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INTRODUCTION

Global warming due to climate change is a threat to humankind. Nuclear energy is one of the promising solutions to reduce fossil fuel usage. Nuclear energy can handle the base load, compensating for the volatility of renewable energy. If nuclear energy could achieve load following capability, the combination with renewable energy would be more suitable. Thermal energy storage (TES) is one of the options for enabling load following of nuclear reactors. The TES makes it possible to store surplus nuclear thermal energy and release it later as needed. In Idaho National Laboratory (INL), a new concept of latent heat TES integrated with high-temperature heat pipe has been proposed and is under development, which is called Heat pipe-Integrated Thermal Battery (HITB). HITB exchanges thermal energy between the reactor system and TES via heat pipe. The heat transferred to TES medium, made of phase change material (PCM), stores energy as sensible heat and/or latent heat. As PCM typically has poor thermal conductivity, however, various heat transfer enhancement techniques are required to achieve a rapid charging cycle.

There are many techniques to enhance the heat transfer ability of TES medium such as disk, fin, and metal foam. Among them, metal foam is an appropriate option to enhance the heat transfer because it maximizes the heat transfer area through metal wicks. Metal foam is a lightweight metal structure that has a high porosity of over 0.9. The typical materials for metal foam are Aluminum, Copper, Nickel, and Silicon Carbide (SiC). Metal foam not only enhances heat transfer via conduction but also increases contact surface area. In the HITB design, the metal foam is being considered as one of the options to enhance the heat transfer of TES medium (PCM) [1].

To predict the enhanced thermal performance of TES, one should properly estimate the effective thermal conductivity of metal foam combined with PCM material or calculate heat transfer in distributed model. There are many experimental works that provides effective thermal conductivity of metal foam with various PCM [2,3]. Also, many theoretical models were developed based on the unit cell model of metal foam [4,5]. With a distributed model, on the other hand, detail heat transfer characteristics between metal foam and PCM material can be analyzed considering the geometry or buoyancy effect. However, due to the complex geometry of metal foam pores, the computational cost for three-dimensional modeling highly increases. Therefore, if metal foam structure can be modeled in simple and repetitive design, the computational cost would decrease Among the various metal foam models [2], lattice model is one of the simple and extendable design. The porosity and pores per inch (PPI) can be characterized by the size and spatial distance of lattice structure. If the three-dimensional metal foam model consists of lattice structure could properly estimate the heat transfer, which is characterized by effective thermal conductivity, it would be a good option to assess the thermal performance of metal foam with PCM.

In this study, a three-dimensional numerical model was developed to simulate conductive heat transfer between metal foam and PCM. The three-dimensional lattice structure of square pillars was selected as a basic structure of the metal foam. The calculation result was characterized by the effective thermal conductivity of the whole domain. A sensitivity study was conducted for mesh size, domain size, and PPI to check whether the calculation result gives a converged result or not. Lastly, the effective thermal conductivity from the lattice model was compared with existing experimental data to validate the model result.

MODEL DEVELOPMENT

The metal foam has a repetitive structure of open cell as shown in Figure 1. As pores per inch (PPI) increases, the metal foam gets denser. Due to the repetitive structure, the unit structure can be defined [2]. There are many models of the unit structure like Kelvin cell or lattice structure [4,5]. Among them, the lattice structure has a simple and intuitive design. This structure can easily be controlled and extended. Wang et al used this design as a unit structure to derive an analytical solution [5]. Figure 1(e) represents the design parameters of the lattice structure used in this study.

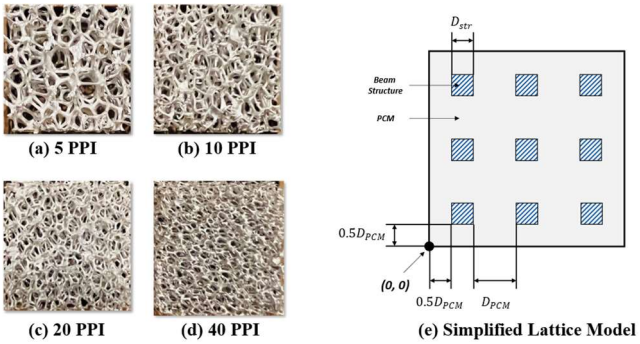


Figure 1. Aluminum Metal Foam and Simplified Model

To build a geometry and mesh of metal foam, SALOME 9.7.0 which is an open-source program from EDF-CEA was used. A python-script based geometry and mesh generation was conducted in the SALOME. It enables the rapid generation of models for sensitivity studies. Figure 2 represents an example of mesh generated for metal foam and PCM. The objective porosity of metal foam was achieved by adjusting the side length of the beam and the distance between beams. The tetrahedral mesh was used for mesh generation. The total number of volume mesh for 0.5 inch and 1-inch models are 370,000 and 4.5 million, respectively.

