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CFD simulation of melting process of phase change materials (PCMs) in a spherical capsule

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ABSTRACT

The present study is focused on CFD simulation of constrained melting of Phase Change Materials (PCMs) in a spherical container. To investigate the melting process of the PCM, its melting fraction was analyzed at different times. The results indicated the existence of thermally stable layers on the top of the sphere. Moreover, inspection of the calculated temperatures at different points along the vertical axis indicates the existence of some disturbances at the bottom of the sphere due to the natural convection. After the validation of the results, the effects of different parameters such as the surface temperature of the capsule, the initial temperature and the size of the spherical capsules, on the melting process were investigated. The initial temperature did not affect the melting rate, whereas melting rate increased by increasing the surface temperature of the capsule and also decreasing the diameter of the sphere. The results showed that the surface temperature of capsule compared to geometrical parameters and other operational conditions can have a greater influence on the melting rate and the heat flux.

Simulation par MFN du processus de fusion des matériaux à changement de phase dans une capsule sphérique

Mots clés : Fusion limitée ; Matériaux à changement de phase ; MFN (mécanique des fluides numérique) ; Conteneur sphérique

1. Introduction

Recently, latent heat thermal energy storage systems have been widely applied in cool storage for central air-conditioning, hot storage for air heating, solar energy, energy efficient buildings and waste heat recovery. Storage systems allow for the efficient and rational utilization of the available resources or renewable energies, by using the time lag between production, as well as the availability of the energy and its

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Nomenclature

C_{pl}	specific heat of liquid PCM [$Jkg^{-1}K^{-1}$]
H	specific enthalpy [Jkg^{-1}]
k	thermal conductivity [$Wm^{-1}K^{-1}$]
L	latent heat [Jkg^{-1}]
P	pressure [Pa]
R_i	internal radius [m]
t	time [s]
T_i	initial temperature [K]
T_m	melting temperature [K]
T_s	surface temperature [K]
V	velocity [ms^{-1}]
Greek symbols	
β	liquid fraction, dimensionless
ρ	density [kgm^{-3}]
μ	dynamic viscosity [$kgm^{-1}s^{-1}$]

consumption in the demanding systems. Phase change materials (PCM) are mainly used to provide higher storage densities. As a serious problem PCMs have relatively low thermal conductivities. Therefore, increasing the surface/volume ratio of PCMs in order to increase the heat-transfer rate is very appealing. This can be done by packing a volume with a great number of PCM capsules. The spherical geometry is one interesting case for heat storage applications, since spheres are much employed in packed beds. Due to the complexity of such systems, it is often more effective to first model the behavior of an individual sphere and then describe it with a simple parametric model in the packed bed modeling.

Roy and Sengupta (1989) examined the melting process with the solid phase initially uniformly super cooled. In order to include the effects of a temperature gradient in the solid core, they modified the heat transfer equation. At each time step, the unsteady conduction equation has been solved numerically using a toroidal coordinate system with a suitable immobilization of the moving boundary to transform the infinite domain into a finite one. In another paper (Roy and Sengupta, 1990), they investigated the outcome of natural convection on the melting process. In order to reduce the computational effort and the time, they made some simplifications. They obtained the non-dimensional melting time and the heat transfer coefficient as functions of the PCM property values, the operating temperature and the physical size.

Ettouney et al. (2005) experimentally evaluated the heat transfer (during energy storage) and release for the phase change of paraffin wax in the spherical shells. They showed that an increment in the Nusselt number of the sphere with a larger diameter is attributed to the increase in the natural convection cells in the PCM inside the sphere. The natural convection role is enhanced upon an increase in the sphere diameter and the air temperature. On the other hand, during solidification the wax layers are formed inward, nucleating on the sphere walls. As solidification progresses, the melt volume becomes smaller and the role of natural convection diminishes rapidly.

Khodadadi and Zhang (2001) also considered the effects of buoyancy-driven convection on the constrained melting of phase change materials within spherical containers. They reported that during the initial melting process, the conduction mode of the heat transfer is dominant. As the buoyancy-driven convection is strengthened due to the increase in the melting zone, the process at top region of the sphere is much faster than at the bottom due to the increment of the conduction mode of heat transfer. They found that buoyancy-driven convection speeds up the melting process compared to the diffusion-controlled melting.

Assis et al. (2007) numerically and experimentally explored the melting process of a PCM in a spherical geometry. The results of their experimental investigation, including visualization, were favorably comparable with the numerical results and therefore suitable for validation of the mathematical approach. Their computational results showed how the transient phase-change process depends on the thermal and geometrical parameters of the arrangement.

Veerappan et al. (2009) investigated the phase change behavior of 65 mol% capric acid and 35 mol% lauric acid, calcium chloride hexa hydrate, *n*-octadecane, *n*-hexadecane, and *n*-eicosane inside the spherical containers to identify a suitable heat storage material. They created analytical models for solidification and melting of PCM in a spherical shell with conduction, natural convection, and heat generation and found a good agreement between the analytical predictions and the experimental data. Both models were validated with the experimental work of Eames and Adref (2002).

Regin et al. (2006) examined the heat transfer performance of a spherical capsule using paraffin wax as PCM placed in a convective environment during the melting process. The model results were in a good agreement with the experimental data.

Tan (2008) investigated the melting of the phase change material (PCM) inside a sphere using n-octadecane for both constrained and unconstrained melting processes. For constrained melting, paraffin wax (n-octadecane) was immobilized, through the use of thermocouples when melting is done inside a transparent glass sphere. Their experimental setup provided a detailed temperature data that were gathered along the vertical diameter of the sphere during the melting process. Tan et al. (2009) also experimentally and numerically investigated the constrained melting of PCMs inside a spherical capsule to understand the role of the buoyancy-driven convection.

In this study, a computational fluid dynamics (CFD) modeling on the constrained melting of phase change material (PCM) in a spherical container was performed. The effects of different parameters like the capsule size, the surface temperature, the initial temperature and the Stefan number, on the PCM melting process were investigated.

2. CFD simulation

CFD simulation was carried out using the commercial Fluent 6.3 software. The physical model and computational procedure are discussed below.