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Experimental and computational study of melting phase-change material in a triplex tube heat exchanger with longitudinal/triangular fins

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ABSTRACT

This study designed, tested, and evaluated an experimental energy storage system that uses a horizontal triplex tube heat exchanger (TTHX) with internal longitudinal fins incorporating phase-change material (PCM), with melting point in the range of 78.15–82.15 °C. The PCM did not entirely melt within the charge time (4 h) for the inside heating at 97 °C. The PCM melting for both-sides heating was successfully accomplished at 90 °C in lesser time than the outside heating method. The changes in the mass flow rates of 16.2, 29.4, and 37.4 min/kg on the PCM average temperature in the axial direction were investigated. The mass flow rate for the non-steady state at 29.4 kg/min consumed a short time to achieve PCM melting, compared with the 16.2 and 37.5 kg/min with different charging temperatures. However, two-types of extended surfaces, namely the longitudinal and triangular fins, were studied numerically. A significant enhancement was achieved using internal, internal-external, and external triangular fins at 11%, 12%, and 15% respectively, compared with the cases with longitudinal fins. Therefore, the external triangular finned tube has been considered the most efficient for the brief melting of PCM (193 min). The total energy stored capacities for the PCM with longitudinal and triangular fins were compared. The simulation agreed well with the experimental results.

1. Introduction

Solar energy is considered, as one of the most prospective sources of energy in many parts of the world. The characteristics of solar energy, such as being abundant and freely available, easily and directly utilizable, renewable and has continuity, and safe and environmentally friendly, make solar energy an attractive alternative to fossil fuels. In addition, the continuous increase in the level of greenhouse gas emissions and the depletion of fossil fuels are identified, as the main driving forces behind the efforts to effectively utilize different sources of renewable energy. Solar energy systems require thermal energy storage (TES) to eliminate the mismatch between energy supply and demand. Considerable emphasis is placed on continuous power generation during cloud transients and non-daylight hours for solar device applications.

Most phase-change materials (PCM) that are used, as storage media in TES systems suffer from a low thermal conductivity ($\leqslant$0.2 W/m K), which results in an incomplete melting/solidification process and a significant temperature difference within the PCM that can cause material failure and system overheating. Enhancing the thermal performance of TES systems is necessary in employing a PCM to various engineering applications, such as building heating, water heating, solar systems, electronic cooling, drying technology, refrigeration and cold storage, air conditioning, and waste heat recovery (Jegadheeswaran and Pohekar, 2009). Furthermore, few attempts have been made to optimize the fin design for maximizing the performance of the LHTES system. The fin design optimization presents two intrinsic difficulties. First, fin design optimization problems result in expensive computational costs. Second, an intrinsic difficulty emerges from the transient behavior of a PCM-LHTES system.

Many researchers studied the performances of different kinds of heat exchangers used in LHTES systems with a PCM, such as concentric-cylinder, shell and tube, and triplex tube heat exchanger (TTHX), and their applications in melting/solidification pro-

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Nomenclature

C	mushy zone constant (kg/m^3 s)
C_p	specific heat (kJ/kg K)
g	gravity acceleration (m/s^2)
h	sensible enthalpy (J/kg)
H	enthalpy (J)
HTF	heat-transfer fluid
k	thermal conductivity (W/m K)
L	latent heat of fusion (J/kg)
LHTES	latent heat thermal energy storage
p	pressure (Pa)
PCM	phase-change material
r	tube radius (mm)
S	momentum source term (Pa/m)
t	time (min)
T	temperature (°C or K)
TTHX	triplex tube heat exchanger
T_m	melting temperature (°C or K)
u	velocity component (m/s)
v	velocity component (m/s)
x, y	x, y-component in a Cartesian coordinate system

Greek letters

β	thermal expansion coefficient (1/K)
ε	constant
γ	liquid fraction
μ	dynamic viscosity (kg/m s)
θ	angle (°)
ρ	fluid density (kg/m^3)

