



A numerical investigation of melting phase change process via the enthalpy-porosity approach: Application to hydrated salts



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ARTICLE INFO

Keywords:

Phase change material
Natural convection
Numerical simulation
Finite volume method
Enthalpy-porosity formulation
Melting
Fusion

ABSTRACT

The convection dominated melting of hydrated salts (PCM 27) is investigated numerically using a pressure based finite volume method (FVM) with an enthalpy porosity technique, which allows a fixed-grid solution of the coupled momentum and energy equations, and trace the solid-liquid interface without resorting to other equations or transformations. This investigation addresses effects of Rayleigh number, the aspect ratio and Prandtl number on the effectiveness of melting process and solid-liquid interface. In addition, the average Nusselt number is set to complete the parametric study conducted. Through the results achieved, the enthalpy-porosity has been found to converge rapidly while producing accurate results for both the position and morphology of the melt front at different times. The results are presented in terms of temperature profiles, streamlines, isotherms, moving interface position, liquid fraction and average Nusselt number. From this survey, it appears that our numerical findings support the experimental observations. These results indicated that, in terms of efficiency of the melting process, the best configuration of the rectangular container is the cavity having an aspect ratio of 0.19 ($H = 21$ cm; $W = 4$ cm). Therewith, it is found that the time required to melt the material is proportional to the Rayleigh number and the convection heat transfer. Finally, this study demonstrates the feasibility for simulating macro-encapsulated hydrated salts via the enthalpy-porosity-based approach.

1. Introduction

Storage of thermal energy is essential for reducing the continuous increase of the gap between energy demand and supply. There are three different ways one can store thermal energy in a storage material: form of sensible heat, latent heat and thermochemical energy. In the thermochemical storage system the corresponding storage materials used are still too expensive and their use requires a technical and economic feasibility study [1]. The sensible heat thermal storage (SHTS) system is very simple and the temperature of the storage material changes with the quantity of energy added or removed from the system. On the other hand, in a latent-heat thermal energy storage (LHTES) system, the density of energy storage is higher allowing the design of more compact systems with less heat losses and allowing energy storage at a nearly constant temperature [1,2]. Several studies have shown that using phase change materials (PCMs) as promising LHTES materials allows absorbing or releasing latent heat during a phase change from solid-state to liquid-state (melting process) or liquid-state to solid-state (freezing process). This system found several potential engineering

applications, such as thermal energy storage, thermal management, heating and cooling systems, electronic products, drying technology, waste heat recovery, solar air collectors, and solar cookers, and so on.

One disadvantage of LHTES systems is the lower thermal conductivities of PCMs used, which slowed the melting/solidification rate. A faster fusion/solidification rate is highly sought after in the field of engineering [3]. Among the techniques for improving the thermal conductivity of PCMs and the heat transfer are microencapsulated PCM [4], porous metals [5], use of stationary highly conductive structures [6] and multiple PCMs [7]. In addition to these approaches, optimization of the conditioning system of PCMs along with the choice of type of PCM is the main interest of this research. These parameters modify the phase change process, as well as the heat transfer rate, which will be discussed in the present work.

Since organic and inorganic PCMs are widely used in various engineering fields, they have been extensively studied in literature. For low-temperature residential applications, the hydrated salts (inorganic PCMs) are the most commonly used because of their low cost, low volumic expansion, stability of melting point and high volumetric

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Nomenclature

A	matrix coefficients
B	porosity function
C	morphological constant (see Relationship (5))
c	specific heat (J/kg·K)
f	liquid fraction
g	gravity vector (m/s ²)
H	total enthalpy (J/m ³)
h	specific enthalpy (J/m ³)
k	thermal conductivity (W/m·K)
L	latent heat of fusion (J/kg)
W	length of rectangular enclosure in x-direction (m)
H	length of rectangular enclosure in y-direction (m)
\overline{Nu}	Average Nusselt number
Pr	Prandtl number
p	pressure (Pa)
R	aspect ratio (H/W)
Ra	Rayleigh number
S	source term
Ste	Stefan number
T	temperature (K)
T_0	initial temperature (K)
T_m	melting point of materials (K)
T_C	isothermal right wall temperature (K)
T_H	isothermal left wall temperature (K)
t	time (s)
u	velocity in the x direction (m/s)
v	velocity in the y direction (m/s)

