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Numerical Evaluation of Effective Thermal Conductivity of PCM with Metal Foam Incorporating Buoyancy Effects for Thermal Energy Storage

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INTRODUCTION

In July 2023, Secretary-General of the UN António Guterres mentioned that the era of global warming has ended; the era of global boiling has arrived [1]. This assertion suggests a significant evolution in the conceptualization of climate change, emphasizing a transition from the recognized era of global warming to a newly acknowledged era characterized by more severe planetary heating. Nuclear power is being recognized as a potential solution to address climate-related challenges, notably in its role as a base load to mitigate the inherent variability in the generation of renewable energy. However, nuclear power generation faces challenges in adjusting its output according to the varying generation levels of renewable energy sources due to its limited load-following ability. Energy storage systems can address the challenges of load following by allowing for the storage of excess energy, without requiring arbitrary adjustments to the output of nuclear power plants or renewable energy sources. Particularly, thermal energy storage (TES) holds significant advantages in energy storage, as it minimizes conversion losses, offers low storage costs, and can be seamlessly integrated into existing power plant systems.

The principal energy storage mechanisms within a TES system include sensible heat, latent heat, and thermochemical energy storage. Among these, Latent Heat Thermal Energy Storage (LHTES) stands out for its high energy storage density and the nearly constant temperature it maintains during both energy storage and retrieval, making it particularly well-suited for application in renewable energy or nuclear power plants. However, despite these advantages, LHTES faces a challenge due to the low thermal conductivity of its Phase Change Material (PCM), which serves as the energy storage substance.

Several methods are being investigated to address the low thermal conductivity of PCM; these methods include the use of structures such as disks, fins, and metal foam, as well as the incorporation of nanoparticles to enhance material properties. Among these methods, the use of metal foam stands out as a promising approach due to its capacity to maximize heat transfer surface area using materials with high thermal conductivity.

To assess the extent of heat transfer enhancement facilitated by metal foam, it is imperative to experimentally verify the improvement in heat transfer through tests or employ a dedicated numerical method to determine the effective thermal conductivity of PCM when integrated with metal foam. Several experiments have been conducted to ascertain the improvement in heat transfer facilitated by metal foam in PCM.[4,5] Additionally, there have been studies employing various modeling approaches through computational analysis methods to interpret and understand the enhancement in heat transfer by metal foam in the context of PCM.[3,5] Among these methods, numerical modeling proves advantageous for detailed analysis of the heat transfer effects induced by metal foam. However, a challenge arises in the increased computational cost when modeling the complex geometry of metal foam in three-dimensions.

To address this issue, various modeling techniques simplifying the geometry of metal foam have been investigated. Among these, lattice models stand out as a simplified approach considering only porosity and pores per inch (PPI). If an appropriate effective thermal conductivity can be derived using this model, it is anticipated that the computational cost associated with modeling metal foam could be significantly reduced. However, when utilizing simplified models, it is essential to analyze dependencies on various factors that may arise due to differences between the model and the actual geometry of metal foam. However, when utilizing simplified models, it is essential to analyze dependencies on various factors that may arise due to differences between the model and the actual geometry of metal foam. In this case, an exemplary instance of potential overestimation due to simplified modeling is the convective heat transfer driven by buoyancy.

In this study, a three-dimensional numerical model of metal foam was employed to analyze the buoyancy effect on the liquid phase of PCM. The numerical model simplified the structure of metal foam to a simple lattice.

The analysis utilized PCM with the same thermal conductivity for both liquid and solid phases. The impact of convective heat transfer due to buoyancy was compared using effective thermal conductivity. Within the same interpretation, a sensitivity study regarding mesh size was conducted, and the results were examined to verify the convergence of the obtained outcomes. Lastly, an investigation was conducted to determine the extent of variation in effective thermal conductivity, obtained by varying porosity, PPI, and the direction of gravity for the liquid phase of PCM. This was compared to the effective thermal conductivity of solid PCM with the same thermal conductivity.

MODEL DESCRIPTION

The analysis model was developed based on the work of Song et al. [3], and verification and validation were conducted for solid PCM as shown in Figure 1. The model is grounded on determining the dimensions of the metal foam's beam structure and the length of Phase Change Material (PCM) using key variables, porosity, and PPI, which represent the geometry of the metal foam. The length variables for each domain can be determined through the following two equations:

$$\omega\left(D_{str} + D_{pcm}\right) = 1 \quad (1)$$

$$1 - \left(3\omega^2\left({D_{str}}^2 \cdot 1\right) - 2\omega^3 {D_{str}}^3\right) = \frac{\varepsilon}{100} \quad (2)$$

D_{str} is the thickness of the metal foam beam observable in the cross-section, D_{pcm} denotes the thickness of the PCM region, and ω and ε serve as parameters for the geometry of the metal foam, corresponding to PPI and porosity, respectively. The thickness used in equations (1) and (2) is standardized to the inch scale, consistent with the units defined in the PPI parameter's definition.

