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Latent Heat Storage in a Random Porosity Metal Foam Filled with a Phase Change Material

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Abstract

The aim of this work is to study the enhancement of a latent heat thermal energy storage system LHTESS using a phase change material PCM by integrating a solid structure (metal foam) of a high thermal conductivity inside the PCM. The role of the metal foam is to increase the effective thermal conductivity to accelerate the storage process. The Metal foam is the porous structure and the PCM is the material that fills the pores. Most of previous works in the literature consider that the porosity is constant. Nonetheless, a random porosity is more realistic. In the present study a random porosity distribution between 0.4 and 1 will be considered. The volume-averaging technique and the Darcy-Brinkman model are adopted for the mathematical formulation. The control-volume-based-finite element method VCEF is used to numerically solve the governing equations. A pseudo-random generation procedure was applied to generate different configurations of random structures. A comparison of the PCM melting (storage stage) in different samples of random porosity distributions will be made with a constant porosity. Results will be presented in terms of isotherms, liquid-fraction and streamlines of the flow induced by natural convection in the liquid phase.

Keywords: Latent heat storage, porous media, random porosity, enhancement of storage efficiency,

I. Introduction

Thermal energy storage TES plays a key role to alleviate the mismatch between energy demand and supply. Latent heat storage using phase change materials shows a great storing capacity compared to the sensible heat storage. However, the low thermal response of various PCMs consists a major drawback that limits the effectiveness of the heat storage and release. Different techniques have been proposed to improve the performance of the thermal stotage. One successful way is based on the enhancement of melting heat transfer by the inclusion of a porous matrix, such metal foams (Jianquing, 2013). The understanding of flow and heat transfer in porous medium and the effect of geometry and pore distribution is a fundamental task in the design of energy storage systems. Liquid-solid phase change in porous media has been extensively studied over years (Nield and Bejan, 1999). Most of works in the past consider the porous medium having an average constant porosity. Few publications are devoted to the phase change in a non-uniform porous media. (Jialin & al.,2015) analyzed numerically the thermal behavior of liquid-solid phase change within copper foam with a varying porosity, they consider a linear vertical gradient on the vertical direction and a homogenous porosity in the horizontal direction. An experimental and numerical investigation was conducted by (Marri & al.,2020) to study the the effect of porosity and PPI (pores per inch) gradients on the performance of an open-cell aluminium foam encapsulated with n-eicosane as PCM. (Ghalambaz & al, 2021) conducted a similar study, but, with a horizontal porosity gradient. Porous materials, whatever they are natural or artificial, all exhibit some degree of randomness. Inspired by the fractal theory (Zilong,2017) conducted a numerical and experimental study of the melting of PCM in a metal foam with a rondom pore distribution. In the liturature review there is still a scarce of publications concerning the phase change in porous media with random porosity. However, there is several studies relative the fluid flow and heat and mass transfer in porous materials of random porosity without phase change (Wu-shung Fu & al.,2000). The present study attempts to contribute to the understanding of liquid-solid phase change in porous media of random porosity. Three selected random porosity samples will be executed and compared to a case of an average uniform porosity.

II. Physical and mathematical modelling

The physical domain is a two-dimensional rectangular cavity filled with a porous structure (metal foam) sturatued with a PCM. The cavity is heated through its left side to a temperature T_H higher than the melting temperature T_m of the PCM. The rest of walls are kept thermally isolated. The volume averaging approach (Whitaker,1999) and the the Darcy-Brinkman model are applied to obtain the governing equations for the fluid flow and heat transfer inside the porous medium. The enthalpy-porosity technique (Brent,1980) is used to describe the solid-liquid phase change term. To facilitate the analysis, the following assumptions are made: (1) the condition of thermal equilibrium between the matrix structure and the PCM is applied, (2) thermophysical properties are constant except for the density where the Boussinesq approximation was held, (3) the fluid in the liquid phase is newtonian an laminar, (4) the volume change upon phase change is ignored. Based on the above approximations, the governing equations for mass, momentum an energy conservation are as follow:

