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Heat transfer characteristics in latent heat storage system using paraffin wax †

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Abstract

An energy storage system has been designed to study the heat transfer characteristics of paraffin wax during melting and solidification processes in a vertical annulus energy storage system. In the experimental study, three important issues are focused. The first one is temperature distribution in the phase change material (PCM) during the phase change processes. The second one is the thermal characteristics of the paraffin wax, which includes total melting and total solidification times, the nature of heat transfer phenomena in melted and solidified PCM and the effect of Reynolds number as inlet heat transfer fluid (HTF) conditions on the heat transfer parameters. The final one is to calculate heat transfer coefficient and effectiveness during solidification process. The experimental results proved that the PCM melts and solidifies congruently, and the melting front moved from the top to the bottom of the PCM container whereas the solidification front moved from bottom to the top along the axial distances in the PCM container. Experiment has been performed for different water flow rates at constant inlet temperature of heat transfer fluid for recovery and use of heat. Time- based variations of the temperature distributions were explained from the results of observations of melting and solidification curves. Charging and discharging processes were carried out. Heat transfer characteristics were studied.

Keywords: Effectiveness; Heat transfer coefficient; Melting; Phase change; Phase transition; Solidification

1. Introduction

Thermal energy storage has been an active area of research for the past 25 years. One approach has been to use phase change materials (PCM) as an efficient medium for the storage of thermal energy. PCMs have been put into use for several innovative applications like cooling of electronic devices, transporting sensitive medications, cooling vest for athletes etc. Thermal energy storage with phase change materials is one of the most efficient ways of storing available energy because of its advantages such as providing higher heat storage capacity, lower storage temperature, isothermal operation and less storage space. Thermal energy storage system can accumulate energy as sensible heat or as heat of fusion, or a combination of both. Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing [1-3]. However, many practical problems are encountered with latent heat storage due to low thermal conductivity, variation in thermo-physical properties under extended cycles, phase segregation, sub-cooling, incongruent melting, volume change and high cost. Over the last decade, a number of studies have been performed to examine the overall thermal behavior and performance of various latent heat thermal energy storage systems. These studies focused on the melting/freezing problem of the PCM and on the convective heat transfer problem of the HTF used to store and/or retrieve energy (solidification) from the unit. Recently; several experiments have been conducted in order to study the thermal characteristics of paraffins during solidification and melting processes [4-13]. The studies show that commercial grade paraffin wax and other pure paraffins have stable properties after 1000-2000 cycles. Paraffin wax did not show regular degradation in its thermal properties after repeated melting/freezing cycles. Paraffin waxes are safe and non-reactive. They are compatible with all metal containers and easily incorporated into heat storage systems. Paraffin wax have been widely used for latent heat thermal energy storage system (LHTES) applications due to large latent heat and desirable thermal characteristics such as little or no super cooling, varied phase change temperature, low vapor pressure in the melt, good thermal and chemical stability and self nucleating behaviour [3, 14-16]. Utilization of PCM for thermal energy storage requires a proper heat exchanger system for charging and discharging the thermal energy. A tube-in-tube heat exchanger system employing paraffin wax for thermal energy storage

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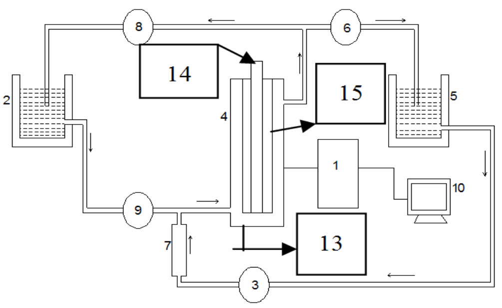
was investigated in this work. The heat transfer aspects and performance of the system were examined here. Phase change temperature of the paraffin wax has been determined.

