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Constrained ice melting around one cylinder in horizontal cavity accelerated using three heat transfer enhancement techniques

Mahmoud Jourabian[a,*], Mousa Farhadi[b], AhmadAli Rabienataj Darzi[c]

[a] *Department of Engineering and Architecture, University of Trieste, Trieste, Italy*
[b] *Faculty of Mechanical Engineering, Babol University of Technology, P.O. Box 484, Babol, Islamic Republic of Iran*
[c] *Faculty of Mechanical Engineering- Thermal and Fluids, University of Mazandaran, Islamic Republic of Iran*

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ABSTRACT

Constrained melting around one hot cylinder inside a horizontal square cavity is inefficient from an energy-saving viewpoint because of the elevated thermal stratification and sluggish advancement of the melting front at the bottom. The situation is exacerbated by the low thermal conductivity of the phase change materials (PCM). To overcome it, four hot cylinders instead of one cylinder are selected in the same cross-section area. Besides, the base PCM is mixed with the small volumetric concentration of the nanometer-sized Cu particles to enhance the melting rate. It has to be clarified in which array the NEPCM is the most effective way. However, increasing the dynamic viscosity of the base PCM using nanoparticles may have a negative effect on the speed of the natural convection flow. Finally, the metallic porous matrix with the thermal characteristics of the Nickel-Steel alloys is inserted in the base PCM to enhance the thermal conductivity and melting rate and to abate the full melting time. The weakening of the natural convection effect within the porous structure could be worthy of attention. The enthalpy-based lattice Boltzmann method (LBM) with a D2Q9-double distribution function (DDF) model at the REV scale is used to model the ice melting in the absence of the subcooling.

1. Introduction

Horizontal concentric annuli [1–3] encapsulated with the phase change materials (PCMs) are the most used latent heat thermal energy storage systems (LHTESS). The solid-liquid phase change process, melting, which occurs in these systems, needs to be analyzed to get the best thermal performance of the system. However, it depends on many operating conditions and thermophysical properties.

If the constrained or fixed mode is considered, the solid PCM is hindered from the vertical displacement due to the buoyancy whereas in the unconstrained or close-contact melting there is the sinking of the solid PCM toward the bottom. Also, the energy input can be provided from the outer square shell which is called the shell heating or from the inner cylinder called the tube heating. The single-tube annulus-type configuration is inefficient from a thermal performance point of view because there is an elevated thermal stratification at the bottom and a low melting rate and a high full melting time. The energy input is mainly wasted to just overheat the melted PCM in the top while there is a sluggish planar progress of the melt front at the bottom due to the presence of the persistent conduction heat transfer. Several methods would be applied to overcome these problems and also the low thermal conductivity of the PCMs.

An innovative strategy could be the use of the nano-sized metallic particles in the base PCMs called the nanopartices-enhanced phase change material (NEPCM). The frequent range of the dispersion is between 0.1 and 5%. However, it is worth mentioning that as the thermal conductivity of the base PCM enhances with the volumetric concentration of the nanoparticles, other thermo-physical properties of the PCM such as the viscosity or latent heat are modified. Subsequently, an optimum value of the volumetric concentration may be employed.

Melting of n-octadecane (PCM) with the CuO nanoparticle suspensions inside a shell-and-tube unit examined numerically and experimentally by Dhaidan et al. [4]. The melting of the NEPCM was accelerated by shifting downwardly the center of the inner cylinder. The numerical analysis of the 2D melting in a concentric cylindrical annulus filled with a NEPCM was accomplished by Mastiani et al. [5]. By enhancing the volume fraction of the nanoparticle, the heat transfer rate boosted and in contrast, the volume occupied by the base PCM was declined. Jourabian et al. [6,7] carried out the LB simulation of the melting process of Cu/water nanofluids PCMs in the annulus. As the inner hot inner cylinder mounted in the top, the effect of nanoparticles on the liquid fraction became more pronounced due to the

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* Corresponding author.
E-mail addresses: mahmood.jourabian@gmail.com (M. Jourabian), mfarhadi@nit.ac.ir (M. Farhadi), a.rabinataj@gmail.com (A. Rabienataj Darzi).

