

NUMERICAL SIMULATIONS OF EFFECTIVE THERMAL CONDUCTIVITY IN ALUMINUM FOAM SANDWICH PANEL

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In this work, the effective thermal conductivities of aluminum foam sandwich panels with the porosity range from 40% to 60% were studied by simulation method. The influence of porosity and pore size on the effective thermal conductivities was analyzed, and their influence mechanism was studied. In addition, simulation results were verified by theoretical formula. This further proves the feasibility of simulation method for research on the effective thermal conductivity of aluminum foam sandwich panels. The results confirmed that the porosity and pore size of aluminum foam sandwich panel had great impact upon its effective thermal conductivity.

Key words: *aluminum foam sandwich panel, effective thermal conductivity, simulation, porosity, pore size*

Introduction

Containing an aluminum foam core and two composite skins, aluminum foam sandwich (AFS) panels have exhibited special mechanical, thermal, electric and acoustic properties and so on [1-6]. The combinations of these remarkable properties make it have a broad application prospect in the industry such as automotive, aerospace and building construction. Above all, the thermal transport properties of AFS panels have attracted increasing attention in the academic and industrial fields, and play a very significant role in the design and use of foam materials [7, 8].

Effective thermal conductivity is one of the key parameters characterizing the thermal transport properties of metal foam. So far, it has been widely concerned and investigated. Solorzano *et al.* [9] discussed the thermal conductivity of AlSi7 foams with different porosities using the transient plane source technique, and reported that the thermal conductivity of AlSi7 foams increased with the density. Fiedler *et al.* [10] investigated the thermal conductivity of cellular metals by the lattice Monte Carlo method, and proposed a theoretical method and formulae to describe the effective thermal conductivities of cellular metals. Ma and Ye [11] explored the effective thermal conductivities of metallic foams using different computational methods, and confirmed that the effective thermal conductivities of cellular metals were the product of cell wall thermal conductivity, relative density and shape factor. In addition, they studied the effective thermal conductivity of closed-cell aluminum foams in the temperature range of 100-500 °C, and the results showed the effective thermal conductiv-

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ity was proportional to the relative density and slightly decreased with the temperature [12]. Unfortunately, as far as we known, the investigation on the effective thermal conductivity of AFS panel has been seldom published.

In this article, based on the inner features of AFS panels, 2-D random models were generated by combing C++ and ANSYS. The effective thermal conductivity of AFS panel was calculated by finite element method, and the influences of porosity and pore size on the effective thermal conductivity of AFS panel were analyzed. Then the simulation results were compared with the theoretical results. In addition, the internal heat transfer mechanism of AFS panel was discussed.

Methods

The 2-D finite element model is often used to analyze the deformation behavior of porous aluminum foam due to the simple geometry shape and convenient and efficient finite element mesh division [13, 14]. So, based on the inner features of AFS panels, the 2-D random models were created by combing C++ and ANSYS. The model of AFS panel consists of two thin aluminum panels (100 mm length and 0.8 mm thickness) and a highly porous aluminum foam core (100 mm length and 20 mm thickness) as shown in fig. 1. The detailed modeling process was reported in our previous work [14]. In this work, to investigate the influence on the effective thermal conductivity of AFS panel with the different porosities (40%, 45%, 50%, 55%, and 60%) of AFS finite element models with two kinds of pore size ranges, 1-3 mm

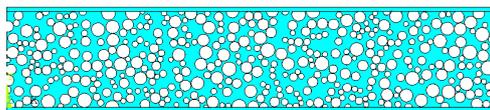


Figure 1. The geometric models of AFS panel

and 3-5 mm, were considered. Furthermore, the effect of the average diameter variation of pores on the effective thermal conductivity of AFS panel was analyzed. The selected models (50% porosity) average pore sizes are 2-7 mm, respectively.

