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Numerical investigation of melting and energy storage of phase change material within a square enclosure

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ABSTRACT

The investigation centers on the phase change processes integral to latent heat thermal energy storage (LHTES) units. These processes hold significant importance due to their capacity to store excess energy generated by both renewable and conventional power plants. The focus of the study lies in the intricate solid-liquid phase transitions, which are highly sensitive to alterations in thermal boundary conditions. In this specific study, a numerical simulation was carried out to analyze the behavior of kerosene, as a phase-change material, during the melting process inside a square cavity heated from one side and insulated from the other sides. The simulation was carried out using COMSOL Multiphysics software. The results of the study indicate that, initially, thermal conduction plays a dominant role in the melting process, while natural convection develops as melting progresses.

1. INTRODUCTION

The increasing in energy crises and environmental concerns are driving people to diversify energy sources [1]. Nowadays, storing thermal energy is one of the best ways to reduce dependence on fossil fuels [2]. Broadly, Thermal Energy Storage (TES) systems can be categorized into three main groups: sensible, latent, and thermo-chemical heat storage. With a focus on enhancing Latent Heat Thermal Energy Storage (LHTES) systems. In this context, certain materials known as phase-change materials (PCMs) have the ability to absorb or release significant amounts of energy. In these systems, thermal energy is stored as the PCM undergoes the melting process and subsequently released as it solidifies. These PCMs can store much more energy per unit volume than materials based on sensible heat [3]. In literature, a wide range of numerical and experimental studies have been conducted. Various geometrical arrangements have been suggested for PCM (Phase Change Material) enclosures, including spherical shells, tall rectangular containers, and cylindrical pipes [4]. Experimental analysis was conducted by F.L. Tan [5] to examine both constrained and unconstrained melting processes of spherical shells with varying temperatures and undercooling levels of the Phase Change Material (PCM).

In the constrained melting scenario, the solid PCM remained fixed during the melting process, and natural convection was quickly established after an initial phase of ephemeral heat conduction. In contrast, during unconstrained melting, the solid PCM caused the liquid to induce natural convection as it descended to the bottom, where heat transfer primarily occurred through heat conduction. Kamkari et al. [6] examined the influence of varying inclinations of a rectangular cavity on the melting process. Their findings indicated that the heat transfer intensity in a horizontal rectangular cavity was more than twice that of a vertical cavity. Petrone and Cammarata [7] carried out a numerical analysis of the melting behavior of the PCM "polyethylene glycol 900". Faraji and El Qarnia's [8] study focused on numerically analyzing the melting of n-eicosane in a rectangular enclosure heated by three uniform heat sources. Their research unveiled three key stages in the melting process: initial conduction dominance, followed by the development of natural convection and intensified flow near the active wall and melting front, ultimately leading to a third stage marked by a downward shift in the intersection of the melting front and the non-active wall. This transition caused a reduction in heat flux at the liquid-solid interface, accounting for the diminishing rate of change in the liquid fraction.

The main objective of this study is to enhance the understanding of heat transfer with phase change by analyzing the heat transfer and fluid dynamics involved in the melting of paraffin within a square cavity. The cavity is exposed to a constant temperature boundary condition on one of its sides. An enthalpy-based formulation was utilized to address this phase change problem, and numerical simulations were performed using COMSOL MULTIPHYSICS version 6.1 software. The numerical model proposed here has broader applicability and can be employed to predict the melting process in other Phase Change Materials (PCMs), even when they are enclosed by different materials and subjected to different boundary conditions.

2. MATERIALS AND METHODS

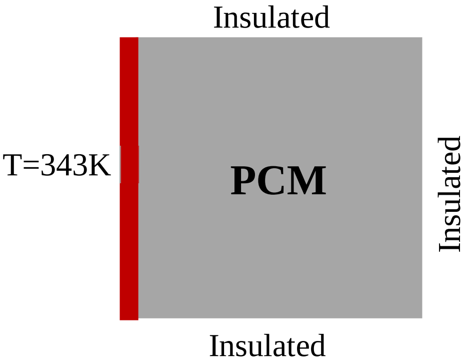

Figure 1. Physical model

The physical model consists of a square cavity with a height of L=4cm as shown in **Figure1.** The cavity is filled with paraffin as Phase Change Material (PCM) and its physical properties are presented on **Table 1.** The initial temperature is held on T_{in}=298 K. The left side of this cavity is maintained at constant temperature T_h=343 K, while the other sides are isothermal. To conduct this analysis, COMSOL MULTIPHYSICS software program is used to develop a 2D numerical model for the melting process of the paraffin.