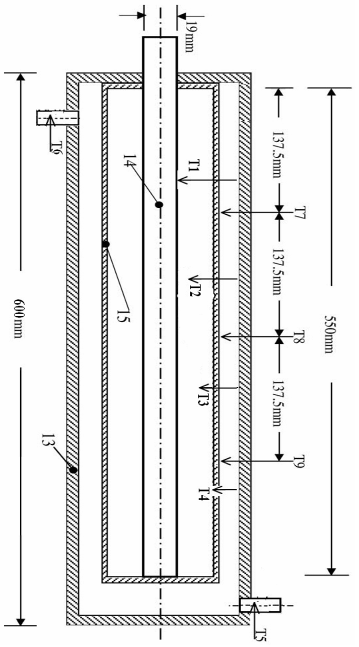
2. Experimental setup and procedure

A schematic diagram of the experimental apparatus is shown in Fig. 1. It mainly consists of a cylindrical tube, a high temperature bath, a low temperature bath, an electrical heating rod, the data acquisition system, K-type thermocouples, HP data logger and a Pentium III PC. The external cylindrical tube made of mild steel is 600 mm long with an inner diameter of 105 mm, while the internal stainless steel PCM cylindrical tube is 550 mm long with an inner diameter of 46 mm. The PCM cylindrical tube, together with the electrical heating rod is placed concentrically into the external tube, which forms an annular space for circulating the cooling water. The electrical heating rod is placed into the PCM tube concentrically to provide an annulus for storing the paraffin wax. The electrical heating rod is also made of stainless steel and has a diameter of 19 mm and runs through the whole PCM tube with an effective heating length of 550 mm. The system consisted of two fluid flow loops: a charging loop which transferred heat from the heating rod to the PCM in the system during the charging process and a discharging loop, which transferred energy from the PCM to water during the discharge process. A 20 mm thick glass wool insulation (thermal conductivity = $0.04\text{Wm}^{-1}\ \text{K}^{-1}$) was wrapped around the PCM container to reduce heat lost to the surrounding and make the surface adiabatic. The location of thermocouple in the PCM along the axis, annotated by A, B, C and D are indicated in Fig. 2 detailing the radial distances of the individual thermocouples from the rod axes are 9.5, 14, 18.5 and 23 mm, respectively. In order to obtain the outer wall temperature of the PCM tube, 3 thermocouples (T7, T8 and T9) were soldered to the wall. The inlet and outlet temperatures of the heat transfer fluid are measured by thermocouples T5 and T6 respectively. The paraffin wax used was of analytical purity. The melting/freezing temperatures were analyzed by differential scanning calorimetry (DSC Q 20 V24.2 Build 107) done at Pondicherry University-Pondicherry India. The melting temperature of paraffin wax is 58- 60°C, and the latent heat is 200-210 kJ kg^{-1} is shown in Fig. 3. The data acquisition system consists of an array of K-type thermocouples (measured at ± 0.1% accuracy), a Rotameter, data logger and personal computer system to measure and record temperatures in the PCM and the mass flow rate of the heat transfer fluid. A 20-channel data logger is used to collect the temperature measurements. The data logger stores the temperature measurement at an interval of 5 min. The logged data were transferred to the PC unit, where they can be processed and analyzed. Rotameter is used to measure the flow rate of the HTF over a range of 1.5–10 kg/min. The test section is placed vertically. Paraffin wax is filled in the annulus formed by the inner tube and the electrical heating rod, and 10% of the whole volume is left unfilled to allow the PCM to



(a) Experimental setup

(1) HP data logger; (2) high temperature bath; (3, 8, 6, and 9) ball valves; (4) heat exchanger; (5) low temperature bath; (10) PIII PC; (7) Rotameter; (13) external tube; (14) electrical heating rod; (15) PCM tube; (16) T1, T2, T3 and T4 – Paraffin wax temperatures; T5 and T6 thermocouples for inlet and outlet coolant temperatures; T7, T8 and T9 thermocouples for wall temperature of the PCM tube.



(b) Thermocouple location in heat exchanger

Fig. 1. Schematic diagram of the apparatus.

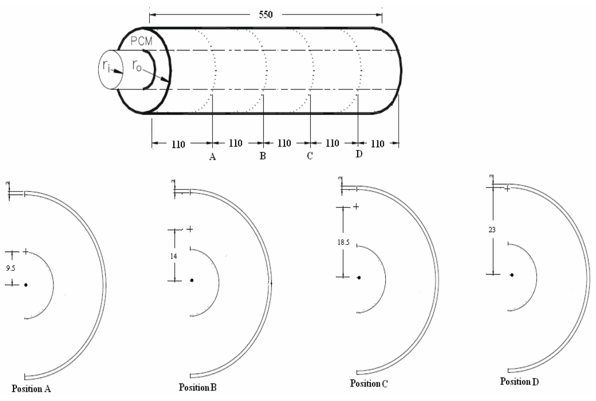


Fig. 2. Location of thermocouple positions in the control system.

