Experimental Investigation of the Horizontal Double Pipe Heat Exchanger Utilized Phase Change Material

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Abstract. The melting of a phase change material (PCM) inside a horizontal concentric two-pipe heat exchanger is experimentally investigated. The PCM RT-42 (Rubitherm) is contained in the annular space between the inner tube of diameter 25 mm and outer insulated shell of diameter 75mm. The hot water as a heat transfer fluid (HTF) flows inside the inner tube at different temperatures, 60, 70 and 80 °C. The experimental setup involves twelve thermocouples to record the transient temperatures of PCM at different locations. Also, the progress of the solid-liquid front during the melting process is tracked photographically by a digital camera. The experimental findings revealed that the heat conduction, accompanied by the same melting rate around the inner tube of the heat storage unit, is predominant at the beginning of the melting process. As time progresses, the natural convection role is strengthened and causes a higher melting at the top part than is shown at the lower part, which is still dominated by conduction. Also, the melting rate is directly affected by the temperature of the HTF. The melting time is reduced by about 27% and 46% when the HTF temperature varies from 60 to 70 °C and 80 °C, respectively. The variation of the Nusselt number during the melting process is evaluated. There is a positive influence of the HTF temperature on the energy stored by the PCM.

Keywords: phase change material, energy storage, natural convection, liquid fraction, melting rate, heat exchanger.

Nomenclature

\( C_p \) specific heat \((J \, kg^{-1} \, K^{-1})\)

\( d \) diameter of the inner pipe \((m)\)
1. Introduction

Energy is an extremely important aspect of daily life, and humans’ energy requirements are constantly increasing. Keeping energy available and sustainable is therefore attracting the attention of many researchers. Studies have been carried out on renewable energies such as solar, wind and tidal energy to avoid the depletion and pollution of fossil energy. However, the problem with renewable energy is a lack of availability at all times, for example, solar energy exists during the day but is lost at night. For this reason, energy storage has become increasingly important, to keep energy until it is needed. Heat energy can be stored using three techniques; sensible, latent and chemical. Latent heat thermal energy
storage (LHTES) is used for storing and releasing energy as sensible and latent. It requires three main parts: a phase change material (PCM), a suitable heat exchanger (container) and the surface of a thermal conductor between the PCM and the source of heat. Phase change materials have the ability to absorb and release a large amount of energy, at an approximately constant temperature, during charging and discharging processes. Also, the variation in volume of PCM phases is small due to phase change processes [1].

