International Journal of Heat and Mass Transfer 54 (2011) 3476–3484

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Enhancement of latent heat energy storage using embedded heat pipes

Christopher W. Robak, Theodore L. Bergman *, Amir Faghri

Department of Mechanical Engineering, University of Connecticut, 191 Auditorium Road, Storrs, CT 06269-3139, USA

ARTICLE INFO

Article history:
Received 8 October 2010
Received in revised form 5 March 2011
Accepted 5 March 2011
Available online 21 April 2011

Keywords:
Energy storage
Heat pipes
Melting and solidification

ABSTRACT

Latent heat thermal energy storage (LHTES) utilizing heat pipes or fins is investigated experimentally. Photographic observations, melting and solidification rates, and PCM energy storage quantities are reported. Heat pipe effectiveness is defined and used to quantify the relative performance of heat pipe-assisted and fin-assisted configurations to situations involving neither heat pipes nor fins. For the experimental conditions of this study, inclusion of heat pipes increases PCM melting rates by approximately 60%, while the fins are not as effective. During solidification, the heat pipe-assisted configuration transfers approximately twice the energy between a heat transfer fluid and the PCM, relative to both the fin-assisted LHTES and the non-heat pipe, non-fin configurations.

1. Introduction

Stimulated in large part by recent interest in solar power as an alternative form of energy production, large scale thermal energy storage (TES) has received renewed attention. Currently, three types of TES are being considered for solar power generation and other applications: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and chemical thermal energy storage (CTES). Of these, LHTES is of particular interest because it is characterized by high energy density and potentially reduced cost relative to SHTES [1]. LHTES has been researched extensively relative to CTES which is in the developmental phase. However, before large LHTES units are constructed, laboratory-scale research should be conducted to verify the potential of LHTES as an effective and inexpensive energy storage option.

A barrier to the development of large scale LHTES is the low thermal conductivity of most phase change materials (PCMs) and much of the previous research regarding LHTES has focused on reducing the thermal resistance posed by the PCM. For example, Velraj et al. [2] incorporated Lessing rings within the PCM and observed increased heat transfer rates from the PCM to a coolant, making the technique suitable for reducing solidification times. The investigators also considered use of extended surfaces to increase heat transfer, concluding that fins also reduce total solidification times by approximately 75% based upon the predictions of a numerical model. Similar results for LHTES melting (charging) experiments utilizing a finned heat transfer fluid (HTF) tube have been reported by Balikowski and Mollendorf [3]. Sparrow et al. [4] showed that small fins can triple the amount of PCM that freezes about a cold tube. In other work, Agyenim et al. [5] demonstrated that faster PCM heating can be achieved by increasing the number of heat transfer tubes embedded in a PCM. Although the preceding approaches increase heat transfer rates in LHTES systems, they all occupy volume within the PCM storage vessel. Ideally, any strategy to increase heat transfer rates would also occupy little space in order to maximize energy storage capacity.

In this study, incorporation of heat pipes with LHTES is of interest. Heat pipes may increase heat transfer rates to or from the PCM, while maintaining small temperature differences between the PCM and HTF. Limited research regarding heat pipe-assisted LHTES has been conducted. Faghri holds two US patents that describe the use of miniature heat pipes in small LHTES modules [6–7]. Experimentally, Lee et al. [8] developed a low temperature LHTES system operating with a variety of PCMs that utilized a two-phase thermosyphon operating with ethyl alcohol as the working fluid. A paraffin LHTES, with copper–water heat pipes embedded within a rectangular PCM enclosure, was developed and tested by Liu et al. [9]. Recently, Shabgard et al. modeled a large scale heat pipe-assisted LHTES and reported predictions showing improvement in both melting and solidification rates [10].

Although some research has been conducted regarding heat pipe-assisted LHTES, the effectiveness of the approach has apparently not been quantified experimentally. Therefore, the objective of this study is to experimentally establish the effectiveness of heat pipes in potentially increasing heat transfer rates in a LHTES system by directly comparing measured performance with: (i) a system with no heat pipes, and (ii) a system utilizing fins in lieu of heat pipes. Results are reported for both melting (charging the LHTES system) and solidification (discharging).

* Corresponding author.
E-mail address: tberg@engr.uconn.edu (T.L. Bergman).