Mass conservation equation: $\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$. (1)

x-Momentum equation: $\frac{1}{\varepsilon}\frac{\partial u}{\partial t}+\frac{1}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\nu}{\varepsilon}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\nu}{K}u+S.u$ (2)

y-Momentum equation: $\frac{1}{\varepsilon}\frac{\partial v}{\partial t}+\frac{1}{\varepsilon^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\nu}{\varepsilon}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\nu}{K}v+\rho g\beta_T(T-T_m)+S.v$ (3)

Energy conservation equation: $(\rho C_p)^*\frac{\partial T}{\partial t}+(\rho C_p)_l\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\lambda_{eff}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-L_H\frac{\partial f_l}{\partial t}$ (4)

Where, ε is the random porosity, K the permeability, λ_{eff} is the effective thermal conductivity of the PCM/metal foam mixture, β_T is the thermal expansion of the liquid PCM, and f_l is the local liquid fraction of the melted PCM. The effective heat capacity and the effective thermal conductivity are calculated in terms of the porosity:

$(\rho C_p)^*=\varepsilon\left[f_l(\rho C_p)_{pcm_l}+(1-f_l)(\rho C_p)_{pcm_s}\right]+(1-\varepsilon)(\rho C_p)_{foam}$ (5)

$\lambda_{eff}=\varepsilon\left[f_l\lambda_{pcm_l}+(1-f_l)\lambda_{pcm_s}\right]+(1-\varepsilon)\lambda_{foam}$ (6)

A source term related to the liquid fraction in the pore volume is added to Eqs. (2) and (3) based on the Carman-Kozney's equation (Nield and Bejan,1999):

$S=C_{mush}\frac{(1-f_l)^2}{(f_l^3+q)}$ (7)

$C_{mush}=1.6\times10^6$ is a mushy zone parameter used to control the velocity damping in the solidified zone. q is a small constant number set by default to 0.001 to avoid division by zero.

The following dimensionless variables are defined:

$X=\frac{x}{H}$, $Y=\frac{y}{H}$, $F_o=\frac{\alpha t}{H^2}$, $U=\frac{uH}{\alpha}$, $V=\frac{vH}{\alpha}$, $P=\frac{pH^2}{\alpha^2\rho}$ and $\theta=\frac{T-T_m}{T_H-T_m}$. α stands for the thermal diffusivity of the PCM and H for the height of the cavity.

In the dimensionless form, the above system of equations is written as:

$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0$, (8)

$\frac{1}{\varepsilon}\frac{\partial U}{\partial F_o}+\frac{1}{\varepsilon^2}\left(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\partial P}{\partial X}+\frac{\sigma_1}{\sigma_2}\frac{P_r}{\varepsilon}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\frac{\sigma_1}{\sigma_2}\frac{P_r}{D_a}U+S.U$ (9)

$\frac{1}{\varepsilon}\frac{\partial V}{\partial F_o}+\frac{1}{\varepsilon^2}\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-\frac{\partial P}{\partial Y}+\frac{\sigma_1}{\sigma_2}\frac{P_r}{\varepsilon}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-\frac{\sigma_1}{\sigma_2}\frac{P_r}{D_a}V+R_a.P_r.\theta+S.V$ (10)

$\sigma_1\frac{\partial\theta}{\partial F_o}+U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\sigma_2\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right)-\frac{1}{Ste}\frac{\partial f_l}{\partial F_o}$, (11)

where: $\sigma_1=\varepsilon+(1-\varepsilon)\left(\rho C_p\right)_{foam}/\left(\rho C_p\right)_{pcm}$ and $\sigma_2=\varepsilon[f_l+(1-f_l)\lambda_{pcm_s}/\lambda_{pcm_l}]+(1-\varepsilon)\left(\lambda_{foam}/\lambda_{pcm_l}\right)$

The dimensionless form of the governing eqautions (8)-(11) leads to a set of non-dimensional controlling parameters: The Rayleigh number $Ra=\frac{g\beta L^3\Delta T}{\alpha\nu}$, the Prandtl number $Pr=\frac{\nu}{\alpha}$, the Stefan number $Ste=\frac{C_p\Delta T}{L_H}$, and the Darcy number $Da=\frac{K}{H^2}$. Where L_H, is the latent heat of fusion.