The behavior of PCM melting is influenced by many factors: the shape of the PCM container, how heat transfers and how the PCM is placed relative to the source of heat. Dhaidan and Khodadadi [2] extensively reviewed the melting behavior of PCM in different geometrical shapes of heat exchanger, such as rectangle, cylinders, sphere and annular. Shmueli et al. [3] investigated experimentally and numerically the melting of RT-27 Rubitherm PCM inside a vertical cylinder. The result showed that the temperature gradient of the upper part dropped faster than the lower part, due to the earlier melting in the upper part. Waghmare & Pise [4] carried out a numerical study on the effects of gravity and buoyancy on the melting of PCM inside concentric vertical cylinders. It was observed that the gravity and buoyancy forces affected the melting process. The initiation of the melt started close to the hot tube and it moved upward then descended to the bottom. Bechiri & Mansouri et al. [5] numerically and experimentally studied the melting of RT-27 inside a vertical cylinder. The effects of different parameters such as Fourier number, Grashof number, wall conductivity and aspect ratio were investigated. The correlations for the melting time and liquid fraction were established as a function of these parameters. Regin et al. [6] experimentally and numerically studied the melting behavior of a PCM (paraffin wax) in a horizontal cylindrical container. The results revealed that melting was governed by the value of the Stefan number, PCM melting point and the radius of the container. Hlimi et al. [7] investigated the role of natural convection on the melting motion of the PCM (gallium) inside a horizontal-cylindrical capsule. It was observed that the natural convection dominated and the shape of melting was asymmetrical between the upper part and lower part of the container. Alsiyabi et al. [8] numerically and experimentally investigated melting of PCM (RT-35) inside a cylindrical container. Their study focused on the effect of inclination from vertical to horizontal with three inclination angles (0, 45, 90). The results showed that the natural convection and the resulting melting rate were directly affected by inclination angles. Khot et al. [9] carried out an experimental study to evaluate the constrained and unconstrained melting of PCM inside a spherical container. It was found that as Stefan number increased, the melting rate increased in both melting modes. The unconstrained melting had a shorter melting time because the solid part of PCM in the bottom was in direct thermal contact with the heated wall. Hosseinizadeh et al. [10] carried out an experimental and
A numerical study of unconstrained melting using n-octadecane as PCM in a spherical container. It was noticed that the melting rate was faster in the upper part, due to the effect of natural convection. Li et al. [11] numerically investigated the effect of the geometrical and operating parameters on constrained melting in a spherical container. Their results showed that the melting time varied positively and inversely with the spherical size and wall temperature, respectively. Gao et al. [12] experimentally investigated the melting of PCM RT-27 inside a spherical container. The result revealed that with the increase of the diameter of the sphere and ratio of PCM filing, the total melting time increased. Yanxia et al. [13] experimentally studied the melting of the ethanolamine-water binary mixture as PCM in a closed rectangular cavity with heated vertical walls. The results showed that the natural convection effect increased the melting rate in comparison with conduction alone. Qarnia et al. [14] presented a numerical study of n-eicosane enclosed in a rectangular container and used as PCM with a melting point of 36 °C to act as the heat sink. The container was heated by three discrete protruding heaters which were located on a vertical wall. It was noticed that the rate of heat absorption rose whenever the discrete protruding heaters were closer to the bottom wall. Kamkari et al. [15] experimentally and numerically studied PCM melting inside a vertical inclined rectangular container. The bottom wall of the container was heated and the other walls were insulated. It was found that the inclination angle caused the development of natural convection, which in turn increased the melting rate. Wang et al. [16] presented numerical and experimental investigations to examine the melting of PCM (RT-60) inside a rectangular container with different inclination angles. One wall of the container was isothermally heated and the other three walls were insulated. The results revealed that the inclination angles had a significant effect on the melting performance of PCM. An increase of angles from 0° to 180° led to a nonlinear reduction in melting rate.

The latent heat thermal storage type utilizing a double pipe is widely used in engineering applications. The annular space between the inner and outer pipes is filled with PCM. Ng et al. [17] numerically studied the melting of PCM (n-octadecane) in a horizontal annulus heated isothermally from the inner tube, while the outer pipe was adiabatic. The results revealed that the increase in Rayleigh number caused an earlier initiation of the natural convection and expediting of the melting process. Ettouney et al. [18] experimentally investigated the latent heat energy storage during energy charging and discharging of PCM contained in the annular space between the inner heated tube and outer insulated shell. It was be noticed that the melting process was controlled by natural convection, whereas conduction was dominant in the solidification process. Dutta et al. [19] experimentally and numerically studied heat transfer of paraffin wax which was filled the horizontal annular of double tubes. The inner tube was
heated isothermally while the outer one was thermally insulated. At the beginning of the melting process, a molten layer of paraffin was formed around the inner tube, due to conduction. Then, the layer grew upwards with the progress of time, as a result of natural convection. Hosseini et al. [20] presented an experimental and computational study on the behavior of PCM (RT-50), melting inside a horizontal annular space the formed between an inner isothermal tube and outer insulated shell. Melting rate was affected by the inlet temperature of heat transfer fluid flowing inside the inner tube. Darzi et al. [21] carried out a numerical study of melting of n-eicosane inside the horizontal annular cavity between the hot inner tube and outer shell, for both concentric and eccentric positions of the inner tube. They found that the melting rate was higher for the eccentric configuration, due to the domination of convection between the hot tube and solid PCM.