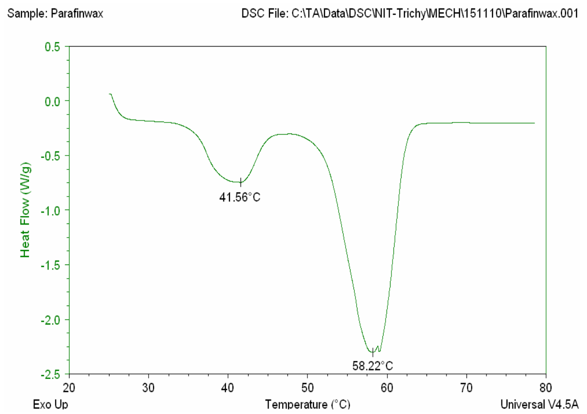


Fig. 3. DSC analysis result of the paraffin wax.

expand freely.

Before the experimental runs, the PCM container is filled with 700 grams of paraffin wax in solid state. A few runs were to be made in order to calibrate the system which allows for the melting of solid paraffin wax. Melting runs start at room temperature. When the electrical heating rod is switched on, the melting process of the paraffin wax starts. Temperature signals were obtained and recorded by the data acquisition system until the outermost thermocouple T4 reaches 60°C. The temperatures of all the thermocouples were recorded at 5 min intervals. The heat flux is changed by altering the heater voltage. The heat flux referred is the heat flux on the outer wall of the electrical heating rod. When the melting process was completed, the paraffin wax was allowed to cool to room temperature. The solidification process was triggered first by circulating the high temperature water from the high temperature bath until the paraffin wax reaches 70°C which is higher than melting temperature of paraffin wax all along its length and cross section. Then low temperature water (HTF) from the low temperature bath was circulated at 32°C at different flow rates into heat transfer fluid pipe. The temperatures were recorded every 5 minutes. The solidification process was repeated at constant inlet temperature of the HTF with different flow rates.

3. Results and discussion

3.1 Thermal performance characteristics of the PCM

The present study reports thermal performance characteristics of paraffin wax during phase change processes includes temperature distribution along the axial distances and total phase transition time by varying the Reynolds number. The variation in Reynolds number influence the heat transfer phenomena throughout the solidification process of the PCM. In order to establish thermal characteristics of the PCM, several experiments are conducted by varying the mass flow rates at constant inlet HTF temperature. Only the temperature data, which exhibit obviously the melting and solidification behaviors were considered.

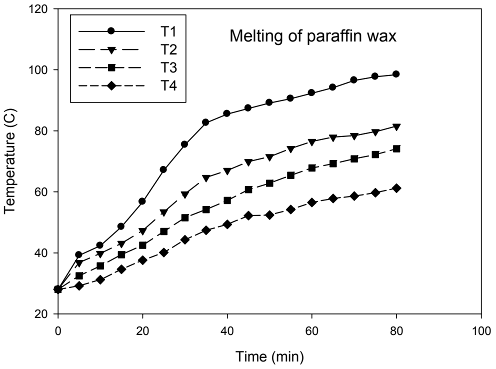


Fig. 4. Temperature distribution in PCM storage (constant heat flux, 2170 W/m^2).

3.2 Melting curve

Fig. 4 shows the temperature variations with time of various axial positions at a heating flux of 2170 W/m^2. The initial energy transferred to the paraffin wax will raise its temperature from the initial temperature to the onset temperature. This sensible heat of the PCM is transferred through the PCM by pure conduction which increases the temperature of paraffin wax gradually to its melting point. As soon as T1 (approximately the wall temperature of the heating rod) equals or raises above the melting point, the melting process of paraffin wax starts. The temperature increases almost linearly with time. Due to low thermal conductivity of the PCM (k = 0.24 W/m K), the temperature near the rod rises very quickly. The temperature rise rates of paraffin wax were significantly slowed during this period. For instance, the temperature of the innermost thermocouple T1 increases nonlinearly during the entire process, whereas the temperature of outermost thermocouple T4 increases linearly with time. This is because the outer layer next to T4 (the outside wall of the tube) is well insulated; the heat transferred from the inner side to it is all stored and, thus raises its temperature. Similar results were reported by [17-19]. Examination of heating curve along the axial direction, as given in Fig. 4, shows that the accelerated melting front interface between solid and liquid phases is observed at the top (T1) compared to the bottom (T4). Such axial movement of the melting front has been reported by other researchers [20]. Hence, the melting front is not cylindrical in shape, as it has a smaller diameter at the upper part of the PCM.

