moves slowly and so the reduction in the PCM temperature from the coil surface (heat transfer surface) nearby the storage shell inward. Accordingly, PCM solid layer like a shell is slowly growing making the centre of the storage almost all liquid. Consistence, the conduction is being dominant which leads to prolong the solidification process. This phenomenon can be shown clearly by Fig. (15). Similar to the melting process above (see Fig. (6)) irregular behaviour of the measured PCM temperature is appeared which support our previous conclusion that based on the asymmetry of the coil turns.

Figure (16) illustrates the colour map of the PCM temperature during solidification process with the pictures that captured during the experiments for initial HTF temperature of 30 °C and flow rate of 3 L/min. Same technique of that used for developing the colour map in Fig. (8) is exploited in the development of Fig. (16). The PCM solidification process started around the heat transfer surface (coil) and then grew up forming shape like a shell. The thickness of this shell increases with time and it covers the cylinder surface area within about 40 min. Therefore, it was difficult to take pictures after this time showing the inner situation of the storage. Nevertheless, the average temperatures PCM during the solidification have an excellent agreement with the pictures of the PCM during the earlier stage of the solidification process which can be confidently used in further discussion. Accordingly, it is clear that at the first stage of the PCM solidification process the storage is divided into three distinctive regions from its bottom to the top; the low temperature layer; the mid temperature layer and finally the high temperature layer. This could be due to the gravity effect where the solidified part of the PCM is settled under the effect of its mass. Therefore, these layers are no longer mixed forming a hot core (liquid PCM) along the storage; while the thickness of the radial (shell) solidified PCM became distinctive. However, this process seems very slow because of the heat conduction was dominated shortly after the beginning of solidification.

Fig. 15. Variation of the measured PCM temperature with time during solidification process for different radial and axial locations along the vertical LHTS, and for initial temperature of HTF of 70°C and flow rate of 3 L/min.

Fig. 16. Measured PCM temperature contour during solidification process for a constant HTF flow rate (3L/min) and HTF initial temperature of 30 °C

Figure (17) shows the effect of the HTF flow rate on the variation of the average temperature of PCM with time for a constant HTF initial temperature (30°C) and three different HTF flow rates (1 L/min, 3 L/min and 5 L/min). The HTF flow rate is only slightly affected the time history and hence the total solidification time of the PCM. This could be due to the dominant of conduction heat transfer throughout the entire solidification process as a result of forming the solid layers around the cooling coil.

Contrary to the melting process, the PCM solidification process with a helical coil was taken long time to complete, where a 10 kg wax is needed about 15 hours to solidify. This could be due to the poor heat exchange process controls by a pure conduction because of the poor thermal conductivity of the PCM. Enhancement of this process is really crucial for being the helical coil suitable for solar thermal applications especially it has superior characteristics during melting phase.

Fig. 17. Effect of HTF flow rate on the variation of the measured PCM temperature (average of 16 thermocouple) for a constant HTF initial temperature (30°C) and three different HTF flow rates (1 L/min, 3 L/min and 5 L/min).

Similar to the melting process, the effectiveness of the PCM storage tank during the solidification process is given in [Fig. \(18\)](#) for three different HTF flow rates (1 L/min, 3 L/min and 5 L/min) and constant initial temperature (30 °C) using Eq. (5). It is clear that the maximum effectiveness was at the beginning of the discharge process, declined rapidly, decreased steadily and then reached the steady value at solidification time about 420 min.

Fig. 18. Effectiveness evolution of the PCM storage tank during solidification process for different HTF flow rates (1 L/min, 3 L/min and 5 L/min) and constant temperature (30 °C)

4. Conclusions

The thermal performance of the helical coiled latent heat thermal energy storage has been investigated experimentally. Both melting and solidification processes were investigated. Paraffin wax (P56-58) was used as a PCM and tap water at three different flow rates (1 L/min, 3 L/min and 5 L/min) were implemented in both processes, while three different of HTF temperatures (70°C, 75°C and 80°C) were utilised only in the case of melting process. For solidification process, only one initial temperature of HTF (30°C) is used. According to the experimental results that obtained, the following conclusions can be made:

- 1- The PCM temperature during melting process was found to be higher at the top of the storage and decreased gradually toward the bottom due to the convection effect. The total time required for completing PCM melting at the different axial positions along the storage was about 186 min, 150 min, 120 min and 80 min for position A, B, C and D respectively for HTF initial temperature and flow rate of 80°C and 3L/min, respectively. On the other hand, for radial temperature distribution, the higher the PCM temperature was near the coil surface and it decreases inward.
- 2- Two melting fronts (axial and radial) were noticed during the melting process. This results in fastening the melting process and made the not melted PCM at the storage's

core having a pyramided shape. This indicates to that the coiled tube LHTS can be successfully used in the thermal applications of the solar energy.

- 3- Initial temperature of HTF was found to have a positive significant impact on the PCM melting process where the higher the HTF initial temperature, the shorter the melting time was. Quantitatively, the increased of HTF temperature from 70 °C to 75 °C and from 75 °C to 80 °C results in shortening the total melting time by about 34.5% and 27.2% respectively. In addition to the HTF flow rate was effected the PCM melting process and an optimal HTF flow rate was determined and it was 3 L/min under the experiments conditions.
- 4- For solidification process, the PCM temperatures along the axial and radial positions deceased sharply at the beginning of the solidification process (few minutes of the beginning of melting process) because of the convection effect. Thereafter, the PCM solidification temperature was significantly affected by the radial location at each axial position along the storage, which indicates of formation of PCM solid and conduction controlled the process. The nearest location the heat transfer surface location, the lowest temperate was.
- 5- The solidification process was found starting as a shell around the heat transfer surface (coil) and moved very slowly inward. Because of the low thermal conductivity of the PCM solid shell, the PCM in the core of the storage need long time solidify (more than 900 min). No, noticeable effect of the HTF flow rate on the solicitation process is shown, while it has only a minor impact on the total effectiveness of the process.
- 6- The PCM melting process in coil configuration is an efficient and seem very suitable for the thermal solar applications, contrary the PCM solidification process seem very poor. Therefore, an enhancement of the solidification process is necessary to be practically viable.

Nomenclature

K	thermal conductivity (W/m.K)
C_p	heat capacity (kJ/kg.K)
$\dot{m}$	mass flow rate (kg/s)

Q_{actual}	actual heat transfer rate (W)
Q_{max}	maximum heat transfer rate (W)
T	temperature (°C)
T_{in}	inlet temperature of heat transfer fluid (°C)
T_{out}	outlet temperature of heat transfer fluid (°C)
Δt	time difference (s)
Greek symbols	
μ	viscosity (kg/m.s)
ε	effectiveness

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Research Highlights

- Thermal performance of horizontal coiled tube LHTS device was experimentally considered
- Both charging and discharging of PCM were investigated
- Effect of initial temperature and flow rate of HTF on PCM in melting and solidification was tested
- Initial temperature of HTF was significantly affected the melting process
- Optimum HTF flow rate for melting was determined and it was 3 L/h
- Flow rate of HTF affected solidification process