To facilitate exerting boundary condition, thermal-conductivity splints with thickness of 5 mm were added on the upper and lower sides of the model. Moreover, its conductivity coefficient accords with that of the skins of AFS panel. The boundary conditions are: the temperature-resolved boundary, $T_0 = 298.15$ K, is exerted on the lower surface of AFS panel model; the heat flux boundary, $Q_0 = 10000$ W/m², is exerted on the upper surface of AFS panel model; the other surfaces are regarded as adiabatic boundary. The prescribed boundary conditions on AFS panel model are shown in fig. 2. Core with closed-cell aluminum foam is 5052 aluminum alloy, panels and splints are 2024 aluminum alloy. The parameters of AFS panels are shown in tab. 1 [15]. In this work, PLANE55 element was used to analyze the 2-D heat-conduction of

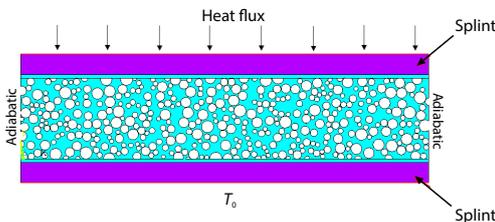


Figure 2. Thermal boundary conditions of AFS panel

Table 1. Material properties for AFS panel models [15]

Parameters parts	Density [kgm ⁻³]	Specific heat [Jkg ⁻¹ k ⁻¹]	Thermal conductivity [Wm ⁻¹ k ⁻¹]
Top and bottom panels	2680	875	190
Core layer	2700	900	137

AFS panel model meshed by Smartsizing tool. This kind of mesh tool can be better adapted to geometric shape and improve the computational accuracy due to it can automatically adjust the grid size according to the pore shape in aluminum foam core. The division of grids has an effect on the accuracy of the analysis results and the economics of the process. In general, the accuracy of the analysis results increases with the increase of the grids. However, it is not true that the smaller the grid division, the better the calculation results. The reason is that the calculation accuracy is improved little and the calculation time has increased significantly with the grids increasing, after the number of grids increases to a certain extent. Through the verification of our previous simulation work, when the grid level is set to level 2, the calculation accuracy and economy are better. In order to ensure the accuracy of test results, each tested data was gathered three times from different models with same porosity or pore size.

Based on the aforementioned prescribed boundary conditions, a steady-state thermal analysis was conducted. The effective thermal conductivity of porous materials can be defined:

$$K_f = \frac{QH}{\Delta T} \quad (1)$$

where Q is the heat flux, ΔT – the temperature difference between the upper and the lower sides of the model, and H – the sample thickness. This equation has been used in the study on the thermal conductivity of metal foam materials, such as: Zhao *et al.* [16] investigated the thermal conductivity of open-celled steel alloy foams and verified its correctness and Kulesa and Robinson [17] calculated the effective thermal conductivity of syntactic foams and found that the error was within the acceptable range.

Moreover, according to the aforementioned boundary conditions and eq. (1), the effective thermal conductivity of AFS panel can be written:

$$K_e = \frac{Q_0 H}{\Delta T} - \frac{2Q_0 h}{K_s} \quad (2)$$

where h is the metal splints thickness and K_s – the thermal conductivity of metal splints.

In addition, many physical properties of the metal foams could be estimated by the exponential rule which was composed by the porosity and a constant of the performance. Solorzano *et al.* [9] have unified several theoretical models for thermal conductivity of metal foam, and compared with the experimental results. They found that the eq. (3) is a good predictor for the effective thermal conductivity of metal foam:

$$K_f = K_1(1-p)^n, \quad n \in [1.65, 1.85] \quad (3)$$

where K_1 is the thermal conductivity of the matrix of aluminum foam and p – the porosity of aluminum foam.

According the structure of AFS panel, containing an aluminum foam core and two aluminum alloy skins, it is a representative series structure [18]. Therefore, the effective thermal conductivity of AFS panel, K_e , is described:

$$\frac{1}{K_e} = \frac{\alpha}{K_1(1-p)^n} + \frac{1-\alpha}{K_2}, \quad n \in [1.65, 1.85] \quad (4)$$

where α is the volume fraction of aluminum foam core and K_2 – the thermal conductivity of aluminum alloy skins.

Results and discussion

The heat transfer of porous material can be divided into four parts: heat conduction between gas in the pore, heat conduction between matrix, convection between the solid matrix, and pores of gas and heat radiation [19]. According [10, 15], if the diameter of pores is less than 5 mm, the effect of convection could be ignored. Besides, when the thermal conductivity of matrix is more than 100 W/mK, and the radiation heat transfer is just about 10% of the heat conduction. Therefore, the heat conduction is the main heat transfer pattern for AFS panels in this work.

