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Experimental study of the phase change heat transfer inside a horizontal cylindrical latent heat energy storage system

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ABSTRACT

This paper presents an experimental study of the phase change heat transfer inside a cylindrical latent heat energy storage system (LHESS), designed with a central finned copper pipe running the length of the cylindrical container, during charging and discharging operations. Longitudinal fins were added to the copper pipe to enhance the overall heat transfer rates during the phase change processes; fins with two orientations, straight fins and angled fins, are used. The phase change material (PCM) used is dodecanoic acid. The experimental work concentrates on studying the heat transfer mechanism during melting and solidification of the PCM, impacts of the heat transfer fluid (HTF) inlet temperature and HTF flow rates. Moreover, heat transfer enhancement effectiveness of straight fins and angles fins configurations is compared. It is observed that conduction is the dominant heat transfer mechanism during the initial stage of charging, and natural convection dominates once enough liquid PCM is present inside the system. Conduction dominates during the entire solidification process. Complete melting time is strongly affected by the HTF inlet temperature but very slightly by the HTF flow rates.

1. Introduction

Latent heat energy storage system (LHESS) can be used to store available thermal energy for later usage and improve its utilization, henceforth providing a promising solution for smoothing the discrepancy between energy supply and demand. The advantages of LHESS are twofold: high energy storage density and nearly constant temperature during phase change [1]. LHESS uses phase change materials (PCMs) as energy storage mediums: energy is stored during melting and released during solidification. Various applications are found in the open literature including space heating and cooling [2,3], solar domestic hot water systems [4], incorporating PCMs into building elements [5–7], and also applications in automobile designed to reduce emission at start-up [8].

Although being a promising medium for energy storage, PCM suffers from low thermal conductivity which limits its wide application in industry [9]. To this end, various heat transfer enhancement methods have been explored by researchers such as adding fins to PCM container [10,11], using multitude arrays [12], PCM microencapsulation [13], and combining the PCM with another material which has a higher thermal conductivity [14,15].

Fins are the most commonly used heat transfer enhancement method at the system size, and various studies have compared fin sizes and orientations. Various numerical studies looking at the impact of fins on overall PCM melting and solidification can be found in the literature; typically those studies still neglect natural convection the in liquid PCM phase [10,16,17]. Although the numerical work can help determine potential fin design and LHESS geometry; this clearly shows the need for experimental studies where the impact of natural convection can be observed.

Such studies, using various PCMs and fin/system geometries have been published [9]. It was observed that the shape of fins have an effect on heat transfer enhancement; in a concentric tube heat exchanger with Erythritol as PCM, longitudinal fins were recommended over circular fins [18]. Experiments were also performed using RT58 as PCM in an LHESS system having one finned copper pipe (eight longitudinal fins) running through the center of a horizontal cylindrical system; although this study was more focused on the overall energetic behavior of the system, it was found that the low conductivity of the PCM was the major limiting factor for fast energy exchange and fins were therefore improving the overall energetic behavior of the system [19]. The same geometry was used to study in part the impact of heat transfer fluid (HTF) inlet temperature and flow rate on the heat transfer and energy storage behavior of Erythritol; presence of natural convection in the system during melting was noticed but was not directly investigated [20].

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Nomenclature

C_p	heat capacity (J kg^{-1} K^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
T	temperature (°C)
A	area (m^2)
q	heat transfer (W)

Greek symbols

Δh	latent heat of fusion (J kg^{-1})
ΔT	temperature difference (°C)

Subscripts

cold	cold inlet temperature
hot	hot inlet temperature
HTF	heat transfer fluid
in	inlet
m	melting

Definitions of non-dimensional variables

Ste	Stefan number ($C_p\Delta T/L$)

A vertical cylindrical LHESS also utilizing longitudinal fins and using dodecanoic acid as PCM was studied experimentally to determine the impact of natural convection during both melting and solidification [21], and to determine the overall heat transfer during simultaneous charging and discharging of the system as used in a potential solar domestic hot water (SDHW) system [22]. It was found that natural convection played a role only during charging, and for that reason, simultaneous exchange of energy were greatly enhanced when the PCM was liquid. The impact of changing inlet orientation on this system was also studied and found to be nearly non-existent [23]. A simpler vertical cylindrical LHESS with eight longitudinal fins, using sodium acetate trihydrate as PCM, was studied experimentally to determine natural convection coefficients and correlations. The study were done during cooling of the PCM, it was found that the solidification time was reduced when fins were used [24]; however, it is not entirely clear if that change in solidification time was actually a consequence of greater natural convection or simply increased surface areas from the fins. Fin parameters were studied both numerically and experimentally and it was reported that fin thickness had a relatively small influence on the solidification time, while fin length and the number of fins strongly affected complete solidification time [25]. Finally, commercially available heat exchangers, some of them using fined surfaces, have also been studied experimentally [26].