3.3 Solidification curve

At the beginning of the solidification period, the temperature of the paraffin wax decreased rapidly by transferring the sensible heat stored to the cooling water. During this period, the temperature of the paraffin wax is high, and the paraffin wax is in liquid state. This is mainly because heat transfer inside the molten paraffin wax is by natural convection and temperature gap between PCM tube and the cooling water is large. As T4 reaches the solidification point, the solidification process starts and proceeds into the phase change controlled period. Then the paraffin wax adjacent to the PCM tube begins to freeze and discharge its latent heat. The frozen layer constitutes the main heat resistance for heat transfer from the inner paraffin wax to outside. Hence we find that the PCM releases its sensible heat very rapidly, and then a longer time is needed to transfer the latent heat during the phase change. Since the paraffin wax is basically in the liquid state, the major portion of heat dissipated from the PCM is its latent heat. However towards the final period of solidification, the amount of latent heat transferred to heat transfer fluid is becoming smaller and smaller, and the heat dissipation from the PCM is again mainly the sensible heat of the solid paraffin wax. Examination of cooling curves along the axial direction, as given in Fig. 5, shows that for all HTF flow rates the solidification front along the axial distances in the PCM moved from the bottom to the top. Hence, the solidification front is not cylindrical in shape.

3.4 Effect of Reynolds number

The Reynolds number of the cooling water during the solidification experiments is defined by the following equation:

$$\mathrm{Re} = \frac{u \times d_e}{\nu_f} \tag{1}$$

$$\mathrm{d}_e = \frac{4A}{\chi} \tag{2}$$

where Re is the Reynolds number, u is the average velocity of the cooling water (m/s), d_e is the hydraulic diameter of the annulus (m), ν_f is the kinematic viscosity of the water (m^2/s), A is the cross sectional area of the annulus (m^2) and χ is the wetted perimeter of the annulus (m). During the experiments, the flow rate of the cooling water is changed from 3.6 lit/min to 6.1 lit/min and the corresponding Reynolds numbers is 693~1175. It is significant to note that the low thermal conductivity of the paraffin wax contributes to the big thermal resistance of heat transfer chain in axial direction. So the increase of Reynolds numbers which originally is intended to decrease the thermal resistance outside the tube has little influence on the solidification process. Fig. 6 presents the average temperature variation with time for different Reynolds numbers with constant inlet temperature of cooling water. From this figure, it was concluded that average temperature variation with PCM is insensitive to Reynolds number. The fact was that the range of the Reynolds number was not large enough to cause significant change in the convection heat transfer coefficient of the cooling water.

