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An experimental study on heat transfer characteristics of paraffin wax in horizontal double pipe heat latent heat storage unit

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ABSTRACT

An experimental study is conducted to investigate the melting and solidification processes of paraffin wax as a phase change material (PCM) in horizontal double pipe heat latent heat storage unit. The present work on phase change process includes study of temperature variations along the axial distances in PCM, determination of heat transfer coefficient as well as the heat flow rate. A series of experiments was conducted to investigate the effect of increasing the inlet temperature and the mass flow rate of the heat transfer fluid (HTF) both on the charging and discharging processes of the PCM. The experimental results show that the PCM melts and solidifies congruently, and the melting front moves from the left to right side of the PCM container whereas the solidification front moves from right to the left along the axial distances in the PCM container. The results indicate that natural convection dominates the melting process in the liquid phase due to buoyancy effects. On the other hand, the solidification process is dominated by conduction. The flow rate and inlet temperature of the HTF in the experiment range has a significant effect on the phase change processes. The results also indicate that the heat transfer coefficient between the HTF and the PCM was affected by the Reynolds number more during the melting process than during the solidification process. Heat flow rate during the melting and solidification process increased by 25% and 11%, respectively, in the case of increase or decrease by 2 °C of the inlet HTF temperature. The results of this study show that by increasing the inlet water temperature from 70 °C to 74 °C, total melting time can be decreased by 31%.

1. Introduction

Energy storage plays an important role in improving the applicability, performance and reliability of a wide range of energy systems. In particular, thermal energy storage (TES) is considered one of the key elements to accomplish energy recovery and utilization of solar energy, industrial waste heat and off-peak electricity. Thermal energy can be stored as a change in the internal energy of certain materials as sensible heat, latent heat or both. 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 medication, cooling vest for athletes etc. Thermal energy storage with PCMs 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. However, many practical problems are encountered with latent heat storage using PCM due to its low thermal conductivity, variation in thermo-physical properties under extended cycles, phase segregation, sub-cooling and incongruent melting. A wide range of PCMs have been explored by different researchers for energy storage including salt hydrates and their mixtures [1,2], paraffin compounds [3], non-paraffins and fatty acids [4]. The choice of PCM is dictated by the temperature range of its application. Among various PCMs applied in low thermal energy systems, such as solar heating system, technical grade paraffin wax has been recently used in a wide range. Apart from PCMs, selection of heat exchanger as LHTS module is critical in achieving good storage/release performance from PCM. In addition to geometry, orientation of heat exchanger is also of particular interest to researchers as they have key roles in controlling buoyancy driven natural convection in the liquid PCM. Among various configurations, shell and tube/concentric double pipe heat exchangers have been proved as high efficient for minimum volume [5,6]. The heat transfer characteristics of PCMs during melting and solidification in double pipe module have been extensively discussed in the literature. Sari and Kaygusuz [7] carried out an experimental study

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Nomenclature

A	external surface area of heat transfer fluid pipe (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 annulus (m)
H	latent heat of phase change material (PCM) (kJ/kg)
h	heat transfer coefficient (W/m^2 °C)
L	length of PCM container (m)
l	length of heat transfer fluid pipe (m)
m_h	mass flow rate of hot water (kg/s)
m_c	mass flow rate of cold water (kg/s)
M	mass of PCM (kg)
k	thermal conductivity (W/m K)
Ste	Stefan number ($Ste = C \times (T_{H,i} - T_m)/H$)
Nu	Nusselt number
Pr	Prandtl number ($\mu C_p/k$)
Q^+	heat fraction for PCM
Q	heat supplied/recovered (J)
q	heat flow rate (W)
Re	Reynolds number ($u \times d_e/\nu$)
r	radial distance (mm)
T	temperature (°C)
T_m	melting temperature of phase change material (°C)
$T1, T2, \ldots, T9$	temperature probe number in heat storage unit
T_h	temperature of hot water (°C)
T_c	temperature of cold water (°C)
T_i	inlet temperature of HTF (°C)
t	time (min)
u	velocity of hot/cold water inside annulus (m/s)
ΔT_L	logarithmic mean temperature difference (°C)

