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Influence of fin size and distribution on solid-liquid phase change in a rectangular enclosure

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ABSTRACT

This paper details a numerical study of solid-liquid phase change heat transfer in a rectangular enclosure with the aim of optimizing the number, dimension, and positioning of fins in the enclosure. The enclosure is exposed on one side to a constant heat flux of 1000 W/m^2 for 3 h and both the total fin mass and the PCM mass are kept constant in all simulated cases. The heat diffusion equation in the PCM uses the equivalent heat capacity method while natural convection driven PCM motion in the enclosure is modeled through the buoyancy force, using a modified viscosity and an additional volume force term in the Navier-Stokes momentum conservation equation. Three efficiency assessment parameters are used: (i) the height-averaged temperature of the front hot plate which should remain as low as possible for the longer possible time, (ii) the energy stored inside the PCM as a function of time, and (iii) the heat transfer rate and heat flux between the front plate and the PCM. For each simulated case, complementary data such as the standard deviation of temperature along the heated plate and the ratio of sensible heat to latent accumulation are also calculated. Results show that increasing the number of fins diminishes both the stabilization temperature and the stabilization time of the front plate during phase change, and accelerates the sensible and latent storage of energy in the PCM. Using thinner but longer fins provides the same impact except that the stabilization time also increases as the fin length is increased. Besides, at constant fin mass, varying fin spacing have marginal impact on the latent heat storage performance and on the hot plate temperature stabilization. The study also shows that the surface area plays the largest role in the increase of the heat transfer rate between the front plate and the PCM, while configurations which can promote stronger natural convection lead to higher heat flux. Finally, it was observed that systems allowing easier heat transfer to the back plate during melting provide a higher ratio of sensible heat to latent accumulation, while the standard deviation of the front plate temperature decreases as the number of fins or the spacing between fins increases.

1. Introduction

Research on thermal energy storage and temperature control using phase change materials (PCMs) is now being done at an accelerated pace all around the world in virtue of its potential wide applications in relations with: renewable energy (PV [1], thermal [2], wind [3]), building energy savings [4,5], heat pumps [6], automotive (conventional [7] and electric [8]) and electronic temperature management [9,10]. Latent Heat Energy Storage Systems (LHESS) used in those applications all need to be designed for specific heat transfer rate from the heat source/sink to the PCM storage enclosure, and this translates to specific charging and discharging rates for a given application.

Different approaches can be used to control such heat transfer rate. One is to combat the inherent low thermal conductivity of most PCM by adding highly conductive particles such as carbon nanotubes [11], aluminum nitride [12], or copper oxide [13], to increase the overall conductivity of the resulting enhanced-PCM [14]; or by integrating the PCM in a high conductivity matrix, which may be of metallic [15] or mineral [16] nature. A second approach is to use ordinary PCM and deal with their low thermal conductivity by focusing the design of the LHESS on the geometry of the system [17,18], principally by adding appropriate fins in key areas of the storage enclosure [19], using a multi-tube assembly [20] or macro-encapsulated PCM in packed beds [21].

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Nomenclature

A	surface area (m^2)
$B(T)$	numerical step function (-)
C	numerical constant (-)
C_p	heat capacity (J/kg·K)
$D(T)$	numerical Gaussian function (-)
Fo	Fourier number
g	gravitational acceleration (m/s^2)
h	convection coefficient (W/m^2K)
H	height (m)
k	thermal conductivity (W/m·K)
l	length (m)
L_F	latent heat of fusion (J/kg)
m	mass (kg)
P	pressure (Pa)
Pr	Prandtl number (-)
Q_{st}	stored energy (J)
q	heat transfer rate (W)
q	numerical constant (-)
q_0	heat flux/solar irradiation (W/m^2)
Ra	Rayleigh number (-)
Ste	Stefan number (-)
t	time (s)
T	temperature (K)
τ	dimensionless time (-)
T_{avg}	height-averaged temperature of the front plate (K)
T_0	initial temperature (K)
T_∞	ambient temperature (K)
U	heat transfer coefficient (W/m^2K)
$\vec{u}$	velocity vector (m/s)
x	coordinate (m)