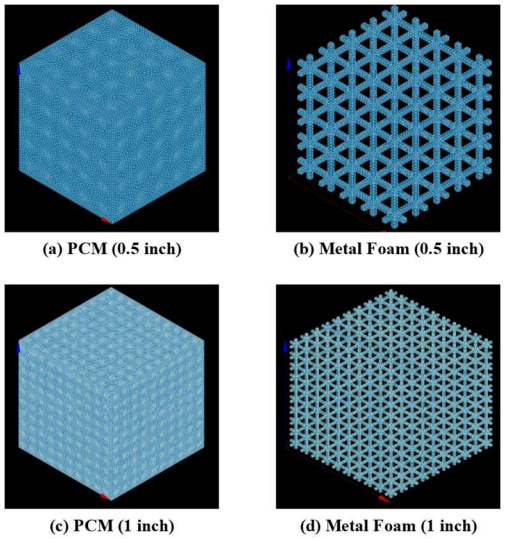


Figure 2. Mesh of PCM and metal foam structure

STAR-CCM+ was used to perform heat transfer analysis with an energy equation. The PCM domain was considered as solid to see only heat transfer via conduction between two domains. Therefore, only the heat conduction equation was solved with a segregated solver.

$$q = -k\nabla T \tag{1}$$

Boundary conditions were applied to both ends of the domain with heat flux and constant temperature as described in Figure 3. The heat was transferred into the domain as a heat flux of 1,000 W/m-K and out at a constant temperature surface of 522 K. To estimate effective thermal conductivity, the average temperature of cross-section of PCM and metal foam was monitored. Each plane spaces 1/5 of the side length. The thermal conductivity of aluminum metal foam was set to 236 W/m-K and the thermal conductivity of PCM was set to be 0.04381 W/m-K which is the thermal conductivity of air.

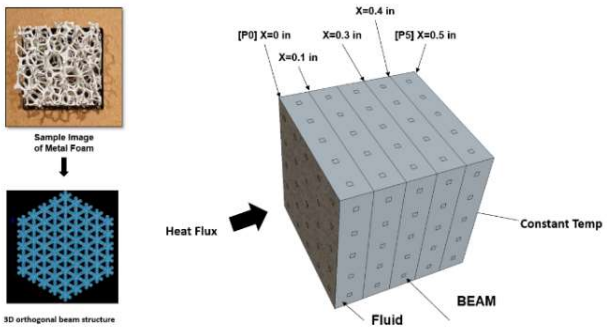


Figure 3. Definition of boundary condition

RESULTS

An example case with the side length of 1 inch was presented in Figure 4. From the temperature distribution in (a) where the temperature of PCM is described, a large inlet effect was observed. Due to the low thermal conductivity of air, a large temperature difference was made through the PCM domain. However, the temperature at metal foam more steadily decreases with less inlet effect. The average temperature at each cross-section in (c) indicates that the temperature gradient is nearly constant from the 0.2 inch, which means that the inlet effect was minimized from the plane at the 0.2 inch location.

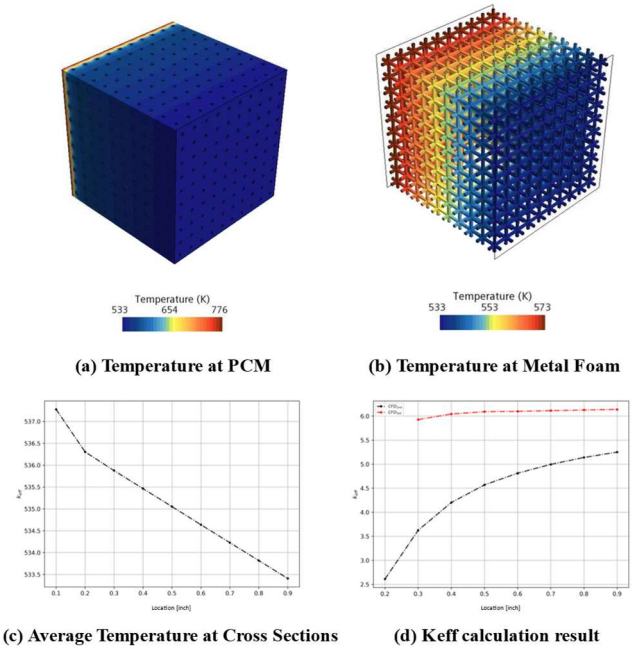


Figure 4. Example of heat transfer calculation with 1 inch model.