This study aims to examine experimentally the melting of PCM inside the annular space between the external insulated cylinder and the inner hot tube. The water as a heat transfer fluid (HTF) passes through the inner tube. The melting behavior is investigated by presenting the transient temperature distribution of PCM during the melting process, shape and progress of solid-liquid interface, melting rate, stored thermal energy and the Nusselt number. The influence of temperature of HTF on the melting characteristics is then discussed and reported.

2. Experimental work

2.1 Experimental Setup

The experimental setup of the water-PCM heat exchanger is presented in Fig. 1. The paraffin wax RT-42 was contained in annular space between inner copper tube and outer thermally insulated transparent acrylic shell. The inner tube is 25 mm outside diameter, 1 mm thickness and 700 mm length. The hot water as heat transfer fluid (HTF) flows inside the inner tube to transmit the thermal energy into the PCM. The outer shell has an inside diameter of 75 mm, thickness of 2.5 mm and a length of 500 mm. An additional length of 1000 mm was added to the pipe inlet to ensure fully-developed flow. The transparency of acrylic provides visual access to observe the melting behavior of PCM. An insulator of 40 mm thickness wool-glass layer is used to reduce the heat losses. The acrylic shell has two vents for filling liquid PCM and accommodating any volume change of PCM during the melting process. In addition, two square acrylic sheets with 10 mm thickness were used to support and guarantee the symmetrical concentric configuration of double tubes. Paraffin wax RT-42 was used as a PCM. This paraffin is white in the solid phase and it becomes transparent in the liquid phase. The thermophysical properties of RT-42 are listed in Table 1.
Fifteen thermocouples (TCs) of type K were utilized as temperature sensors. Two of them were used to measure the inlet and outlet temperatures of water. Also, one thermocouple was used for monitoring the temperature of by-passing water. The hot water is not allowed to flow inside the inner tube of the storage cell unless its temperature is reached at the required level. The other twelve thermocouples were placed inside the test rig to record the transient temperature distribution of the PCM in different locations during the melting process. The positions of thermocouples are indicated in Table 2 and Fig. 2. Two temperature data loggers of 12 channels each were used to record the temperature readings every five minutes. The thermocouples were placed and fixed accurately at a radial distance of 8 mm apart using a plastic rake. The liquid PCM was fed into the annular gradually through the vent to avoid air gaps. The filling process was achieved in several stages, whereby the liquid PCM was left to solidify layer by layer in each stage.

2.2 Procedure

In each test, the water was heated inside the tank to above-required temperature to accommodate the heat losses in the piping system before it entered the test rig. The temperature of the bypass thermocouple was observed so that when it reached the required level, the bypass valve was closed and the hot water was allowed to enter the storage unit through the inlet valve. The experiment was terminated when the solid PCM was fully melted. The readings of all thermocouples were recorded and the images of the solid-liquid front captured by digital camera. Three different temperatures of HTF were considered (60, 70 and 80 °C) to show their influence on the melting process. Each experiment was repeated three times to confirm the reproducibility of the measured data. The volume flow rate of the HTF remained constant at 0.006 m³/min for all experiments.
Fig. 1. Schematic diagram of the experimental setup.

Table 1. Thermo-physical properties of paraffin wax RT-42 (PCM)

| Property                              | Value          |
|---------------------------------------|----------------|
| Tsolidus                              | 38°C           |
| Tliquidus                             | 43°C           |
| Latent heat of melting                | 174 kJ/kg      |
| Density                               | 880 kg/m³ (solid) |
|                                       | 760 kg/m³ (liquid) |
| Thermal expansion coefficient         | 0.0008 1/°k   |
| Specific heat capacity                | 2 kJ/kg K      |
| Thermal conductivity                  | 0.2 W/m²°K    |
Fig. 2. The location of thermocouples inside the annular space in a horizontal position.