This paper presents an experimental study of the phase change heat transfer inside a cylindrical LHESS, designed with a central finned copper pipe running the length of the cylindrical container, during charging and discharging operations. Longitudinal copper fins were added to the copper pipe to enhance the overall heat transfer rates during the phase change processes as recommended by Ref. [18]; and their number has been limited to four in order to provide more space in the PCM filled cavity to observed a fuller extend of the impact of natural convection in the liquid melt. The PCM used is dodecanoic acid, also known as lauric acid.

The objective of this work is to determine the phase change behavior of the PCM during both modes of operation of the LHESS, as well as the heat transfer processes of importance within the LHESS. The importance of natural convection in the PCM melt will be specifically highlighted. Moreover, tests were performed with two different fin orientations to compare their heat transfer enhancement effectiveness. Finally, the effect of varying flow rates and inlet temperatures of the heat transfer fluid (HTF) is studied.

2. Experimental setup

2.1. Phase change material

Based on data collected from an existing solar domestic hot water (SDHW) system in Halifax, the desirable melting temperature range for a PCM used in that context was determined to be 42 °C–48 °C and solidification temperature range to be 35 °C–40 °C [27]. Based on this phase change temperature, dodecanoic acid, also known as lauric acid, was selected (melting and solidification temperature of 42.5 °C observed experimentally [28]). Dodecanoic acid is a suitable PCM having minimal supercooling, chemical stability, non-corrosiveness and reasonable cost (approximately CAD$16.50/kg for non bulk quantities). Thermophysical properties of dodecanoic acid are shown in Table 1.

2.2. Experimental setup

A schematic of the experimental setup is presented in Fig. 1. The experimental setup is a loop consisting of a hot water bath (using a 500 W immersion heater: model TSP02793), a circulation centrifugal pump (Grundfos model UPS 15-58 FS), a flow meter (pulse counter from OMEGA: model FTB 4605), the horizontal cylindrical LHESS filled with PCM (testing section) and the data acquisition system from National Instrument. The cylindrical LHESS is a container made of acrylic plastic 12″ long and has a 6″ outside diameter, a 1/4″ thickness, and is transparent for the convenience of visualization. During the experiments, the container is insulated by a first layer of glasswool having a thickness of 0.3 cm, and a second layer of Reflectix bubble insulation. Both layers can be opened to allow for visual inspection of the phase change process. A 1/2″ copper pipe passes through the container center, along its length, and four fins are attached to it, 90° from each other. All fins are also made of copper which extend outwards from the pipe, leaving a 1/4″ gap between them and the container wall. For this study, two fin configurations are studied as shown in Fig. 2: i) Horizontal and vertical fins, called straight fins, and ii) Fins at 45° angle (rotation of the first configuration by 45°), called angled fins. The HTF (water in this experiment) is run through the copper pipe to transfer energy. The rest of the container is filled with PCM (dodecanoic acid) with probe thermocouples inserted inside the PCM to monitor temperatures.

In this setup, seven type-T probe thermocouples (probe diameter of 0.0625 inch with ungrounded junction) are connected to a National Instruments 16-channel thermocouple module (NI9213) CompactDAQ data acquisition system with the temperatures recorded using LabView at a time interval of 30 s. The pulses from

Table 1
Thermophysical properties of dodecanoic acid [29,30].

Molecular weight	200.31 (kg/kmol)
Density of solid at 20 °C	950 (kg/m^3)
Density of liquid at 45 °C	873 (kg/m^3)
Fusion temperature	44 (°C)
Latent heat of fusion	182 (kJ/kg)
Specific heat solid/liquid	2.4/2.0 (kJ/kg K)
Thermal conductivities solid/liquid	0.150 (W/m K)/0.148(W/m K)
Dynamic viscosity	0.008 (Pa s)[a]
Thermal diffusivity of solid	6.5×10^{-5} (m^2/s)
Thermal diffusivity of liquid	8.48×10^{-5}(m^2/s)

[a] Data obtained near the fusion temperature.