The mesh for the metal foam structure was created using a 3*3 hexahedral mesh in the cross-sectional direction to ensure minimal conduction heat transfer.

Table 1. Thermodynamic properties of paraffin RT58 and copper foam

Properties	Paraffin RT58	Copper
Density-solid ($kg \cdot m^{-3}$)	850	8933
Heat capacity-solid ($J \cdot K^{-1} \cdot kg^{-1}$)	2100	385
Dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)	0.0269	-
Thermal conductivity-solid ($W \cdot K^{-1} \cdot m^{-1}$)	0.2	401
Density-liquid ($kg \cdot m^{-3}$)	775	-
Heat capacity-liquid ($J \cdot K^{-1} \cdot kg^{-1}$)	2100	-
Thermal conductivity-liquid ($W \cdot K^{-1} \cdot m^{-1}$)	0.2	-
$\beta(K^{-1})$	1.1×10^{-4}	-

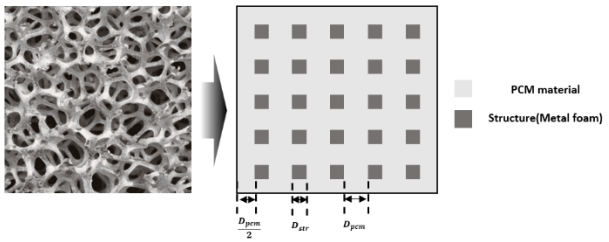


Figure 1. Schematic design of simple lattice model

Simultaneously, the PCM region was composed of a tetrahedral mesh.

To simulate the heat transfer in the analysis model, Ansys CFX was employed, and the Buossinesq approximation was utilized to interpret heat transfer due to the buoyancy of the liquid PCM. The corresponding mass and momentum equations are as follows:

$$\nabla \cdot V = 0 \quad (3)$$

$$\rho_0\left(\frac{\sigma \mathrm{V}}{\sigma \mathrm{t}} + \mathrm{V} \cdot \nabla \mathrm{V}\right) = -\nabla \mathrm{P} + \mu \nabla^2 \mathrm{V} + \rho_0 \mathrm{g}(\mathrm{T} - \mathrm{T}_{\mathrm{ref}})\alpha \quad (4)$$

The liquid utilized in the analysis was assumed to be incompressible, and laminar flow was considered. Additionally, thermal radiation and volume expansion effects were neglected. The thermodynamic properties of the material employed in the analysis are presented in Table 1.

The boundary conditions employed in the analysis involved applying heat flux conditions at each end plane of the domain, along with a constant temperature condition. The heat flux was set at $10\mathrm{kW/m^2K}$ in -Z direction and the temperature on the surface under constant temperature conditions was fixed at 350K (Figure 2). To calculate the effective thermal conductivity, the heat transfer direction was divided into 10 segments. The effective thermal conductivity was then determined based on the area-average temperature of the nine boundary planes.

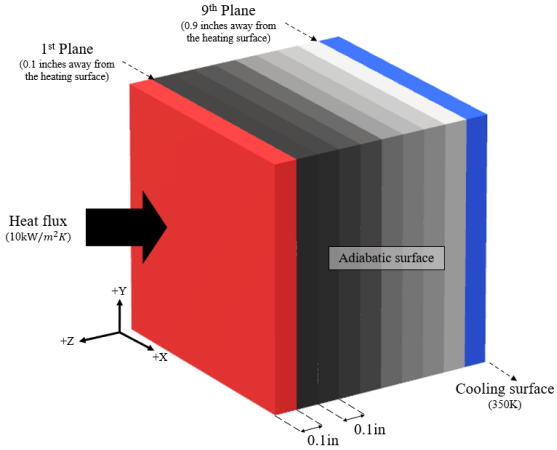
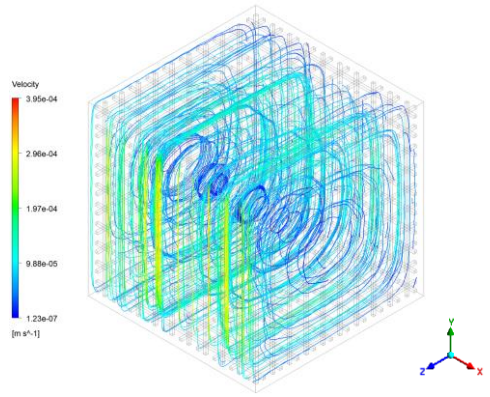
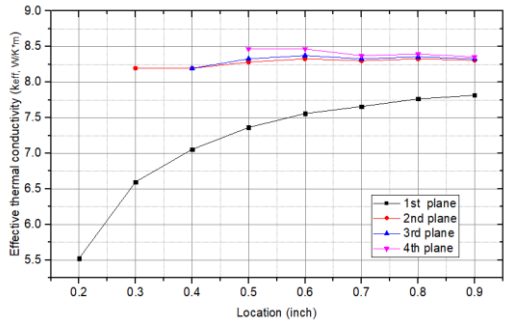