Table 1. PCM Paraffin's thermo-physical properties

Properties	Value (Solid/ Liquid)
$\rho(\mathrm{kg\ m^{-3}})$	860/780
$C_p(\mathrm{kJ\ kg^{-1}K^{-1}})$	2.9/2.1
$k(\mathrm{W\ m^{-1}K^{-1}})$	0.24/0.15
$T_m(\mathrm{K})$	325
$\Delta H(\mathrm{kJ\ kg^{-1}})$	210
$\mu(\mathrm{Pa\ s})$	5.42×10^{-3}
$\beta(\mathrm{K^{-1}})$	1.8×10^{-4}

The mathematical model we have developed here is based on the enthalpy-porosity method. In this approach, we treat the solid-liquid interface as a porous zone, which is achieved through the inclusion of a source term in the momentum equation

The governing equations for the considered problem can be written as follows:

The continuity:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{v})=0 \qquad (1)$$

The momentum equation:

$$\frac{\partial\rho\vec{v}}{\partial t}+\nabla\cdot(\rho\vec{v}\vec{v})=(\mu\nabla^2\vec{v})-\nabla P+S_b+S_p \qquad (2)$$

The energy equation:

$$\frac{\partial\rho H}{\partial t}+\nabla\cdot(\rho\vec{v}H)=\nabla\cdot(K\nabla T) \qquad (3)$$

Where $\rho,\vartheta,\mu,P,g,K,T,S_b,S_p$ are respectively: density, velocity vector, dynamic viscosity, pressure, gravity, thermal conductivity, temperature, term source of buoyancy and term source of porosity function.

3. RESULTS AND DISCUSSION

This section is divided into four distinct parts: The first part focuses on the localization and the configuration of the melting front, as shown in Figure 2. The second part will examine the evolution of the PCM's velocity field, as presented in Figure 3. The third part will analyze the evolution of the melting fraction during the phase change process (see Figure 4). The last part is dedicated to investigating how the stored energy evolves during the phase change material's melting process (see Figure 5).

As shown in Figure 2, the melting interface was initially parallel to the heated side, indicating the predominant influence of conductive heat transfer. Over time, this interface expanded and gradually curved as the liquid melted. This was the result of the development of natural convection. The curvature was more apparent on the upper surface, mainly due to the buoyancy force resulting from density variations.

Figure 3 illustrates that velocity field is ascending near the heated wall and descending near the melting front. At the onset of melting, the solid-liquid interface is located close to the heated wall, where the velocity is very low. Over time, natural convection becomes dominant, resulting in a larger solid-liquid interface, particularly in the upper part of the cavity, where velocity reaches its maximum value.

Figure 4 presents the progression of the melting fraction, representing the fraction of phase change material (PCM) that has transformed into a liquid state. Initially, at t=0 seconds, all PCM within the domain is solid, resulting in a melting fraction of zero.

As time elapses and the PCM is subjected to heating, it gradually undergoes the phase transition, leading to a steady increase in the melting fraction. Specifically, the melting fraction values at time intervals of 10, 50, 100, 200, 500, 800, 1000, and 1500 seconds are 0.016, 0.041, 0.063, 0.116, 0.295, 0.464, 0.629, and 0.883, respectively.

Upon the completion of the melting process, which occurs after 1989 seconds, all PCM within the domain has transitioned into a liquid state, resulting in a melting fraction of 1.

It is worth noting that the rate of melting maintains a consistent pace at the outset of the process, experiences an acceleration during the middle phase, and further accelerates as the process approaches its conclusion.