0017-9310/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2011.03.038

Nomenclature

C	free convection constant
c_p	specific heat
E_t	thermal energy
Fo	Fourier number, $\alpha_s t/H_s^2$
g	gravitational acceleration
h	heat transfer coefficient
H	PCM height
k	thermal conductivity
L	length
m	mass
$\dot{m}$	mass flow rate
n	free convection constant
Nu	Nusselt number, hH_ℓ/k_ℓ
Ra	Rayleigh number, $g\beta\Delta TH_\ell^3/\nu_\ell\alpha_\ell$
Ste	Stefan number, Eqs. (1) and (5)
t	time, thickness
T	temperature

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
ε	effectiveness
η	efficiency
λ	latent heat of fusion
ν	kinematic viscosity
ρ	density

Subscripts

BM	benchmark
c	charging
$crit$	critical
dc	discharging
f	fusion
Fin	fin
HP	heat pipe
HTF	heat transfer fluid
HX	heat exchanger
i	initial
in	inlet
ℓ	liquid
LH	latent heat
LS	large scale
out	outlet
PCM	phase change material
s	solid
SH	sensible heat
SS	small scale
∞	ambient

Superscripts

i	index
n	summation limit
$\sim$	modified value

2. Experimental design

A paraffin, *n*-octadecane ($C_{18}H_{38}$, T_f = 27.5 °C) of 99% purity, the properties of which are listed in Table 1, was used as the PCM. This material was selected because it is stable and non-toxic, and will not cause corrosion. Moreover, the thermophysical properties of *n*-octadecane are well-established and the material has a transparent liquid phase, permitting visual observation of melting and solidification phenomena. As is well known, this material has been used extensively as an experimental, low-temperature PCM [3,11–17].

An overall schematic of the experimental apparatus is shown in Fig. 1(a). As shown in Fig. 1(b), the test cell consists of a vertical, cylindrical PCM enclosure and underlying heat exchanger. The acrylic enclosure has an inside diameter of 127 mm, a height of 200 mm, and a wall thickness of 6 mm. It is mounted to a heat exchanger that serves as the heat source (sink) for melting (solidification). The cylinder is mated to the heat exchanger by way of a 7-mm wide, 4-mm deep channel housing a synthetic rubber O-ring.

Table 1
Thermophysical properties of *n*-octadecane.

Melting point [17]	T_f = 27.5 °C
Latent heat of fusion [17]	λ = 243.5 kJ/kg
Liquid density [3]	ρ_ℓ = 770 kg/m^3
Liquid specific heat [3]	$c_{p,\ell}$ = 2160 J/kg K
Liquid thermal conductivity [17]	k_ℓ = 0.148 W/m K
Liquid thermal diffusivity [17]	$\alpha_\ell = 8.64 \times 10^{-8}$ m^2/s
Kinematic viscosity [17]	$\nu = 4.013 \times 10^{-6}$ m^2/s
Liquid thermal expansion coefficient [17]	β_ℓ = 0.0009 K^{-1}
Solid density [3]	ρ_s = 800 kg/m^3
Solid specific heat [20]	$c_{p,s}$ = 1912 J/kg K
Solid thermal conductivity [17]	k_s = 0.358 W/m K
Solid thermal diffusivity [17]	$\alpha_s = 2.14 \times 10^{-7}$ m^2/s

Note: Minor differences exist between properties from various sources.

Two heat exchangers were utilized, the first with a plane top surface for benchmark experiments involving neither heat pipes nor fins. The bottom section of the heat exchanger was constructed of aluminum (6061) block of length 203 mm, width 187 mm, and thickness 52 mm. HTF flow channels of width 9.4 mm and depth 40 mm were milled into the block in a serpentine pattern. A 6-mm thick aluminum top plate was attached to the block to complete the heat exchanger assembly. The top of the test cell cylinder was covered with an aluminum plate using a similar O-ring sealing arrangement as described previously. Leaks were prevented by compressing the O-rings with four all-threaded rods, as shown in Fig. 1(b). The entire test cell was insulated with a box made from 37-mm thick extruded polystyrene board lined with Fiberfrax ceramic insulation.

The second heat exchanger incorporated a top plate that was modified to accommodate heat pipes or fins. Specifically, five 13-mm diameter threaded holes accepted Swagelok fittings that were, in turn, used to secure either heat pipes or fins that penetrated through the top plate. Five 175-mm long, 6-mm outer diameter copper–water heat pipes (Enertron, model HP-HD06DI17500BA) were installed during the heat pipe-assisted experiments. One heat pipe was centered in the cylindrical test cell, while four heat pipes were mounted in a square pattern, 37 mm from the centerline. During charging or discharging L_{HTF} = 40 mm sections of the heat pipes were inserted within the HTF flow channels, in direct contact with the HTF. Heat pipe lengths of L_{PCM} = 129 mm were exposed to the PCM. For experiments involving fins, the heat pipes were replaced with 316 stainless steel rods of the same dimensions. The low thermal conductivity fin material was specified in order to achieve a fin efficiency similar to that which might be expected in a large scale LHTES system incorporating high thermal conductivity fins (see Appendix A).

Distilled water was used as the HTF, its temperature regulated by a RM 5 Lauda constant temperature bath to within an accuracy of ±0.1 °C of the set point. The HTF flow rate was set using an