3.5 Heat transfer coefficient

A laminar flow prevails over the experimental flow rate

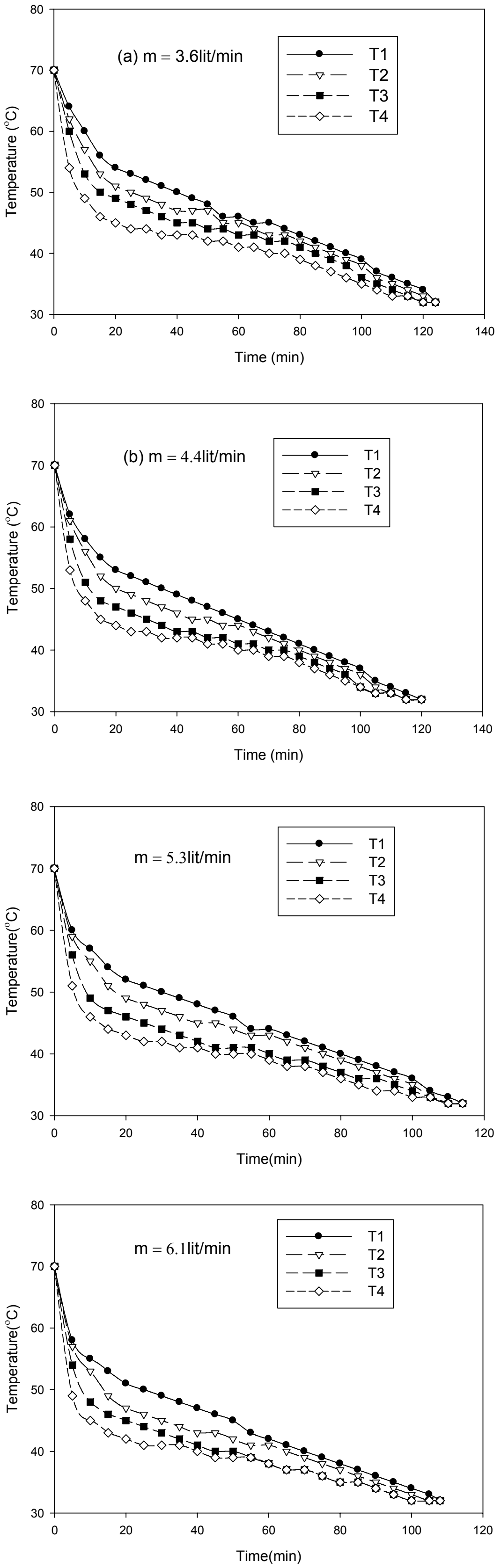


Fig. 5. Temperature distribution in PCM storage for different coolant flow rates.

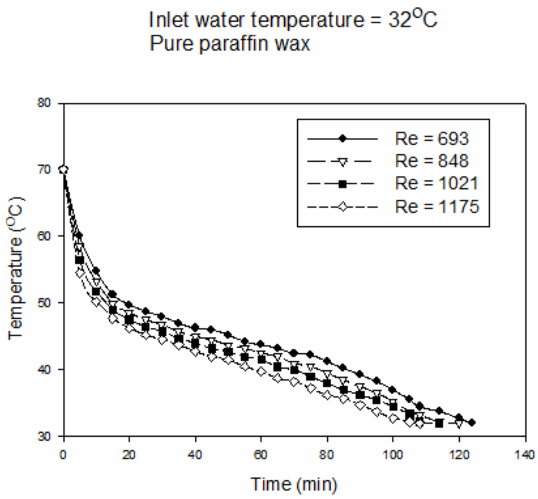


Fig. 6. Comparison of average temperature variation with constant inlet water temperature during solidification of Paraffin wax.

range of 3.6-6.1 lit/min which corresponds to changing the Reynolds number from 693 to 1175. When Δr_m is less than 6mm, the heat transfer coefficient between the pipe and the PCM is augmented by natural convection and the following equation can be used to estimate the heat transfer coefficient. During natural convection the Rayleigh number ($Ra = Gr * Pr$) is the main parameter.

$$Nu = 0.133 Ra^{0.326} \left(\frac{l}{\Delta r_m} \right)^{-0.0686} \tag{3}$$

where Ra is Rayleigh number,

Δr_m is the thickness of the heat storage material $(d_o - d_i)/2$

l is the heat exchanger length.

The heat transfer coefficient is described by a constant Nusselt number [21] which is found to be 37.81 as calculated using Eq. (3) during solidification of the paraffin wax.

3.6 Heat fraction and effectiveness

Heat fraction (Q^+) is defined as the energy input to the PCM system divided by the total required energy to charge the system from some initial temperature to some final temperature. Then heat fraction can be obtained from the following curve. Such charging fraction is a realistic figure describing the charging status of the PCM system since it includes the required sensible – as well as the latent heat of the PCM. Fig. 7 exhibits the charging fraction of the system as a function of time for a constant water inlet temperature. The curve shows a linear increase of heat fraction during the entire charging process due to the increase in sensible heat of the PCM.