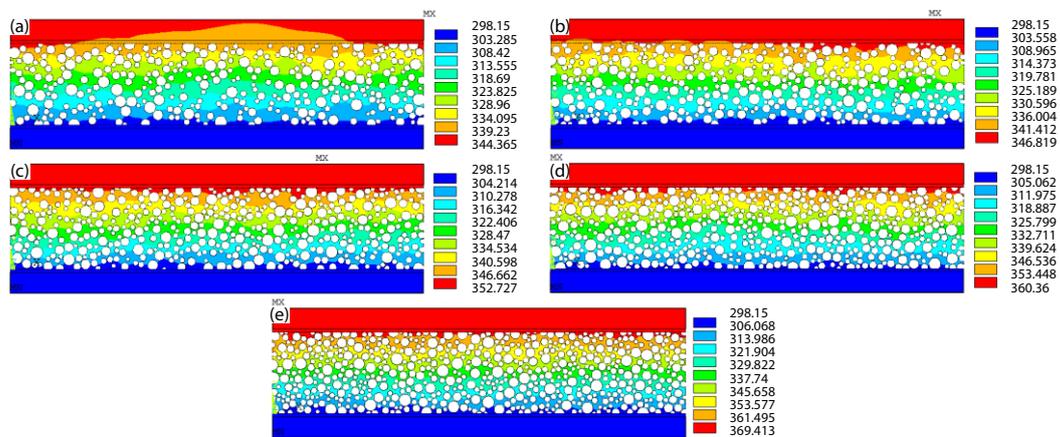


Figure 3. Temperature distributions of AFS panels at 1-3 mm pore size with different porosities; (a) 40% porosity, (b) 45% porosity, (c) 50% porosity, (d) 55% porosity, (e) 60% porosity.

The temperature distributions of AFS panels with pore size range 1-3 mm are shown in fig. 3. As seen from fig. 3, the temperature gradually increases from bottom to top of AFS models as a whole. However, it can also be seen that the temperature distributions are uneven, especially in fig. 3(a). This result shows the heat transfer in AFS panels obviously depend on the porosity. Ye *et al.* [20] considered, in heat conduction, the practically curved cell walls were the paths of the heat flow. However, the shape and size of cell wall vary with the porosity of AFS core. When the porosity is relatively small, there are big differences in the shape and distribution of cell walls, which leads to the heat transfer process to vary accordingly [21]. Furthermore, it will also affect the heat transfer in the panel and splint, as shown in fig. 3(a).

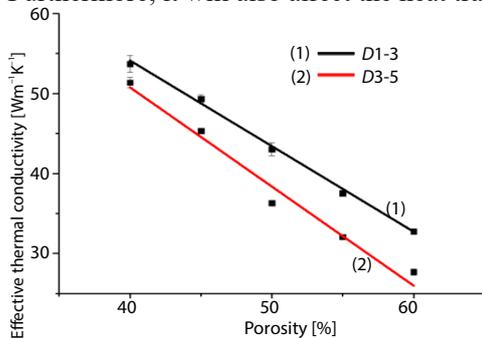


Figure 4. Effective thermal conductivity as a function of porosity for AFS panels with pore size range 1-3 mm and 3-5 mm

The calculation values of the effective thermal conductivities for AFS panels by ANSYS and eq. (2) are plotted in fig. 4. It can be seen from fig. 4, the effective thermal conductivity of AFS panel almost linearly decreases with the increase of porosity. The reason could lie in that the porosity of the structure parameters directly reflects the ratio of the solid skeleton in the porous material, and lower porosity value is associated with a higher volume of solid skeleton which provides high conductive paths for the heat flow [20, 22, 23]. On the contrary, the increment in the porosity enhances the resistance to heat-flow and lessens

the heat transfer surface area, and, as a result, the effective thermal conductivity of the sample has a corresponding decrease [24]. In addition, seen from fig. 4, the two curves of thermal effective conductivities follow the same trend. Therefore, the porosity plays a leading role in the effective thermal conductivity of AFS panel.

In order to verify the previous simulation method, the simulation data is used to compare with the theoretical results of eq. (4), which is shown in fig. 5. As can be seen, the simulation results are very close to those from theoretic calculation. Consistent with increased porosity, both results of the simulation and calculation almost decrease linearly. This illustrates the 2-D model used in this work can better simulate the thermal conductivity of closed-cell aluminum foam at different porosity. In addition, a possible explanation for the differences between simulation results and predictions is related to the cellular structure. As described by Lu and Chen [25], the thermal conductivity of the foam depends upon the cell shape, connectivity and topology. Therefore, the simulation results are distributed on both sides of the theoretical results. The reason may lie in the effect of pore size on effective thermal conductivity is not considered in this numerical formula.