III. Numerical procedure and validation

The governing equations are discretized using the CVFE (Baliga, 1998). The SIMPLER algorithm is used on a staggered grid to solve the set of the discretized equations by TDMA solver. After a grid sensitivity study, a 101x101 grid size was selected for the next simulations. The validation is examined by applying the own source code to compare our results with some results of the literature (Lauriat, 1987). The comparion test is relative to the calculation of the average Nusselt number for the naturat convection is square porous enclosure using the Darcy-Brinkman model (Table 1).

Table 1. Average Nusselt number, natural convection in porous medium $(A=1, Pr=0.71)$ Darcy- Brinkman model

	Ra.Da	Da= 10^{-5}	Da=10^{-2}
Present work	500	8.42	3.30
Lauriat & al.		8.41	3.30
Present work	10^3	12.45	4.26
Lauriat & al.		12.42	4.26

IV. Results and discussion

A Fortran library code for generating pseudo-random numbers can be used to obtain infinity of porosity distributions. In our case, three samples of random porosity distributions named (RUN1, RUN2 and RUN3) are obtained by generating random numbers between a minimum porosity of 0.4 and a maximum porosity of 1. Fig. 1 illustrates the global porosity maps and shows that different patterns are observed, although the mean porosity and the standard deviation values are close to each other for the three RUNs. The effect of the porosity distributions on the flow, the

temperature field, liquid-solid interface location and the evolution of the melting process will be investigated during this study. The dimensionless parameters selected for this study are $Ra = 5.0 \times 10^6$, $Pr = 50$, $Ste = 0.1$ and $Da = 10^{-3}$.