Greek symbols

μ	dynamic viscosity (kg/m s)
Δ	difference or interval
ρ	density (kg/m^3)
ν	kinematic viscosity of water (m^2/s)

Subscripts

c	charging
d	discharging
H	heat transfer fluid
i	inlet HTF flow or inner HTF tube
L	logarithmic
m	melting point
o	outlet HTF flow or outer HTF tube
p	pressure
pcm	phase change material
l	liquid or length
s	solid or solidification
w	water

on melting and solidification in a vertical double pipe energy storage system and found that the average heat transfer coefficient and the heat flow rate were more affected during the melting process due to the natural convection effect. Ettouney et al. [8] investigated the thermal and heat transfer characteristics of paraffin wax as PCM in a vertical double pipe heat exchanger system where the heat transfer fluid (HTF) flow direction are reversed. They reported that the heat transfer coefficient is higher and PCM is heated from bottom to top of the system during the melting process. The role of natural convection in enhancing the melting rate in horizontal circular cylinder is presented by Ismail and da Silva [9]. The results of their numerical study prove that the intensification of natural convection reduces the time for complete melting and also stabilizes the melting rate. In order to enhance the thermal performance, various performance enhancements are proposed [10]. Seeniraj et al. [11] investigated transient behaviour of high temperature PCMs stored in shell and tube heat exchanger. They observed that if an unfinned tube is used, then some quantity of PCM nearer to the exit of the tube would remain in solid state. This is because, nearer to the exit, the difference between HTF temperature and PCM's melting point would be very small. It is also reported that the presence of a few number of annular fins maintains relatively high temperature difference between HTF and melting point and thus melting could be found everywhere in the axial direction. The results of Liu et al. [12] indicate that the fin can enhance both the conduction and the natural convection heat transfer of the PCM. According to Ismail et al. [13] thickness, length and number of fins should be carefully chosen to optimize the system performance as the presence of fins result in the loss of available storage capacity. As a novel way, Ismail et al. [14] have used turbulence promoters in the form of twisted coil in the HTF side and have found high local heat transfer coefficient due to turbulence. However, the results of Ismail and Lino [15] reveal that the effects of such promoters on phase change process are relatively less significant than fins. On the other hand, these promoters do not affect the storage capacity as they are in the HTF side. In case of LHTS units, the variation of operating conditions of HTF is expected to have significant influence on thermal performance of PCM. Ismail and Abugderah [16] have proved that the Reynolds and Stefan number are important parameters in influencing the system performance. In the light of the above studies, it can be concluded that paraffin wax in general possess the desirable thermal characteristics like high latent heat, little or no super cooling, varied phase change temperature, low vapour pressure in the melt, small volume change, low cost, good thermal and chemical stability and self nucleating behaviour [17–20] and is suitable for application in solar energy storage systems. In this study, thermal characteristics of the paraffin wax as a PCM were investigated experimentally in horizontal double pipe latent heat storage unit using water as HTF which flows through the inner pipe at constant inlet temperature. Hence, electric source is used to supply heat transfer fluid at constant temperature to the thermal energy storage system. In many process industries the process steam after condensation is available at constant hot water temperatures. The primary objective of the present work is to investigate the thermal performance of PCM in terms of charging fraction, heat flow rate and heat transfer coefficient for various inlet temperature and mass flow rates of HTF. The present study differs from the previous works in that, it compares the influence of HTF operating conditions during melting and solidification process and reported. The distinguishing feature of this study is the determination of the temperature profile in the axial direction by measurements during melting and solidification process for horizontal double pipe heat exchanger configuration.

2. Experimental study

2.1. Heat storage material

In the present study, paraffin wax obtained from the commercial sources was used as a latent heat energy storage material. Paraffin wax is chemically stable and non-toxic material without