In addition, to better understand the heat transfer mechanism of porous foam material, a number of attempts have been focused on thermal tortuosity, τ , which is defined as the ratio of the route length of heat conduction and the linear conduction [26-28]. The effective thermal conductivity of porous material can be evaluated by porosity and thermal tortuosity, namely, it is a function of the porosity and thermal tortuosity:

$$\frac{K_e}{K_c} = \frac{1 - \varepsilon}{\tau} \quad (5)$$

where K_c is the thermal conductivity of the matrix of AFS panel and ε – the volume fraction of the pores. The effective thermal conductivity of aluminum foam with 60% porosity and 1-3 mm pore size calculated by this method is 30.871 W/mK. From tab. 1, the thermal conductivity of the panel of AFS panel is 190 W/mK, which is 6.19 times than that of aluminum foam. Therefore, the skin of AFS panel has a certain influence on the effective thermal conductivity, and the influence of the panels could not be ignored in the calculation of thermal tortuosity. Furthermore, the matrix of AFS panel is defined as a 3 layers composite plates containing a 5052 aluminum alloy core (100 mm length and 5 mm thickness) and two 2024 aluminum alloy skins (100 mm length and 0.8 mm thickness), which is a representative series structure [18]. The effective thermal conductivity of the matrix of AFS panel is described:

$$\frac{1}{K_c} = \frac{\alpha}{K_1} + \frac{1 - \alpha}{K_2} \quad (6)$$

The thermal tortuosity for AFS panels with different porosities is shown in fig. 6. It can be found that the values of thermal tortuosity increases with the increase of porosity. This indicates that AFS panel with larger porosity has a longer heat transfer path, which is in agreement with the results of Yang *et al.* [28]. Seen from fig. 6, it can be observed that the values of thermal tortuosity for AFS panels are more than 1. This phenomenon is due to the large number

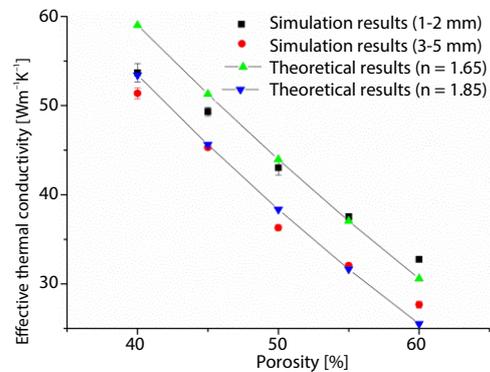


Figure 5. The thermal conductivity derived from simulation and theoretical results

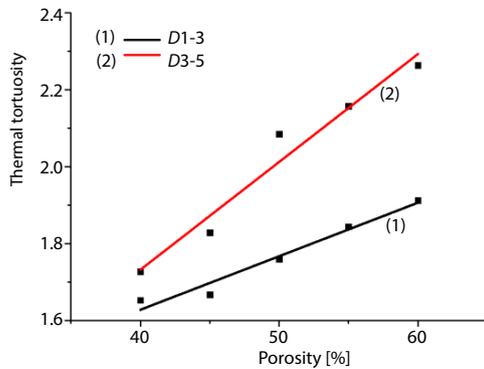


Figure 6. Thermal tortuosity as a function of porosity for AFS panels pore size range 1-3 mm and 3-5 mm

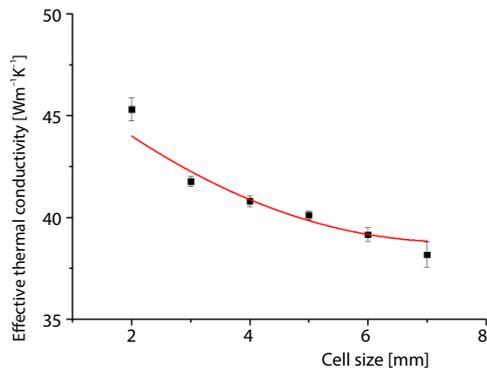


Figure 7. Effective thermal conductivity of AFS at 50% porosity with different pore size

smaller pore size [19, 31]. Therefore, a smaller pore size results in a higher effective thermal conductivity.

