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Numerical study for enhancement of solidification of phase change materials using trapezoidal cavity

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ABSTRACT

This paper reports the results of a numerical study on the heat transfer during process of conduction dominated solidification of copper–water nanofluid in isosceles trapezoidal cavity under controlled temperature and concentration gradients. The suspended nanoparticles have proven to increase the heat transfer rate substantially. The horizontal walls of the cavities are insulated while side walls are kept at constant but different temperatures. The total solidification time of pure fluid and nanofluid filled in the cavity is investigated for three different inclinations of side walls and the results are compared with square cavity. Results revealed that the total solidification time for pure fluid as well for nanofluid for all nano particle concentrations decreases. The effects of Grashof number (10^5–10^7) on the heat transfer phenomenon and solid–liquid interface are also numerically investigated and presented graphically. The enthalpy–porosity technique is used to trace the solid–liquid interface. Inclination angle can be used efficiently to control the solidification time. In addition, average Nusselt number along the hot wall for different angles, nanoparticles volume fractions, and Grashof number is presented graphically. The proposed predictions are very helpful in developing improved latent heat thermal energy storage for solar heat collector and for casting and mold design.

1. Introduction

A continuous increase in the gap between the energy demand and supply and the depletion of fossil fuels have received the attention of researchers in the last few decades. This increasing demand forces researchers to develop renewable energy sources. This demand and supply gap is efficiently bridged by employing a suitable energy storage system. As an example, solar energy is not available during the night and on cloudy days, so the heat stored in phase change materials (PCM) during sunny days can be used as and when needed during cloudy hours or in the night. Latent heat thermal energy storage (LHTES) devices are more attractive than sensible heat storage devices due to their high energy storage density and constant charging and discharging temperature. In general, these devices use a PCM such as pure water, paraffin wax, etc. Solid–liquid phase change problems, sometime also known as moving boundary or Stefan problems are encountered in many industrial applications such as casting and laser drilling, latent heat thermal energy storage, food and pharmaceutical processing, microelectronics, and protective clothing. Depending on the initial temperature of the material, they are categorized as one-region, two-region or multiple region problems [1]. This phase change conversion (solid–liquid) absorbs latent heat during charging (melting) and releases it during solidification (discharging). Design and development of such devices have been greatly assisted by many experimental and numerical investigations.

The low thermal conductivity of PCMs is the primary limitation in many engineering devices, however the dispersion of solid particles in the base fluid overcomes this limitation which can be done either at micro or nano levels. Dispersion of micrometer or millimeter sized particles may cause the clogging in the fluid flow and increase the pressure drop because of the rapid settling characteristics. Nano sized particles behave like liquid particle, show little or no pressure drop and flow with or without little chance of clogging in the pipes. A mixture of a base fluid and solid particles of nano size is called a nanofluid [2]. Khodadadi and Hosseinizadeh [3] reported that the latent heat decreases as the mass fraction of dispersed particles increases. They numerically analyzed the solidification of nanofluid (water + nano copper particles) in a square cavity and found that the speed of the solid/liquid interface increases as the time elapses for nanofluid of higher mass fractions. This resulted in considerable reduction in the total solidification time of the nanofluid. Encapsulation of PCMs is a promising way to store the latent heat energy due to numerous advantages such as large heat transfer area, reduction in PCMs interaction

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Nomenclature

A	Aspect ratio (L/H)
c_p	Specific heat at constant pressure
d_p	Nanoparticle diameter
f	Liquid fraction
g	Acceleration due to gravity
Gr	Grashof number, $g\beta_f \Delta T H^3/\vartheta_f^2$
h	Specific enthalpy
H	Height of the cavity
H_e	Total enthalpy
k	Thermal conductivity
k_f	Fluid thermal conductivity
k_{eff}	Effective thermal conductivity
k_s	Solid thermal conductivity
L	Length of the cavity
L_x	Length of square enclosure in the x direction
L_y	Length of square enclosure in the y direction
L_h	Latent heat of fusion
M	Mushy zone constant
n	Direction normal to the surface
Nu_L	Local Nusselt number
Nu_{ave}	Average Nusselt number
Pr	Prandtl number, $\mu c_p/k$
Q	Total heat transfer from left wall
S	Source term
t	Time
T	Temperature
u	Velocity component along x-axis
v	Velocity component along y-axis
U, V	Dimensionless velocity components
x, y	Cartesian coordinates
X, Y	Dimensionless coordinates