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Nomenclature

A	Surface area [m^2]
$\overrightarrow{B}$	Scalar function
c	Streaming speed [m.s^{-1}]
ci	Discrete lattice velocity
cp	Heat capacity[J.kg^{-1}.K^{-1}]
cs	Speed of sound [m.s^{-1}]
dp	Nanoparticle diameter [m]
d_{por}	Solid particle diameter [m]
D	Scalar function
Da	Darcy number
E	Tensor function
En	Enthalpy [J]
Ens	Enthalpy of solid phase [J]
Enl	Enthalpy of liquid phase [J]
fl	Liquid fraction
$\overrightarrow{F}$	Total body force [kg.m.s^{-2}]
Fo	Fourier number
F_ε	Geometric function
g	Acceleration due to gravity[m.s^{-2}]
$\overrightarrow{G}$	Buoyancy force [kg.m.s^{-2}]
I	Unit tensor
k	Thermal conductivity [w.m^{-1}.K^{-1}]
k_b	Boltzmann constant
K	Permeability [m^2]
l	Length scale [m]
L	Latent heat [J.kg^{-1}]
p	Pressure [kg.m^{-1}.s^{-2}]
P	Dimensionless pressure [kg.m^{-1}.s^{-2}]
Pe	Peclet number
Pr	Prandtl number
R	Source term of the temperature field
Ra	Rayleigh number
Ste	Stefan number
t	Time [s]
$\overrightarrow{u}$	Fluid velocity [m.s^{-1}]
$\lvert\overrightarrow{u}_p\rvert$	Brownian motion velocity [m.s^{-1}]
$\overrightarrow{U}$	Dimensionless fluid velocity
$\overrightarrow{V}$	Auxiliary velocity [m.s^{-1}]
T	Temperature [K]
T_0	The initial temperature of PCM [K]
T_1	The temperature of heated surfaces [K]
X,Y	Dimensionless coordinates

Greek symbols

α	Thermal diffusivity[m^2.s^{-1}]
β	Thermal expansion coefficient [K^{-1}]
γ	Force term for the fluid flow
Δt	Lattice time step size
Δx	Lattice cell size
δ_{ij}	Kronecker delta
ε	Porosity
θ	Dimensionless time ($=Ste \times Fo$)
μ	Dynamic viscosity [kg.m^{-1}.s^{-1}]
ν	Kinematic viscosity [m^2.s^{-1}]
ρ	Density [kg.m^{-3}]
σ	Thermal capacity ratio
τ	Lattice relaxation time
ϕ	Volume fraction of nanoparticles
ψ	Scalar quantity
Ω	Viscosity ratio
ζ	Source term of the TDF

Superscripts

$*$	Dimensionless symbol

Subscripts

e	Effective property in porous media
eff	Effective property in Nanofluid
f	Liquid phase of PCM
i, j	Directions
lbm	Lattice scale
m	Solid matrix
nf	Nanofluid
p	Nanoparticles
ref	Reference
s	Solid phase of PCM

augmentation of the thermal conductivity.

Making the geometry like a multitube configuration could be another solution. Agyenim et al. [8] compared experimentally the thermal performance of multitube to a single tube shell and tube storage unit filled with Erythritol. Liu et al. [9] designed a hierarchical array of tubes inside an annulus for the *RT27* and found as the number of the inner tubes increased, the melt region enlarged and the vortices strengthened.

By developing a double-population lattice Boltzmann method (LBM), Luo et al. [10] determined the heat transfer performance of the shell and tube LHTESS with the multifarious arrangements of the inner hot tubes. Esapour et al. [11] performed a numerical study on the melting characteristics of *RT35* in a multitube heat exchanger.

In recent years, the use of a metallic porous matrix or foam to increase the thermal conductivity of the PCMs has attracted researchers because frequently porous materials have a light weight and high surface area.

On the other hand, pay attention that the more the porosity abates, the more the volume faction of the PCM available in the LHTES system diminishes. So the capacity of the heat storage unit becomes limited. Furthermore, due to the structure of the porous media, the convection flow may be suppressed. Hence, an optimized value of the porosity may be used in each configuration. Lafdi et al. [12] experimentally scrutinized the phase change heat transfer within a composite of the PCM and foam. When the porosity of the aluminum foam increased, the steady-state temperature obtained faster compared to the samples with a lower porosity. Zhao and Tian [13] explored experimentally the charging and discharging processes of the paraffin wax *RT58* in a cavity filled with the metallic foam. The overall heat transfer rate boosted and the temperature difference of the porous samples appreciably diminished. Liu et al. [14] explored numerically the *Paraffin-RT58* melting in a shell-and-tube system or a concentric cylindrical annulus. It was pointed out that a low porosity caused a rapid process. Hossain et al. [15] performed the numerical and analytical examinations on the NEPCM (*Cyclohexane* + *CuO* nanoparticle) melting in a cavity filled with the aluminum foam. The NEPCM melted at a quicker rate in the porous medium with a lower porosity so a higher porosity required a larger energy input for the melting process. However, Tasnim et al. [16] reported numerically that the effect of the natural convection in the porous media was qualitatively similar to the NEPCM melting in a porous cavity. Wang et al. [17] conducted an experimental investigation on the melting of the porous metal fiber sintered felt/paraffin