Figure 2. Analysis domain and boundary conditions



(a) Streamline of PCM for example case ($\varepsilon = 95\%, \omega = 10$)



(b) Effective thermal conductivity with respect to the reference plane

Figure 3. Result of example case analysis

RESULTS AND DISCUSSION

As an example case for liquid PCM, the analysis results for 95% porosity and 10 PPI are depicted in Figure 3. Gravity acts in the -y direction, and the temperature difference near the heating and cooling surfaces generates streamlines, as observed in Figure 3(a).

The effective thermal conductivity can be calculated using the following equation (5):

$$k_{eff} = \frac{q"_{in}}{T_x - T_{ref}} \cdot (X_x - X_{ref}) \qquad (5)$$

Where q_{in} is the inlet heat flux, T_x denotes the area-average temperature of the cross-sectional plane, and T_{ref} is the reference temperature. X_{ref} is the location of base plane of the calculation. In Figure 3(b), each plane refers to a surface located at 0.1 to 0.4 inches from the heating surface. As observed, there is a tendency for the effective thermal conductivity to converge towards a specific value when calculated based on planes located more than 0.2 inches away from the heating surface, where the influence of the inlet effect diminishes.

A mesh sensitivity study was conducted for Coarse and Fine meshes, each consisting of 1,506,000 and 4,917,000 volume mesh elements, respectively. The results of the mesh sensitivity study are presented in Figure 4, indicating an error of 1.33% or less. Therefore, considerations related to mesh size were negligible.

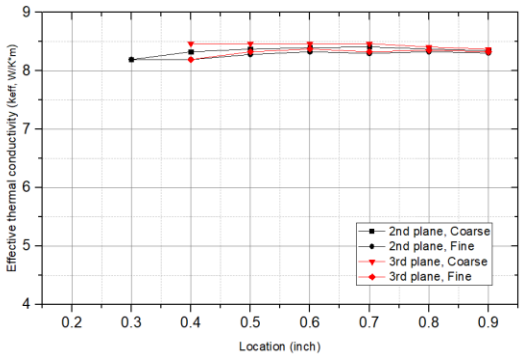


Figure 4. Mesh sensitivity test result

To figure out the impact of gravity on effective thermal conductivity, analyses were conducted by assuming gravity in both the -y and +z directions. As the direction of heat propagation is -z, the gravity direction in each case is perpendicular and reverse to the heat propagation direction. As evident from Figure 5, when gravity acts in the opposite direction to the heat propagation, specifically in the +z direction, the effective thermal conductivity is evaluated to be approximately 29-47% higher compared to the analysis results for solid PCM. Similarly, when gravity acts in the -y direction, it is estimated to be around 22-38% higher. The reason for this is that when the direction of gravity is opposite to the heat propagation direction, the natural circulation of the heated fluid from the heating surface aligns with the direction of heat propagation. Therefore, the effective thermal conductivity is higher when gravity acts in the opposite direction of heat propagation (+z direction) compared to the analysis results when gravity acts in the vertical direction (-y direction).

An increase in porosity may lead to a potential overestimation of convective heat transfer due to Buoyancy in this analysis model, which simplifies the complex geometry of metal foam. Therefore, an analysis of

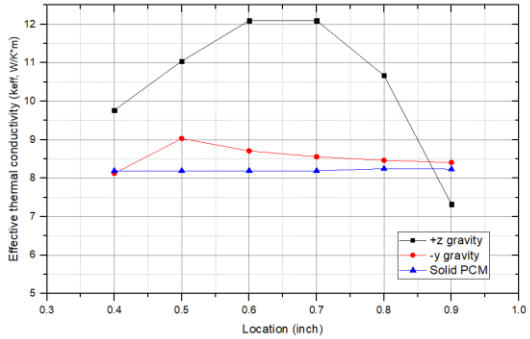


Figure 5. Effective thermal conductivity as a function of gravity direction

the trends in effective thermal conductivity influenced by buoyancy was conducted for conditions with 10 PPI and varying porosities of 90%, 95%, and 98%. Figure 6 indicates an overall increase in velocity as porosity increases. Hence, it can be inferred that convective heat transfer is likely to occur more effectively with higher porosity. This observation aligns with the comparison of the analysis results for solid PCM with the same thermal conductivity, where a larger porosity corresponds to a more significant difference in effective thermal conductivity. This trend is evident in the graph presented in Figure 7.