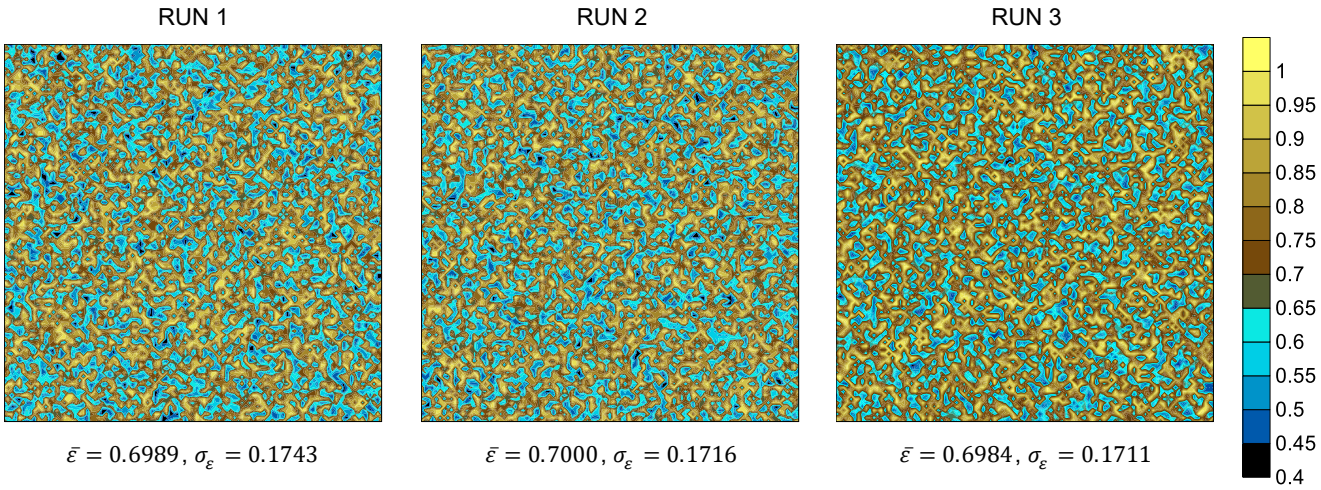

Fig. 1: Porosity patterns for three random distributions

The random porosity samples are confronted to the case of constant porosity equal to the mean porosity $\bar{\varepsilon} = 0.7$. Results are illustrated in Figs. 2-4. In Fig. 2 the liquid-solid interface location is plotted at two dimensionless times $\tau = 0.075$ and $\tau = 0.15$. It is clearly shown from this figure that the interface is more in advance for the constant porosity model than for the random porosity distribution. This can be explained by the fact that in the constant porosity model there is some kind of morphological uniformity, leading to uniform physical properties and then a low dispersion of heat. The melting of the PCM is faster as natural convection is dominant and the interface loction is more in progress. Oppositely, in the random porosity model which is more realistic for most of porous materias, there is a higher dispersion, the interface shape is less smooth and their locations fluctuate around an average position. Fig. 3 shows the time evolution of the melting volume fraction and confirms that the melting process is more in advance in the case of constant poroisty model.

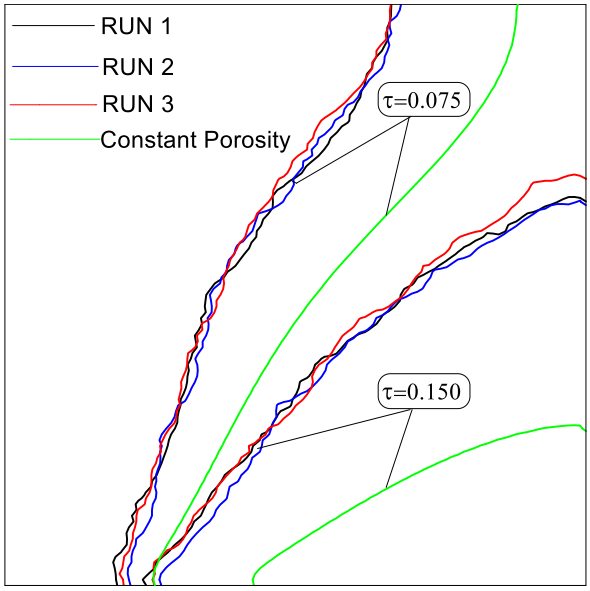

Fig. 2: Interface location

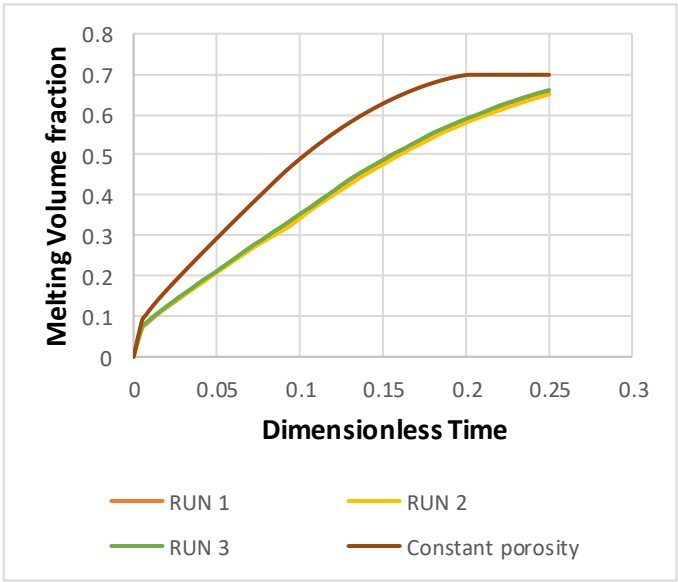

Fig. 3: Melting volume fraction

Fig. 4-a shows that the isotherm lines of the random samples RUN 1-3 are close to each other and fluctuate around average lines. Then whatever the random run the global behavior of the melting progress is the same. Nevertheless, all of them are shifted back compared to the isotherm lines of the constant porosity model. The same finding is observed for the streamlines reported in Fig. 4-b.

V. Conclusion

During this study the melting of PCM mixed porous metal foam is numerically investigated. Tow approaches have been used. The first is based on constant porosity model an the second on a random porosity distribution. The main result of the study reveales a clear discrepancy between both approaches. As natural porous materials are

random, the uniform porosity models have to be revised. It seems an experimental study could give a final answer to this question.