Table 2. The location of thermocouples inside annular space in horizontal position according to \((r, \theta)\)

| TC no. | TC1  | TC2  | TC3  | TC4  | TC5  | TC6  | TC7  | TC8  | TC9  | TC10 | TC11 | TC12 |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|
| r (mm) | 20.5 | 28.5 | 37.5 | 20.5 | 28.5 | 20.5 | 28.5 | 20.5 | 28.5 | 20.5 | 28.5 | 37.5 |
| \(\theta\) (degree) | 90   | 90   | 90   | 45   | 45   | 0    | 0    | -45  | -45  | -90  | -90  | -90  |

2.3. Data reduction

The measured temperatures during the experiments were the surface temperature of the inner pipe and the temperature of PCM at different locations. Also, the liquid fraction of the PCM was calculated by using image-processing software by analyzing the captured images of the melting front.
The heat transmitted from the surface of the inner tube into the PCM was estimated by the average Nusselt number which is defined as:

\[ N_u = \frac{h (D-d)}{k} \]  

where \( h \) represents the heat transfer coefficient and it is obtained as:

\[ h = \frac{q_w}{(T_w-T_d)} \]  

\[ q_w = \frac{k (T_w-T_d)}{\Delta X} \]

\[ \Delta X = \Delta X = \Delta X = \Delta X \]

Where \( q_w \) is the wall heat flux, \( \Delta X \) distance between surface inner pipe and thermocouples and \( T_w, T_l \) and \( T_C \) are the temperatures of wall, melting point and thermocouples, respectively.

Also, \( (D-d) \) and \( k \) represent the characteristic length and the thermal conductivity of PCM, respectively.

The thermal energy stored in the PCM equals the sensible heat absorbed by solid, liquid phases and latent heat absorbed during the phase-change process. The stored energy is estimated as [22]:

\[ Q_s = m_{pcm} [C_p_s (T_{avs} - T_s) (1 - f) + f L + f C_p_l (T_{avl} - T_l)] \]

where \( T_{avs}, T_{avl} \) and \( T_i \) represent the average temperature of the solid phase, the average temperature of the liquid phase and initial temperature, respectively. While \( f \) represents the liquid fraction, which can be defined as:

\[ f = \frac{V_l}{V_s + V_l} \]

where \( V_s \) and \( V_l \) represent the volumes of solid PCM melted PCM, respectively.

3. Results and Discussion

The experiments of transient melting features of PCM inside the horizontal annular cavity were performed. The temporal temperatures distribution of PCM inside the cavity is illustrated in Fig. 3. It is obvious that the readings of the thermocouples vary according to their locations inside the cell. The readings of temperatures \( T_1, T_2, T_3, T_4, T_5, T_6, \) and \( T_7 \) reach the melting point faster than the rest of
thermocouples, due to earlier initiation of natural convection in the upper part of the storage cell. Also, the temperatures $T_1$, $T_4$ and $T_6$ arrive at the melting point and steady state condition before the other locations ($T_8$ and $T_{10}$) even though the five thermocouples have the same radial positions from the center but different angular locations. This difference in temperatures is due to the privilege of natural convection in the upper region of the storage unit. On the other hand, temperature fluctuations are observed for the temperature readings of TCs in the upper portion of the unit. The variations of temperature in the lower part of the cell are uniform and un-fluctuating due to the domination of conduction heat transfer at that region.

![Temperature distribution of PCM at a water temperature of 70 °C.](image)

**Fig. 3.** Temperature distribution of PCM at a water temperature of 70 °C.
The effect of dominated heat transfer is explained by a comparison between two temperatures, $T_1$ and $T_{10}$, as presented in Fig. 4 for different temperatures of hot water. Clearly, the increase in temperature of hot water leads to an intensification of thermal energy that transferred from HTF into PCM, earlier evolution of natural convection currents and acceleration of the melting process. Thus, the temperature values are raised with the increase of temperature of hot water. On the other hand, due to the effect of natural convection the values of temperature $T_1$ exceed that of $T_{10}$ although they have the same radial positions but different angular locations. Also, the increase rate in temperature $T_1$ is higher than that of temperature $T_{10}$.