$$\text{Heat fraction } (Q^+) = Q / Q_T. \tag{4}$$

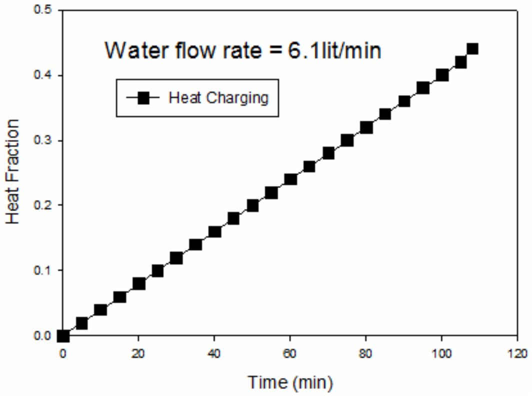


Fig. 7. Heat fraction of paraffin wax: initial temperature 40°C and final temperature 70°C.

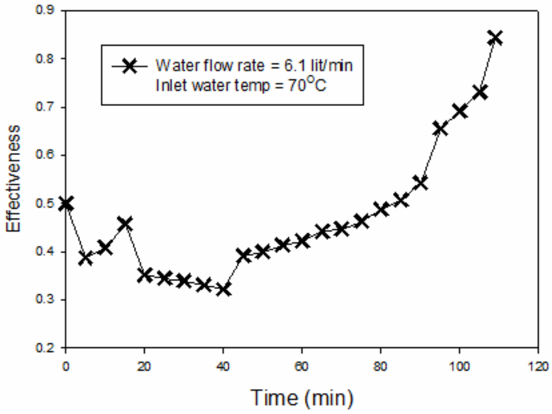


Fig. 8. Effectiveness of heat exchanger system during solidification of paraffin wax.

The effectiveness of the heat exchanger ε is defined by Eq. (5) below [22] and is presented in Fig. 8 for the solidification process.

$$\varepsilon = \frac{T_{iw} - T_{ow}}{T_{iw} - T_{pcm}} \tag{5}$$

Such effectiveness is the ratio of actual heat transfer to the maximum possible heat transfer. It can be seen in Fig. 8 that the effectiveness is high in the beginning and at the end of the solidification process, while it is smaller in between. Such behavior corresponds to a high effectiveness for transfer of sensible heat of the PCM and a lower effectiveness during the solidification process, which might arise from the slow rate of releasing latent heat during solidification.

4. Conclusions

Based on this experimental work, the following conclusions could be drawn:

Paraffin wax is a good PCM for energy storage in latent heat storage system. It has a suitable transition temperature range of 58-60°C and a relatively high latent heat of 210 kJ/kg. In addition, it does not exhibit any subcooling. A simple tube-in-tube heat exchanger system can be used for energy storage with reasonable charging and discharging times and heat release rates. The Reynolds number of the cooling water has only a very weak influence on the solidification process of the paraffin wax within the range tested. The melting front moved from the top to the bottom in an axial direction in the PCM whereas the solidification front moved from the bottom to the top along the axial length. Heat transfer coefficient during solidification of paraffin wax is given by a constant Nusselt number as 37.81.

Nomenclature

A : Cross sectional area of annulus (m^2)
C : Specific heat of PCM/water (kJ/kg°C)
d : Diameter of heat transfer fluid pipe (HTFP) (m)
d_e : Hydraulic diameter of the annulus (m)
Gr : Grashof number [-]
H : Latent heat of phase change material (PCM) (kJ/kg)
h : Heat transfer coefficient (W/m^2 °C)
l : Length of heat exchanger (m)
m : Flow rate of heat transfer fluid (HTF) (kg/s)
M : Mass of PCM (kg)
Nu : Nusselt number [-]
Pr : Prandtl number [-]
Q^+ : Heat fraction [-]
Q : Heat value of PCM during charging or discharging period at any time (kJ)
Q_T : Total heat value of PCM during charging or discharging period (kJ)
T : Temperature (°C)
T_{iw} : Inlet water temperature (°C)
T_{ow} : Outlet water temperature (°C)
T_{PCM} : Temperature of phase change material (°C)
u : Average velocity of cooling water inside the annulus (m/s)
v_f : Kinematic viscosity of the cooling water (m^2/s)
χ : Wetted perimeter of the annulus (m)
ε : Effectiveness of heat exchanger [-]
Δr_m : Thickness of heat storage material (m)

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