The effective thermal conductivity was calculated as equation (2).

$$k_{eff} = \frac{q_{in}}{T_x - T_{ref}} \quad (2)$$

Where, q_{in} is inlet heat flux, T_x is average corss-sectional temperature at x, and T_{ref} is a refrence temperature.

In graph (d), T_x at 0.1 inch and 0.2 inch was used as reference temperatures. The result shows that k_{eff} calculated with a reference value of 0.2 inch converged gives a converged result. The result of T_{ref} at 0.1 inch case didn't converge due to the inlet effect.

The sensitivity study on the mesh (coarse and fine) and domain size (0.5 inch and 1.0 inch of side length), and PPI (5, 20, 40) was conducted for the model with porosity of 0.934 and PPI of 10. The effective thermal conductivity was calculated from the temperature difference between planes from the 1st, 2nd , and 3rd planes. Figure 5(a) verifies that the effective thermal conductivity calculated from the 1st plane and 2nd plane gives low and not-converged values. These results mainly come from the inlet effect which gives different temperature gradient. The effective thermal conductvitiy calculated from the 3rd plane gives a converged value. The effect of mesh size was negligible as of 1.19%. In the sensitivity result for domain size in Figure 5(b), the effect of size was negligible for the converged value. Lastly, the effect of PPI was checked by varying PPI from 5 to 40. As shown in Figure 5(c), it was observed that as PPI increased, the effective thermal conductivity decreased. Considering that the PPI was not usually included in the calculation of the analytical model for effective thermal conductivity, this simple lattice model could be an alternative option to take into account PPI. In summary, normal mesh with 0.5 inch model size gives converged results when effective thermal conductivity is calculated from the 3rd plane. The result was also sensitive to PPI.

To validate the distributed model, effective thermal conductivity calculated from the numerical model was compared with experimental data [2] and existing correlations. According to the review research on the assessment of existing models with experimental data [2], the Calmidi and Mahajan model [4] has the lowest mean square error (MSE) for the difference with experimental data. This model is valid for metal foam with porosity (ε) over 0.9.

$$k_{eff} = \varepsilon k_f + A(1-\varepsilon)^n k_s \quad (3)$$

Where, n=0.763, A=0.181(Air) and 0.195(Water).

And Wang's model [5] was added because this analytical model was developed for the lattice structure.

$$k_{eff} = k_s \left[0.5 - \cos\left(\frac{\pi + arccos(1-2(1-\varepsilon))}{3}\right)\right]^2 \quad (4)$$

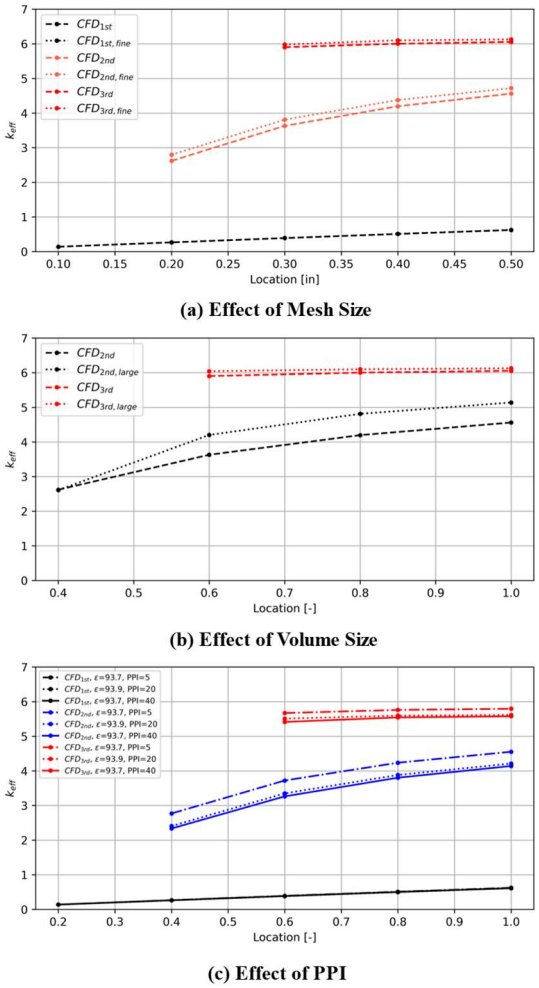
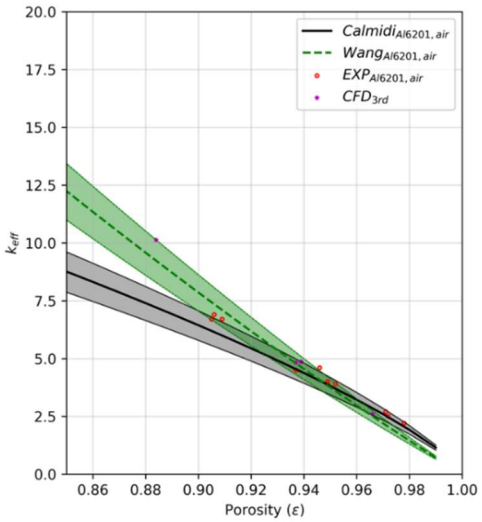
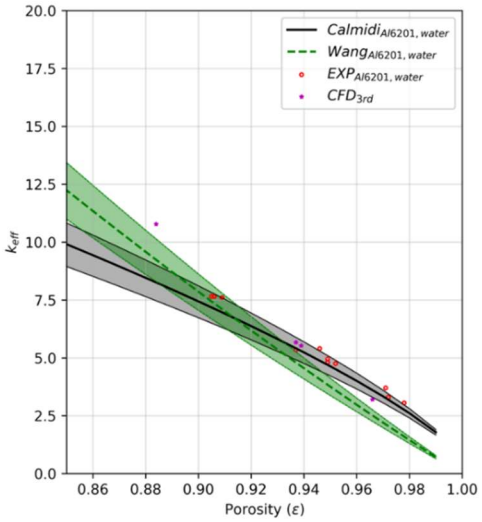