Conclusion

In this work, the effective thermal conductivities of AFS panels were calculated by ANSYS based on the 2-D random models, and the simulation results were verified by theoretical formula. The results showed that the temperature gradually increased from bottom to top of the samples and the distributions were uneven. With the increase of the porosities of AFS panels, the effective thermal conductivities decreased. In addition, it is found that the effective thermal conductivities of AFS panels also decreased with pore size increasing when the porosity was the same. Therefore, the effective thermal conductivity of AFS panel depended on both porosity and pore size. This work proved the feasibility of the geometrical method for research on the effective thermal conductivities of AFS panels and offered a theoretical support in this research field.

References

- [1] Li, Z. B., *et al.*, Local Indentation of Aluminum Foam Core Sandwich Beams at Elevated Temperatures, *Composite Structures*, 145 (2016), June, pp. 142-148

of cells in AFS core, which leads to the increase of the flow resistance and make the capability of heat transport of AFS panel decrease [29, 30]. In addition, the thermal tortuous curve of 3-5 mm pore size is steeper than that of 1-3 mm pore size, which indicates that with the porosity increase, the effective thermal conductivity of AFS panel with 3-5 mm pore size declines at a faster rate, as showed in fig. 4.

As seen from fig. 6, the thermal tortuous value of samples with 3-5 mm pore size is higher than that of 1-3 mm pore size. In addition, the calculation results of AFS panels under the same porosity varies according to the pore size, as shown in fig. 4. All of these show that pore size has an effect on the effective thermal conductivity of AFS panel. Furthermore, in order to investigate the influence of pore size on the effective thermal conductivity of AFS panel, the effective thermal conductivity is calculated in the same porosity but different pore size.

As shown in fig. 7, the influence of pore size on the effective thermal conductivity of AFS panel is described. It can be seen that the effective thermal conductivity of AFS panel decreases with the increase of the pore size when the porosity is fixed. That is because if the porosity is approximate, the larger number of cells and the faster heat dissipation in the foam of