ΔV	control volume
x, y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity (m ² /s)
β	expansion coefficient (K ⁻¹)
ε	arbitrary computational constant
∇	Nabla operator
ν	kinematic viscosity (m ² /s)
Δt	time step (s)
Γ	diffusion coefficient
μ	dynamic viscosity (kg/m·s)
ρ	density (kg/m ³)
φ	generalized variable
ω	relaxation factor

Superscripts/subscripts

c	interface position
k	iteration level
l	liquid phase
m	melting
P	present node
ref	reference temperature value
S	solid phase
W, E, P, N, S	west, east, center, north and south nodes
0	initial value

energy storage density [8]. In this context, the calcium chloride hexahydrate $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ is one of potential materials for the low-temperature thermal storage, and thereby it has been explored extensively in the literature research [9–12]. Younsi et al. [12] have investigated experimentally the melting characteristics of salt hydrates in a rectangular cavity heated through its sides. Their results indicated that the melting efficiency has great potential for storing heat. Tyagi and Buddhi [13] have experimentally studied the thermal stability of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ after any thermal cycling tests. They concluded that $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ is the material which has a promising potential for heating and cooling applications with small variations in the material latent heat of fusion during thermal cycling [8].

Macro-encapsulation of PCMs is a promising technic for storing the latent heat energy where the material is sealed in an enclosure which can be of any shape (rectangular, cylindrical, and spherical). It should be noted that the choice of the enclosure's geometry is a key parameter for improving the heat transfer rate. The rectangular and cylindrical containers are the most used due to their facility and low production cost [14]. To assess the potential use of macro-encapsulated PCMs in rectangular containers, many numerical, analytical and experimental studies have been conducted over the last decade [15–19].

The melting of PCMs aroused great interest because of its important role in the thermal energy storage. Several analytical, numerical and experimental studies were carried on phenomena associated with melting in different geometry configurations [20–23]. These works have concluded that the onset of melting is clearly dominated by diffusion, while buoyancy-driven convection has a paramount role in the melting process. However, little effort has been made on the optimization of the melting of a PCM packaged in a rectangular envelope and lay out vertically. Gau and Viskanta [24] have investigated experimentally solid-liquid interface motion and heat transfer during melting and solidification in a rectangular cavity filled with Gallium (Ga). They found that the heat transfer at the beginning of melting is dominated by conduction as time progresses, and that the convection develops on top

of the cavity. Brent et al. [25] were among first authors to develop the enthalpy-porosity technique to trace the solid-liquid interface during the melting and solidification process. This approach has been validated by replicating the results of experimental work [24] using a 2D rectangular cavity. Shamsundar and Sparrow [26] proposed a multi-dimensional conduction phase change model for a solar energy storage system using the enthalpy-based method. Hamdan and Elwerr [27] have developed a mathematical approach to handle solid-liquid interface propagation during the two-dimensional melting process. Dhaidan et al. [28] have explored experimentally and numerically the melting of n-octadecane with CuO nanoparticle suspensions in a square enclosure. Their findings showed a significant effect of natural convection and an increase of the Rayleigh number on the shape of the solid-liquid interface.

One of the most successful applications for PCM is thermal energy storage for air heating. Younsi et al. [29] have provided a new air heating system with a PCM energy store called Trombe wall improved, and allowing reducing energy consumption by 30% compared to conventional wall systems. As shown in Fig.1, the Trombe wall improved

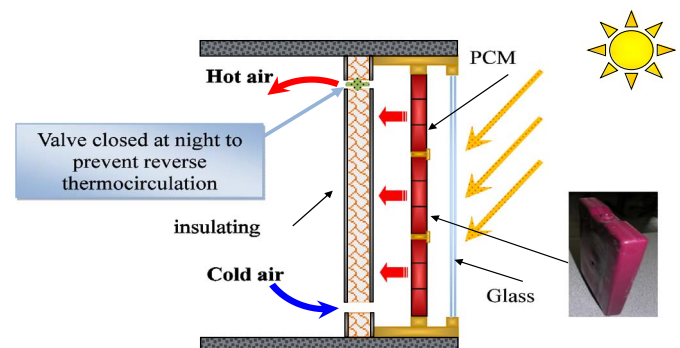


Fig. 1. Illustration of a latent heat thermal energy storage system [29].

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