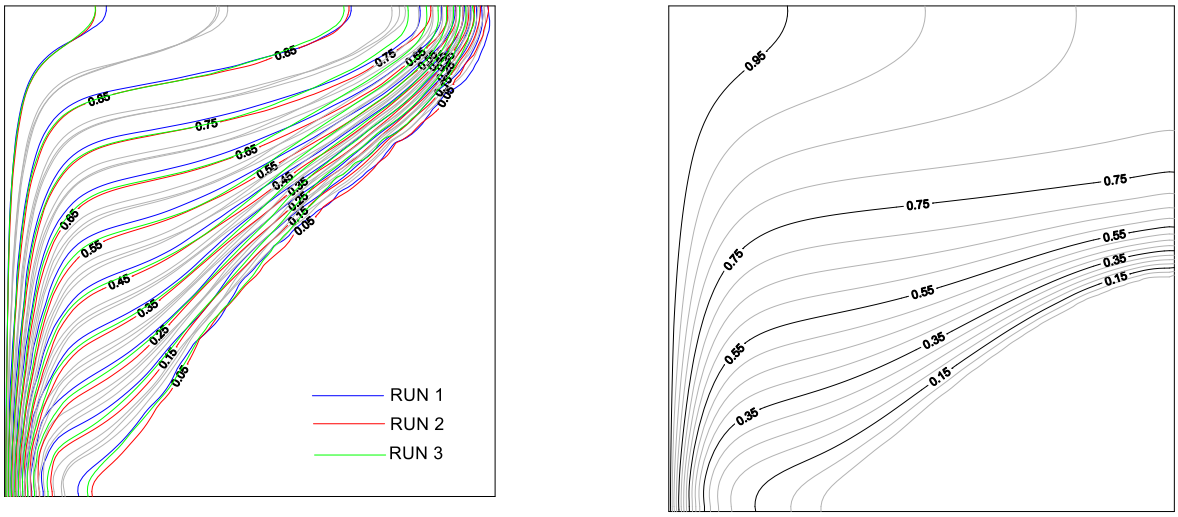

Fig. 4-a Isothermes for for the random (left) and unform(right) porosities

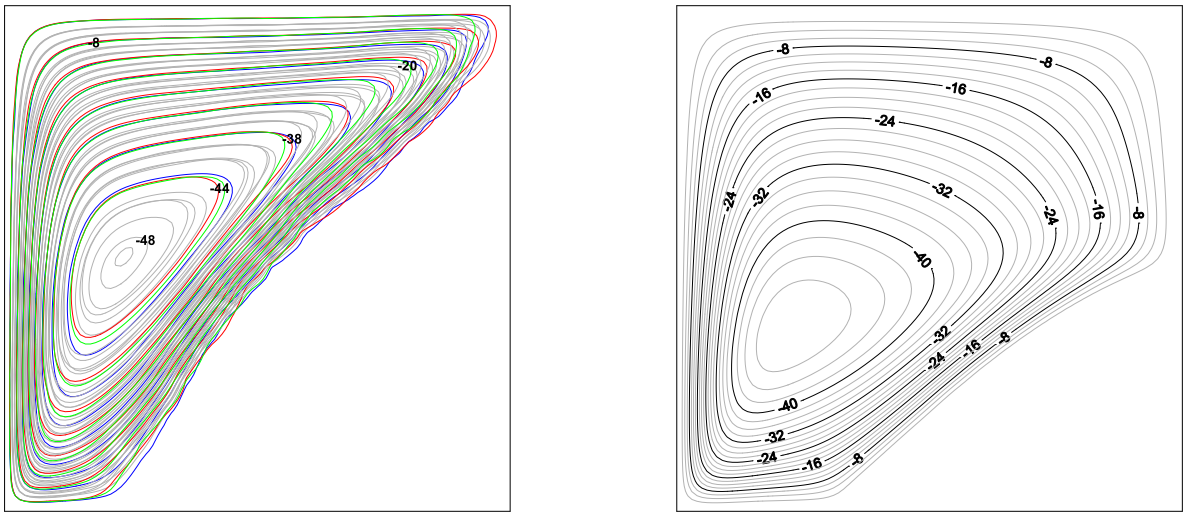

Fig. 4-b Streamlines for the random (left) and unform(right) porosities

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