Experimental Thermal and Fluid Science 50 (2013) 201–212

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental investigation on melting heat transfer characteristics of lauric acid in a rectangular thermal storage unit

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ARTICLE INFO

Article history:
Received 28 March 2013
Received in revised form 6 June 2013
Accepted 9 June 2013
Available online 24 June 2013

Keywords:
Lauric acid
Phase change material
Melting heat transfer
Thermal storage

ABSTRACT

This paper presents an experimental effort to visualize temperature field and melt front evolution during solid–liquid phase change process. The study is focused on the melting of lauric acid in a rectangular thermal storage unit heated from one side. Thermophysical properties of lauric acid are determined and found to be desirable for application as a medium temperature phase change material (PCM). Image processing of photographs together with recorded temperatures are used to calculate the melt fractions, temporal heat storage and heat transfer characteristics, including the average Nusselt number on the hot wall as well as the local heat transfer rates on the melt front. Moreover, solid–liquid interface morphology and temperature field are employed to infer dominant heat transfer mechanisms and time-dependent flow structures during different stages of the melting process. Results indicate that during the initial stage of melting, heat conduction is the dominant mode of heat transfer, followed by transition from conduction to convection regime and convection dominated heat transfer at later times. Approaching the end of the melting process, bulk temperature of the liquid PCM increases and stratified temperature field appears at upper part of the enclosure which reveals depression of the convection currents.

1. Introduction

Heat transfer processes involving solid–liquid phase change have been of growing interest for researchers in recent years. This is prompted by various applications that are associated with phase change materials (PCM). The major advantages of these materials are their large heat storage capacity, variety of phase change temperatures and their nearly isothermal behavior during charging and discharging processes [1,2]. These materials can be incorporated with other thermal systems such as solar thermal systems [3,4], waste heat recovery [5,6], thermal regulator of buildings [7,8], electronic devices [9–11], spacecrafts [12] and smart textiles [13] to increase their performances and reliabilities.

In order to maximize the performance of thermal storage systems using PCMs, it is required a knowledge about the thermal behavior of the PCM that is employed. Accordingly, some works have been devoted to investigate the detailed thermal behavior of PCMs during the phase change process.

In the past decades, several experimental efforts have been made to study the interface transition and heat transfer characteristics of low Prandtl number materials when they experience a phase change process. One of the first studies in this field was conducted by Gau and Viskanta [14]. They investigated the role of natural convection on solid–liquid interface motion during melting from below and solidification from above for a pure metal (gallium) in a rectangular enclosure. The measurements of both temperature distribution and temperature fluctuations were used as qualitative indications of the natural convection flow regimes. In addition, photographs of the solid–liquid interface shape revealed complicated time-dependent flow structure in the liquid. In another experiment, they studied melting of gallium on a heated vertical wall. Interface position and temperature field were determined by pour-out and probing methods. It was found that in spite of large thermal conductivity of gallium, the interface evolution and melting rate were greatly affected by buoyancy driven natural convection [15].

Wolff and Viskanta [16] studied the solid–liquid interface position and temperature field during the solidification of superheated tin in a rectangular cavity using probing technique. The results showed that since the thermal conductivity of tin is two orders of magnitude higher than the ones of ordinary liquids, the effects of natural convection on the shape and motion of the solid–liquid interface is not as large as non-metallic substances during the phase change heat transfer.

More recently, solid–liquid phase change in high Prandtl number materials such as paraffin based materials, hydrated salts and fatty acids have gained extensive attention due to their increasing usage in thermal storage and thermal regulating units [1,17,18]. A number of experimental studies have been conducted to

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http://dx.doi.org/10.1016/j.expthermflusci.2013.06.010

Nomenclature

A_w	cross sectional area of hot wall (m^2)
Cp	specific heat at constant pressure (kJ/kg K)
H	height of the rectangular enclosure (m)
h_{sl}	latent heat (kJ/kg)
$\bar{h}$	average heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
n	number of thermocouples
NP_0	number of pixels with 0 value
NP_t	total number of pixels
$\overline{Nu}$	average Nusselt number
$Q_{sensible}$	sensible absorbed energy (kJ)
Q_{latent}	total absorbed energy (kJ)
q_{slice}	local solid–liquid heat transfer rate (W)
t	time (t)
T	temperature (°C)
T_{m1}	onset of melting temperature (°C)
T_{m2}	endset of melting temperature (°C)

T_{mean}	mean temperature (°C)
T_w	hot wall temperature (°C)
V	volume (m^3)
V_e	volume of enclosure (m^3)
V_{slice}	volume of solid slice (m^3)

Greek symbols

ρ	density (kg/m^3)
β	solid–liquid volume change
γ	melt fraction

Subscripts

a	apparent
i	initial
l	liquid
r	real
s	solid

understand the phase change process of high Prandtl number materials in different geometries.