- [2] Elnasri, I., Zhao, H., Impact Perforation of Sandwich Panels with Aluminum Foam Core: A Numerical and Analytical Study, *International Journal of Impact Engineering*, 96 (2016), Oct., pp. 50-60
- [3] Fiedler, T., et al., Numerical Analyses of the Thermal Conductivity of Random Hollow Sphere Structures, *Materials Letters*, 63 (2009), 13-14, pp. 1125-1127
- [4] Banhart, J., Manufacture, Characterisation and Application of Cellular Metals and Metal Foams, *Progress in Materials Science*, 46 (2001), 6, pp. 559-632
- [5] Lu, W., et al., Thermal Analysis on Metal-Foam Filled Heat Exchangers – Part I: Metal-Foam Filled Pipes, *International Journal of Heat and Mass Transfer*, 49 (2006), 15-16, pp. 2751-2761
- [6] Boomsma, K., et al., Metal Foams as Compact High Performance Heat Exchangers, *Mechanics of Materials*, 35 (2003), 12, pp.1161-1176
- [7] Feng, Y. et al., Thermal Conductivity of Closed-Cell Aluminum Alloy Foam, *Acta Metallurgica Sinica*, 39 (2003), 8, pp. 817-820
- [8] Wulf, R., et al., Experimental and Numerical Determination of Effective Thermal Conductivity of Open Cell FeCrAl-Alloy Metal Foams, *International Journal of Thermal Sciences*, 86 (2014), Dec., pp. 95-103
- [9] Solorzano, E., et al., An Experimental Study on the Thermal Conductivity of Aluminium Foams by Using the Transient Plane Source Method, *International Journal of Heat and Mass Transfer*, 51 (2008), 25-26, pp. 6259-6267
- [10] Fiedler, T., et al., Theoretical and Lattice Monte Carlo Analyses on Thermal Conduction in Cellular Metals, *Computational Materials Science*, 50 (2010), 2, pp. 503-509
- [11] Ma, M. Y., Ye, H., An Image Analysis Method to Obtain the Effective Thermal Conductivity of Metallic Foams via a Redefined Concept of Shape Factor, *Applied Thermal Engineering*, 73 (2014), 1, pp. 1279-1284
- [12] Ye, H., M. et al., An Experimental Study on Mid-High Temperature Effective Thermal Conductivity of the Closed-Cell Aluminum Foam, *Applied Thermal Engineering*, 77 (2015), Feb., pp.127-133
- [13] Hardenacke, V., Hohe, J., Local Probabilistic Homogenization of Two-Dimensional Model Foams Accounting for Micro Structural Disorder, *International Journal of Solids and Structures*, 46 (2009), 5, pp. 989-1006
- [14] Qiu, S. W., et al., Simulation of Apparent Elastic Property in the Two-Dimensional Model of Aluminum Foam Sandwich Panel, *Materials Transactions*, 56 (2015), 5, pp. 687-690
- [15] Li, Z. Q., et al., Thermal-Mechanical Behavior of Sandwich Panels with Closed-Cell Foam Core under Intensive Laser Irradiation, *Thermal Science*, 18 (2014), 5, pp. 1607-1611
- [16] Zhao, C. Y., et al., The Temperature Dependence of Effective Thermal Conductivity of Open-Celled Steel Alloy Foams, *Materials Science and Engineering A- Structural Materials Properties Microstructure and Processing*, 367 (2004), 1-2, pp. 123-131
- [17] Kulesa, A. T., Robinson, M. J., Analytical Study of Structural Thermal Insulating Syntactic Foams, *Composite Structures*, 119 (2015), Jan., pp. 551-558
- [18] Ranut, P., On the Effective Thermal Conductivity of Aluminum Metal Foams: Review and Improvement of the Available Empirical and Analytical Models, *Applied Thermal Engineering*, 101 (2016), May, pp. 496-524
- [19] Zhu, X. L., et al., Thermal Conductivity of Closed-Cell Aluminum Foam Based on the 3-D Geometrical Reconstruction, *International Journal of Heat and Mass Transfer*, 72 (2014), May, pp. 242-249
- [20] Ye, H., et al., A Lattice Monte Carlo Analysis of the Effective Thermal Conductivity of Closed-Cell Aluminum Foams and an Experimental Verification, *International Journal of Heat and Mass Transfer*, 86 (2015), Apr., pp. 853-860
- [21] Liu, Z. Y., Wu, H. Y., Pore-Scale Study on Flow and Heat Transfer in 3-D Reconstructed Porous Media Using Micro-Tomography Images, *Applied Thermal Engineering*, 100 (2016), May, pp. 602-610
- [22] Xia, D. H., et al., Study of the Reconstruction of Fractal Structure of Closed-Cell Aluminum Foam and Its Thermal Conductivity, *Thermal Science*, 21 (2012), 1, pp. 77-81
- [23] Sadeghi, E., et al., Thermal Conductivity and Contact Resistance of Metal Foams, *Journal of Physics D – Applied Physics*, 44 (2011), 12, 125406
- [24] Ghosh, I., Heat-Transfer Analysis of High Porosity Open-Cell Metal Foam, *Journal of Heat Transfer – Transactions of the ASME*, 130 (2008), 3, 034501
- [25] Lu, T. J., Chen, C., Thermal Transport and Fire Retardance Properties of Cellular Aluminium Alloys, *Acta Materialia*, 47 (1999), 5, pp. 1469-1485
- [26] Zhang, B. Q., Liu, X. F., Effects of Fractal Trajectory on Gas Diffusion in Porous Media, *AIChE Journal*, 44 (2003), 12, pp. 3037-3047

- [27] Lanfrey, P. Y., *et al.*, Tortuosity Model for Fixed Beds Randomly Packed with Identical Particles, *Chemical Engineering Science*, 65 (2010), 5, pp. 1891-1896
- [28] Yang, X. H., *et al.*, A Simplistic Model for the Tortuosity in Two-Phase Close-Celled Porous Media, *Journal of Physics D – Applied Physics*, 46 (2013), 12, 125305
- [29] Paek, J. W., *et al.*, Effective Thermal Conductivity and Permeability of Aluminum Foam Materials, *International Journal of Thermophysics*, 21 (2000), 2, pp. 453-464
- [30] Traxl, R., *et al.*, Thin-Shell Model for Effective Thermal and Electrical Conductivity of Highly Porous Closed-Cell Metal Foams, *Transport in Porous Media*, 113 (2016), 3, pp. 629-638
- [31] Sundarram, S. S., Li, W., The Effect of Pore Size and Porosity on Thermal Management Performance of Phase Change Material Infiltrated Microcellular Metal Foams, *Applied Thermal Engineering*, 64 (2014), 1-2, pp. 147-154