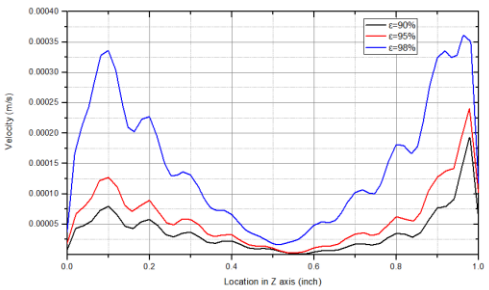
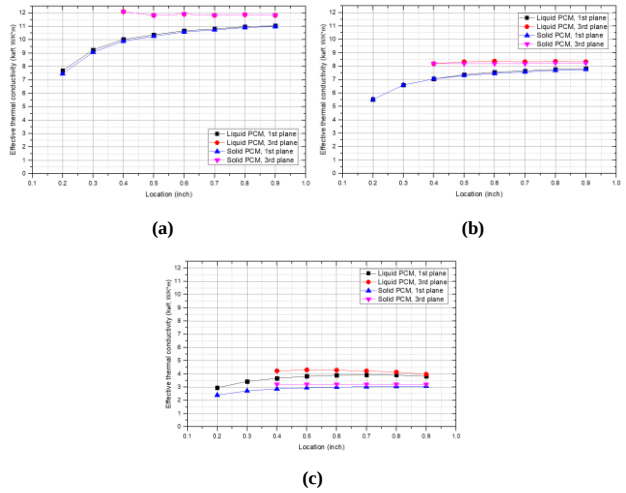


Figure 6. The velocity profile at z axis in the analysis results for each porosity (x=0.5in, y=0.5in)



(a) **(b)**

(c)

Figure 7. The effective thermal conductivity for 10 PPI with porosity (a) 90%, (b) 95%, and (c) 98%.

For the case with 98% porosity, the effective thermal conductivity is estimated to be approximately 24-33% higher compared to the analysis results for solid PCM. In contrast, for the 90% porosity case, the difference is minimal, ranging from 1.3% to 2.19%.

CONCLUSION AND FUTURE WORK

In this study, the directional changes in effective thermal conductivity induced by buoyancy were investigated using a three-dimensional numerical model of metal foam, specifically the simple lattice model. The variables employed in this analysis were the direction of gravity and porosity. The study involved analyzing the influence of convection by comparing the results of the respective cases with solid PCM, where effective thermal conductivity was determined. Given the assessment of how much heat transfer is enhanced by natural convection in the analysis results, it is imperative to subsequently examine the extent of heat transfer enhancement by metal foam when utilizing actual liquid PCM and determine any disparities that may arise. Hence, validation studies are planned in subsequent research when applying liquid PCM to the simple lattice model. If successful, such studies will enable a more accurate interpretation of heat transfer enhancement in simplified metal foam. Leveraging this understanding, there is a prospect of developing a more precise porous media model by integrating it into the system code.

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REFERENCES

[1] Jones, Fabian, editor. “Hottest July Ever Signals ‘Era of Global Boiling Has Arrived’ Says UN Chief.” UN News Global Perspective Human Stories, United nations, 27 July 2023

[2] Boomsma, K_, and D. Poulikakos. "On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam." International Journal of Heat and Mass Transfer 44.4 (2001): 827-836.

[3] Song, Minseop, Jun Soo Yoo, and Sunming Qin. Development of Numerical Model of Metal Foam with PCM for the Estimation of Effective Thermal Conductivity. No. INL/CON-22-67867-Rev000. Idaho National Lab.(INL), Idaho Falls, ID (United States), 2022.

[4] Ranut, Paola. "On the effective thermal conductivity of aluminum metal foams: Review and improvement of the available empirical and analytical models." Applied Thermal Engineering 101 (2016): 496-524.

[5] Calmidi, Varaprasad V., and Roop L. Mahajan. "The effective thermal conductivity of high porosity fibrous metal foams." Journal of heat transfer 121.2 (1999).