Greek letters

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
ΔT	melting temperature interval (K)
ρ	density (kg/m^3)
σ	standard deviation (K)
μ	dynamic viscosity (Pa.s)
ν	kinematic viscosity (m^2/s)

Subscripts

1	related to the front plate
2	related to the back plate
avg	averaged
AL	aluminum
b	base
l	liquid
m	melting
max	maximum
PCM	Phase change material
s	solid
st	stored

The research work presented in this paper focuses on the second approach, *i.e.*, the effects of fins on the overall phase change heat transfer process. Earlier work in this area focused on determining numerical methods to simulate the effect of vertical fins on melting of a PCM from a heated wall, including the effect of natural convection in the process [22]. In 2004, two studies, with horizontal fins by Huang et al. (melting – numerical and experimental) [23] and with vertical fins by Stritih (melting and solidification - experimental) [24] showed that, compared to the similar system with no fins, natural convection was enhanced during the melting phase, while fins greatly helped increase the solidification rates. Huang et al. (2006, 2011) compared different finned systems to a metal foam system, and the use of various PCM, for use in temperature control of photovoltaic (PV) panel and found that the finned systems provided the lowest mean front panel system temperature during operations [25,26]. However, no parametric studies for this system/fin geometry have been performed, specifically looking at the impact of fin number, size and distribution on the overall melting process, and the resulting natural convection patterns within the enclosure.

Fins in cylindrical geometry have also been studied, starting with the experimental study of radial and longitudinal fins positioned on the outside surface of a horizontal heat transfer fluid central pipe within a PCM enclosure [6,27]. Further studies focused on experimentally determining the impact of natural convection in both finned horizontal [28] and finned vertical cylindrical systems [29]; it was found that combining fin design and natural convection driven melting could lead to expected heat transfer rates for a given application, however natural convection plays no role during solidification which is where fin design becomes more of a priority. The increase of melting rates achieved through the combination of fins and close-contact melting in a cylindrical geometry with radial fins was investigated by Kozak et al., finding very good agreement between numerical results and experimental measurements [30]. The impact of fins during simultaneous charging/discharging of a vertical cylindrical finned LHESS was also studied [31]. Other numerical studies focused on determining the behavior of a finned cylindrical system when multiple PCMs are used along the length of the system [32] or evaluating the amount of energy, both latent and sensible, that can be stored in a given system as a function of the number and distribution of fins [19].

The area of PCM embedded heat sink for electronics cooling is also one where research on fin/PCM interaction is of the upmost importance. Here, two main finned configurations are found in the literature: in hybrid heat sinks, part of the fin surface is in contact with a coolant, which may be air or water, while another part is in contact with the PCM. This configuration allows alternating passive cooling by the use of PCM to absorb, for example, high peak loads, and active cooling by blowing the coolant through the fins to evacuate the excess heat and regenerate the PCM [33–35]. The second configuration, pertaining to this paper, occurs when the fins are totally immersed in the PCM volume, the cooling being achieved in a passive way only. Here, due to the small volumes of PCM used between each fin of a heat sink, earlier numerical studies looked at enhanced melting driven solely by conduction [36]. The effect of natural convection with plate-type and rod-type finned heat sinks were added in later work, with both two- and three-dimensional simulations, with the conclusion that thinner fins were providing the greatest thermal conductivity enhancement [37–39]; but it was also found that the optimum fin dimensions would be a function of considered heat flux and critical operating temperature [40]. Experimental work also went in this direction showing the added impact of finned PCM heat sink in reducing the overall electronics operating temperature, with pin fins being more efficient than plate fins [41]. Finally, fins are found in multiple types of commercial heat exchangers. The usefulness of such commercial heat exchanger when used with PCM for thermal storage was studied in a paper by Medrano et al. [42]. It was found that the heat exchanger with fins, or metal foam, were more adequate for thermal storage.

It was also made clear that textbook fin efficiency and effectiveness calculations could not be applied to systems where fins interacted