![Fig. 4. Comparison between the temperatures $T_1$ and $T_{10}$ for different temperatures of HTF.](image)

The photographic representation of the time-progress of melting process is illustrated in Fig. 5 for three different temperatures of water. It is observed that the symmetric melting front and diffusion-heat
transfer is dominated at the early periods (15 min) of melting at water temperatures of 60 and 70 °C. For the same period of 15 min, but for water temperature of 80 °C, it is noticed that the natural convection is developed and the melting rate is faster at the upper half of the cell. After initial periods, the movement of natural convection currents strengthens the melting rate at the upper part of the cell for different water temperatures. However, as time progresses the overall melting rate of the PCM inside the cell is decelerated as the transmitted thermal energy from HTF is carried from natural convection currents to the upper part of the cell, rather than melting extra solid PCM at the lower part. Therefore, the overheating and thermal stratifications occur for the PCM melt at the upper part of the storage unit. However, the temperature of HTF has a positive influence on the melting rate as confirmed by Fig. 6. The melting time is decreased by about 27% and 46% when the HTF temperature varies from 60 to 70 °C and from 60 to 80 °C, respectively.
Fig. 5. Instantaneous photographs of the melting of RT-42 at 15, 30, 60 and 90 min for various temperatures of water.

Fig. 6. Time-variation of the liquid fraction for different values of HTF temperatures.
The transient variations of the Nusselt number for different temperatures of water are revealed in Fig. 7. It is obvious that for all cases, the Nusselt number increases greatly at a very small initial period, as the conduction dominated and there is a higher temperature gradient over a thin melted PCM. Thereafter, the Nusselt number decays in a dramatic manner as the role of conduction is decreased and the thickness of melted PCM is increased and this causes a reduction of transmitted thermal energy from HTF into solid PCM. However, the role of natural convection is evolved and will be dominated heat transfer of the melting process.

![Temporal variations of the Nusselt number](image)

**Fig. 7.** Temporal variations of the Nusselt number.

The time-variations of thermal energy stored inside PCM for different temperatures of water are shown in Fig. 8. The energy is stored sensibly for both phases of PCM (solid, liquid) and latently during the phase-change process. In the beginning, the transmitted energy from the hot water is absorbed sensibly by solid PCM. As the PCM starts to melt, a large part of the transmitted energy is consumed for solid-to-
liquid phase change conversion. Also, the liquid melt of PCM starts to absorb energy sensibly. It is noticed that the accumulated thermal energy stored increases with time for all temperatures of HTF. When all solid PCM melted, the increase of thermal energy storage is damped as all transmitted energy is absorbed sensibly by liquid PCM. Moreover, increasing the temperature of the water causes higher transmitted energy and higher stored energy of PCM. The stored energy inside PCM can be retrieved when it is required when the solidification (discharging) mode is activated.

![Thermal energy stored vs. time for different temperatures of water.](image)

**Fig. 8.** Thermal energy stored vs. time for different temperatures of water.

4. Conclusions

The experimental investigation of the melting behavior of paraffin wax RT-42 inside horizontal concentric double tubes is performed for different HTF (water) temperatures. The storage cell can be considered as a heat exchanger to transmit the thermal energy between hot water inside the tube and PCM
in annular space. The results revealed how the mechanisms of heat transfer related to the melting process. Conduction is dominated at the beginning of the melting process. Then, the role of natural convection starts and accelerates the melting rate in the upper part of the storage cell. The melting time was clearly affected by the temperature of HTF as it is reduced by about 27% and 46% when the HTF temperature varies from 60 to 70 °C and from 60 to 80 °C, respectively. Also, it is observed that the stored thermal energy by PCM varies positively with the HTF temperatures.

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