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i	inner
ini	initial time
l	liquid PCM
m	middle
o	outer
pcm	phase-change material
ref	reference
s	solid PCM

cesses (Niyas and Muthukumar, 2013; Jian, 2008). Compared experimentally three-configurations, a concentric tube system with no fins and an augmented with circular and longitudinal fins by Agyenim et al. (2009). The system with longitudinal fins showed the best performance with increasing thermal response of PCM during charging, and reduced sub-cooling during discharging. The performance enhancement of a small TTHX used in the LHTES system has attracted significant interest by (Mat et al., 2013; Al-Abidi et al., 2013a,b). Moreover, numerical and experimental investigations were performed using a longitudinal fin technique. Besides this technique, the melting time of the pure PCM has been significantly reduced. Tay et al. (2013) simulated the PCM-LHTES system, including the plain tubes, which contained the heat transfer-fluid (HTF) modified to accommodate the techniques of the pin and the circular fins attached to the tube. Comparisons were conducted based on the solidification process. The finned tube design was found to yield better average effectiveness and shorter phase-change duration (25% faster in terms of the phase-change duration) because of the large heat-transfer surface area of the finned tube design, compared with the pinned tube design. Manish and Jyotirmay (2015) experimentally estimated the augmentation in the heat-transfer for melting and solidification of the PCM in a shell and tube with three-longitudinal fins installed on the HTF tube. Solomon and Velraj (2013) experimentally performed the heat-transfer enhancement of the PCM used in free cooling application during outward cylindrical solidification in a double pipe heat exchanger, in which the PCM was filled in the annulus along with eight-longitudinal uniformly spaced copper fins of different heights and air, as the HTF passes through the inner tube. The solidification time was decreased because of the utilization of longitudinal fins in the heat storage media. Celador et al. (2013) presented three-different modeling approaches in LHTES systems, namely, numerical, simplified analytical, and simplified numerical approaches for an innovative finned plate in the LHTES system. Sciacovelli et al. (2015) simulated the use of two-kinds of tree shaped fins, namely, single and double bifurcation configurations, to optimize and achieve the maximum performance of PCM-LHTES system. Consequently, the longitudinal fins are the most common extended surfaces for enhancing the heat-transfer rate in LHTES systems. Moreover, when a TTHX is used, the heat-transfer area is directly augmented to the PCM surface, and the thermal performance is enhanced, compared with a cylinder or shell and tube-heat exchanger.

This study presents the numerical and experimental investigations for a large TTHX with two-types of extended surface incorporating the PCM. The triangular fin model has been simulated, as a unique extended surface to enhance the heat-transfer rate between the PCM and the HTF, which contains fewer materials and may be more efficient than the familiar configurations of fins.

2. Experiments and procedures

2.1. Selection of PCM

The melting temperature of a PCM, when used in TES, must match the operation range of the application. Akgun et al. (2008) reported commercial-grade phase-change materials that exhibited stable properties after 1000–2000 cycles. Table 1 shows the selected RT82 paraffin (RUBITHERM GmbH-Germany) with thermal properties (78.15–82.15 °C melting temperature) for our system. The system satisfies the minimum temperature requirement for air conditioning systems, which is in the range of 65–70 °C (Al-Abidi et al., 2013a,b). The properties, such as the latent heat of fusion (kJ/kg), melting temperature, and solidification temperature (°C), were measured using a differential scanning calorimetry (METTLER TOLEDO; Model DSC1). Approximately, 20 mg was used and repeated for 10 thermal cycling tests. The PCM was heated

Table 1
Thermos-physical properties of the PCM.

Properties	PCM (RT82)
Density, solid, ρ_s (kg/m^3)	950
Density, liquid, ρ_l (kg/m^3)	770
Specific heat, C_{pl}, C_{ps} (J/kg K)	2000
Latent heat of fusion, L (J/kg)	176,000
Dynamic viscosity, μ (kg/m s)	0.03499
Melting temperature, T_m (K)	350.15–358.15
Thermal conductivity, k (W/m K)	0.2
Thermal expansion coefficient (1/K)	0.001