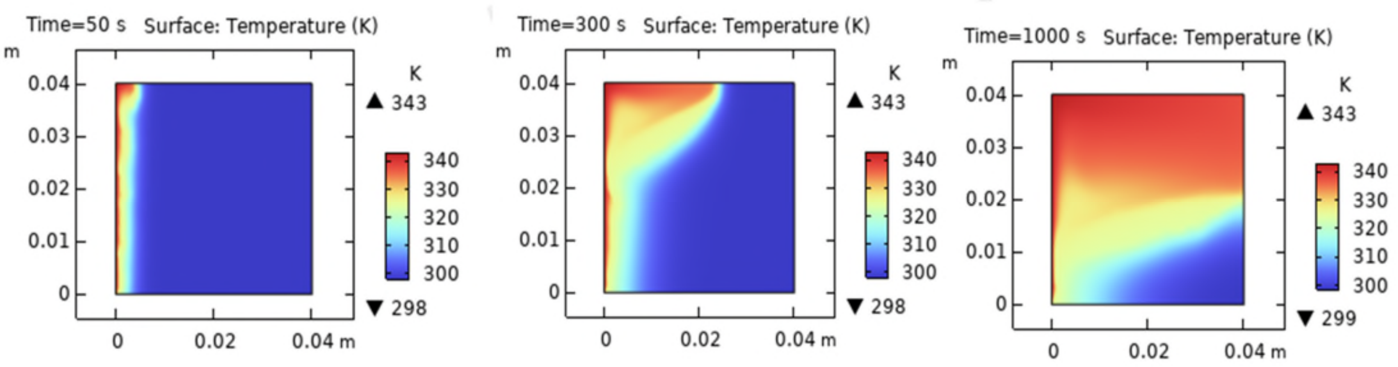

Figure 2. Time evolution of PCM temperature and melting front at different times

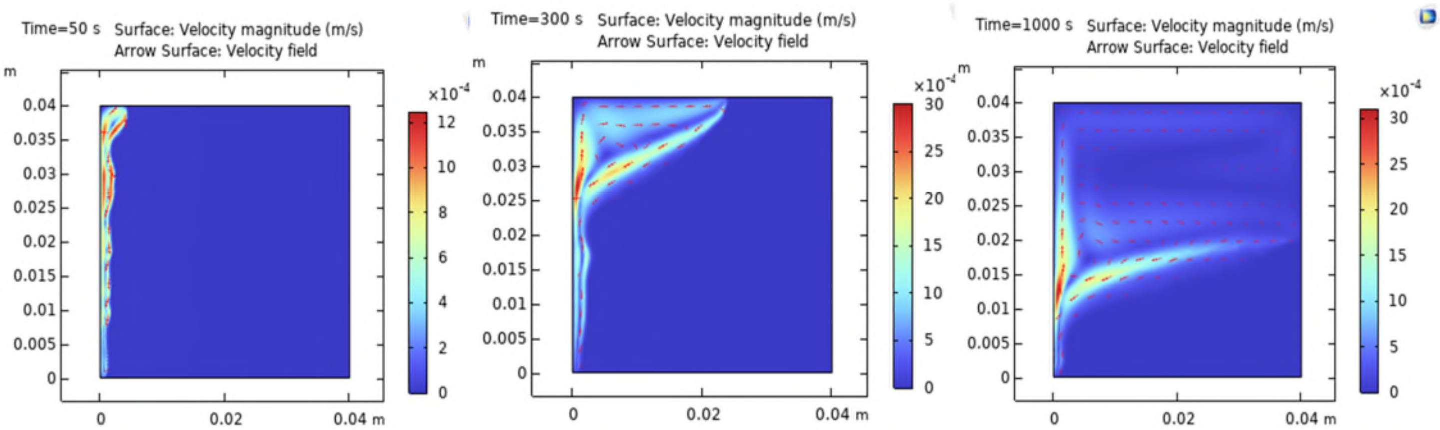

Figure 3. Velocity field evolution at different times

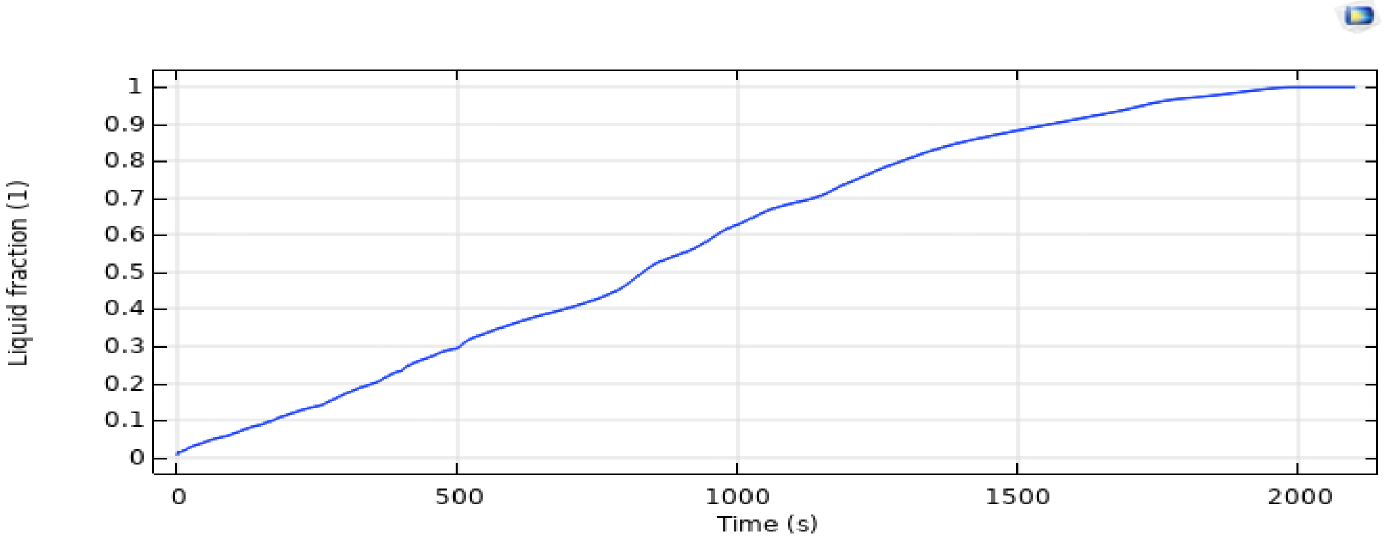

Figure 4. Melting fraction evolution

Fig.5 illustrates the variation of sensible, latent, and total energy stored per unit volume over time for the studied model. It is observed that the amount of energy stored as latent heat predominates in the total energy expression compared to sensible heat storage. The total energy stored by paraffin can reach up to 2 MJ/m^3.

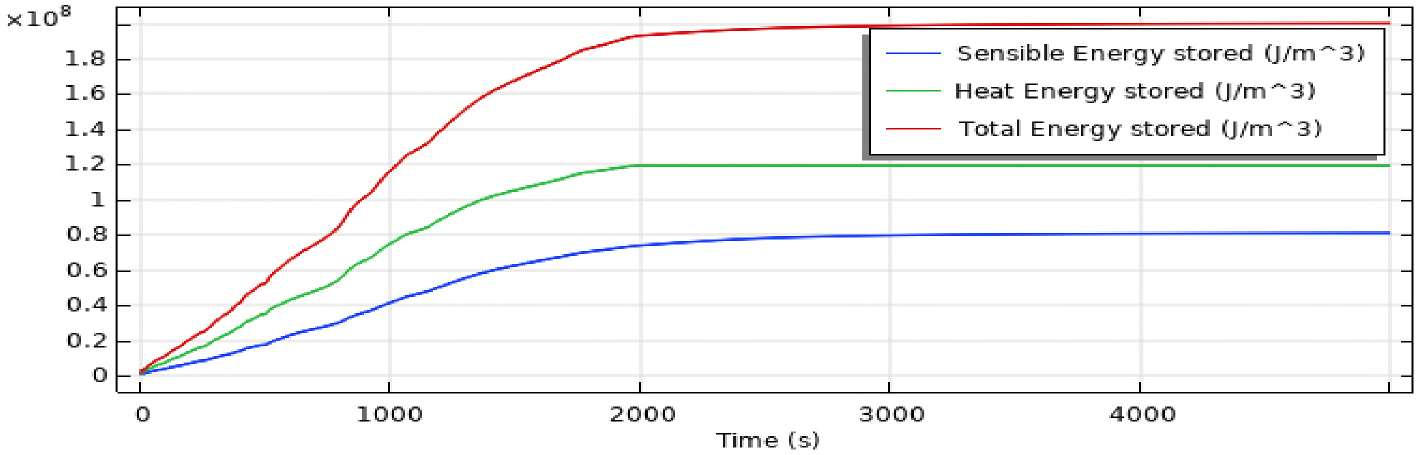

Figure 5. Energy storage evolution

4. CONCLUSIONS

In this study, we conducted a numerical simulation of PCM melting within a square cavity. We employed the enthalpy-porosity approach and used the COMSOL Multiphysics software to solve this problem. This approach allowed us to determine the dominant heat transfer mode during melting and, consequently, gain a better understanding of the phase change phenomenon.

The results show that:

- During the early stages of the melting process, heat transfer is primarily dominated by conduction. As the process continues and more heating occurs, it transitions to natural convection as the dominant mode of heat transfer.
- The rate of melting accelerates as time advances. Initially, it remains relatively constant, with the most significant acceleration occurring during the middle and towards the end of the melting process.
- The paraffin is capable of storing a maximum of 2 MJ per unit volume in total energy.

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