Benard et al. [19] conducted a numerical and experimental analysis of heat transfer process during melting of pure n-octadecane in a rectangular enclosure with two vertical hot and cold walls. The melt interface was captured photographically and the temperature distribution was recorded using thermocouples. They found that the melting process could be considered as a two-staged process, based on the melt front location with respect to the cold wall.

Wang et al. [20] investigated the melting process of polyethylene glycol 900 (PEG900) in a rectangular enclosure. A flat-plate heat pipe was used to establish a uniform wall temperature. Experiments were conducted at different wall temperatures and revealed the considerable role of natural convection on the melt front shape.

Assis et al. [21] explored the process of melting of paraffin wax (RT27) in a spherical geometry submerged in a constant temperature water bath. Melting images were recorded by a digital camera at various stages of the melting process and used to calculate the transient melt fraction. The results showed the relation of transient phase change of paraffin with thermal and geometrical parameters of the system.

Tan [22] studied experimentally the phase change of n-octadecane inside a spherical capsule for both constrained and unconstrained melting processes. It was observed that in constrained melting, heat conduction only exists at the beginning of the melting process, followed by natural convection in the liquid PCM while in unconstrained melting, the solid PCM sinks and melting at the bottom half augments due to the continuous heat conduction at lower part of the solid PCM. It was concluded that closed contact melting in unconstrained melting process accelerate the phase change rate of the PCM in the spherical container. In another experimental and computational study, Tan et al. [23] investigated the role of buoyancy driven convection during constrained melting of paraffin wax inside a spherical capsule. It was found that after a short period of symmetric melting, phase change rate is enhanced in the top region of the sphere and a wavy surface at the bottom of the is formed. Also temperature measurements at the bottom of the sphere revealed unstable fluid layer with chaotic temperature fluctuations which is responsible for waviness of the bottom of the solid PCM.

Rizan et al. [24] performed an experimental study on melting of n-octadecane inside a sphere subjected to different constant heat rates. It was concluded that with a higher power rating, the melting rate increase as the result of internal convection enhancement.

Regin et al. [25] investigated the heat transfer characteristics of the melting process inside a horizontal cylindrical capsule filled with paraffin wax as PCM. The focus was to study the roles of natural convection and contact melting on heat transfer enhancement during the melting process. Also three stages of melting were revealed by visualization technique.

The design of more practical and efficient thermal storage units requires a deeper understanding of the heat transfer phenomena which govern the melting process of PCMs. To the best of our knowledge, there is no detailed study of thermal behavior and heat transfer characteristics of lauric acid (dodecanoic acid) during melting process in rectangular geometry. Therefore, the objective of this paper is to investigate the heat transfer process during the solid–liquid phase change of lauric acid as a high Prandtl number material in a rectangular enclosure. In addition, photographic observation was employed to calculate the temporal melt fraction which is a more accurate technique than the previous probing and pour-out methods. Well-characterized experiments were conducted to visualize the solid–liquid interface and to record the instantaneous temperature distribution inside the PCM. Melt front morphologies and recorded temperature distributions were applied to obtain the temporal heat storage and heat transfer characteristics of lauric acid during the melting process. Also the local solid–liquid heat transfer rates were investigated which has not been reported in the previous studies.

2. Experimental apparatus and procedure

2.1. Measurement of thermophysical properties

The PCM used in this experimental study was lauric acid ($C_{12}H_{24}O_2$), which is a fatty acid, with 99% purity (Panreac Chemical). It has favorable characteristics such as, non toxicity, good chemical stability as well as medium-temperature phase change which qualify it as a promising PCM for medium-temperature thermal storage applications.

Thermal properties of lauric acid including melting temperature range, latent heat of solid–liquid phase change and specific heat