Figure 5. Sensitivity Test Result

Figure 6 shows the comparison result with experimental data and the above correlations. The experimental data have air and water as working fluids. Therefore, thermal conductivity of Al6201 (k=205W/m-K), air (k=0.04381W/m-K) and water (k=0.6W/m-K) were used. For Calmidi and Wang's correlation, the lower (k=184W/m-K) and upper (k=225W/m-K) bound of thermal conductivity of aluminum were applied because of uncertainty from impurities. For the air case, both models predict the experimental data well at high porosity. The effective thermal conductivity from the numerical result also follows the trend of experimental data closely at high porosity over 0.92. When the working fluid is water, the experimental data agree well with Calmidi and Mahajan model than Wang's correlation. The result from CFD studies gives a similar trend with experimental data at the porosity around 0.94. However, at high porosity, the CFD value underestimated effective thermal conductivity.



(a) keff calculation result for air



(b) keff calculation result for water

Figure 6. Validation Result with Experimental Data and Correlations

Given these results, it can be concluded that the simplified lattice model gives reliable heat transfer calculation results and effective thermal conductivity can be derived from the result.

CONCLUSION AND FUTURE WORK

In this study, a three-dimensional numerical model for metal foam combined with PCM was made to simulate heat transfer. The structure of metal foam was modeled by lattice structure which is a simple and easily extendable design. The 0.5-inch model was selected as the reference model based on the sensitivity result. The result was compared with experimental data and existing correlations for validation. It was found that the result from the distributed model with air follows the Calmidi model and agrees closely with the experimental data at porosity over 0.92 and the model with water follows the experimental data and Calmidi correlation faithfully. Therefore, the distributed model with lattice structure can be applied to the conductive heat transfer at the metal with PCM, which is needed to estimate the heat transfer performance of HITB. This method will be applied to the convective heat transfer between metal foam and PCM with validation.

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REFERENCES

1. J. Yoo, M. Song, S. Qin, J. Hartvigsen, H.S. Kim, J. Seo, High-Temperature Laten Heat Storage System using Transportable Heat Pipes for Versatile Integration with Emerging Microreactors, ANS 2022 Winter, (2022)
2. K. Boomsma, D. Poulikakos, On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam, Int. J. Heat Mass Tran. 44 (4) (2001) 1827–1836.
3. P. Ranut, 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.
4. V. Calmidi, R. Mahajan, The effective thermal conductivity of high porosity fibrous metal foams, ASME J. Heat Transf. 121 (1999) 466–471.
5. J. Wang, J. Carson, J. Willix, M. North, D. Cleland, A symmetric and interconnected skeleton structural (SISS) model for predicting thermal and electrical conductivity and Young's modulus of porous foams, Acta Mater. 56 (2008) 5138–5146.