Greeks symbols

β	Volumetric expansion coefficient
$\propto$	Thermal diffusivity
$\varnothing$	Solid volume fraction
ϑ_f	Kinematic viscosity
ρ	Density
μ	Dynamic viscosity
θ	Inclination angle

Subscripts

ave	Average
c	Cold
eff	Effective
f	Fluid
h	Hot
nf	Nanofluid
o	Reference value
s	Solid
w	Wall

Abbreviations

CW	Clockwise
CCW	Counter clockwise

with the external environment, and controlling the variation in volume change during phase change. The geometry of the enclosure (e.g. rectangular, cylindrical, and spherical) also plays an important role in the heat transfer rate in fluid which has been extensively reviewed by Ostrach [4].

Most of the previous studies are concerned with the analysis of the conduction or natural convection heat transfer of PCMs in regular shapes like asquare/rectangular cavity [3,5–13], cylindrical cavity [14–22], and spherical cavity [23–31]. Gau and Viskanta [8] experimentally investigated the buoyancy driven flow in gallium and its effect on solid–liquid interface motion and heat transfer during melting and solidification in a rectangular cavity. They found that at the beginning of melting, the fluid motion was very slow and the interface was flat and parallel to the heated wall, which can be interpreted as conduction dominated heat transfer. As time progresses, buoyancy-driven flow increases and the solid–liquid interface no longer remains straight and appeared to be receding from top to bottom wall. Later, Brent et al. [32] proposed the enthalpy–porosity technique to trace the solid–liquid interface in melting and solidification phenomenon. They used this approach to reproduce the results of experimental work [8] using a 2D rectangular cavity, keeping the same boundary conditions and material used and found that their numerical predictions are in very good agreement with the experimental results. Recently Arasu and Majumdar [5] carried out a numerical investigation on the melting of a PCM (paraffin wax + Al_2O_3) in a square enclosure heated from the bottom side and from a vertical side with different volume fractions of nanoparticles (0.02 and 0.05). They reported that the effective thermal conductivity of a paraffin wax latent heat storage medium could be increased significantly by a smaller volumetric concentration of alumina particles in the paraffin wax in both cases.

Darzi, Farhadi, and Sedighi [18] numerically simulated the melting process of n-eicosane in concentric and eccentric double pipe heat exchangers and studied the effect of the internal tube position on the melting rate. They found that the melting rate was same in the early stage of melting, and then decreased in the concentric model. Spherical geometry represents an interesting case for heat storage application, since spheres are often used in packed beds and other energy storage applications. Recently an experimental and numerical study [23,24] has been carried out for constrained melting of PCMs in a spherical shell. It was mentioned that the conductive heat transfer dominates during the early period of melting, but as the buoyancy-driven convection is strengthened, melting in the top region of the sphere is faster than in the bottom region.

As discussed earlier, most of the solidification/melting studies at present are based on regular shapes and limited studies are carried out using irregular shapes. To the best of our knowledge, there is no solidification analysis of NEPCM filled in a differentially heated trapezoidal cavity. The trapezoidal cavity has received significant attention of researchers due to its applicability in various fields, for example in the moderate concentrating solar collector [33]. Solidification of a binary mixture in a trapezoidal cavity is of practical importance in the casting and mold design because of the common practice to make the ingot wall with a small slope to facilitate withdrawal of the casting [34]. One of the possible methods to improve the performance of LHTES devices is to enhance the heat transfer rate in the nanofluid by increasing the surface area normal to the direction of heat transfer which can be done using trapezoidal cavity. Duggiralaet al. [34] experimentally investigated the effect of initial concentration of ammonium chloride (NH_4Cl) in the range of 0–19.8% and boundary temperatures in the range of −30 to 0 °C on the solidification of binary alloy ($NH_4Cl + H_2O$) in a trapezoidal cavity. However, this study does not explicitly investigate the effect of the trapezoidal cavity on solidification rate; Moreover, this study is not based on NEPCM. Therefore, a detailed study is required to understand the true effect of using a trapezoidal cavity for the solidification of NEPCM especially since the presence of non-vertical walls in a trapezoidal cavity makes the conduction/convective flow analysis more difficult than that in a square and rectangular cavity.