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Numerical investigation of the effect of fins added to metal foam on heat transfer using air and water coolants

Metal süngere kanatçık eklenmesinin hava ve su akışkanları ile ısı transferine etkisinin sayısal yöntemlerle incelenmesi

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Numerical Investigation of The Effect of Fins Added to Metal Foam on Heat Transfer Using Air and Water Coolants

Metal Süngere Kanatçık Eklenmesinin Hava ve Su Akışkanları ile Isı Transferine Etkisinin Sayısal Yöntemlerle İncelenmesi

Highlights

- ❖ The heat transfer in a metal foam is analyzed using a non-equilibrium thermal porous medium model, and the findings are validated against existing literature.
- ❖ Examining the effect of using fins with metal foam on heat transfer.
- ❖ Comparing the effect of using fins with metal foam on heat transfer when the working fluid is air and water.

Graphical Abstract

In this research, the heat transfer in a metal foam is numerically analyzed using a non-equilibrium thermal porous medium model, and the results are validated against existing literature for both water and air as working fluids. Subsequently, the heat transfer performance is numerically investigated with the addition of up to four fins to the metal foam.

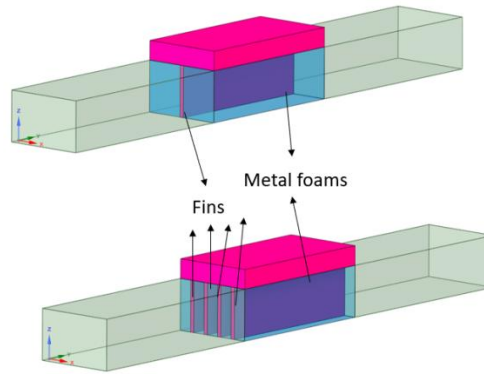


Figure. Addition of 1 fin and 4 fins to the metal foam

Aim

The aim of the research is to examine the use of fins with metal foam using numerical methods with water and air as working fluids, and to compare the results.

Design & Methodology

Fins, varying from one to four, have been integrated along the metal foam's height, and the influence of fin utilization on heat transfer has been systematically investigated through numerical methods, employing water and air as working fluids.

Originality

The effect of using fins with metal foam on heat transfer has been examined for a small thermal conductivity working fluid, such as air, and a high thermal conductivity working fluid, such as water, with results compared systematically.

Findings

Fins addition to the metal foam has enhanced heat transfer for both fluids; however, the relationship between this enhancement and fluid velocity has differed for the two fluids.

Conclusion

Fins addition to the metal foam has significantly enhanced heat transfer at high fluid velocities when air is used, while in the case of water, it has shown to be more effective at low fluid velocities.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Numerical Investigation of the Effect of Fins Added to Metal Foam on Heat Transfer Using Air and Water Coolants

Araştırma Makalesi / Research Article

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ABSTRACT

Advancements in technology have led to a continuous increase in the amount of heat generated within electronic equipment, despite the reduction in their size and the increase in their functionalities. Due to the escalating heat loads, enhancing cooling performance has become more critical in applications. Metal foams have recently emerged as a prominent method to enhance heat transfer in cooling systems, primarily due to their great surface-to-volume ratios. However, the issue arises when high porosity values are involved, particularly when a high thermal conductivity fluid such as water is used, as it presents difficulty in ensuring heat conduction along the height of the metal foam. Consequently, integrating fins with metal foams has been documented in the literature as a means to increase the Nusselt number on the heated surface. In this study, in contrast to the existing literature, the effect of using metal foam combined with fins was examined with two separate fluids possessing dissimilar thermal conductivities: a high thermal conductivity fluid (water) and a low thermal conductivity fluid (air). The metal foams were modeled using Computational Fluid Dynamics (CFD) software with porous medium parameters. The metal foam used is made of aluminum material and exhibits a high porosity level of 90%. Additionally, the impact of varying the number of fins was investigated as a parameter, and its effect on the heat transfer from the heated surfaces for both fluids was examined using ANSYS Fluent software. In the study, it was observed that when air is used as the fluid, the addition of fins increases efficiency with increasing air velocity, while the temperature rise on the wall can be reduced by up to 43%. Conversely, when water is used as the fluid, the addition of fins decreases efficiency with increasing water velocity, yet the temperature rise on the wall can be reduced by up to 48%.

Keywords: Liquid cooling, metal foams, computational fluid dynamics, heat transfer in porous media.

Metal Süngere Kanatçık Eklenmesinin Hava ve Su Akışkanları ile Isı Transferine Etkisinin Sayısal Yöntemlerle İncelenmesi

ÖZ

Teknolojideki ilerlemeler ile birlikte ısı üreten elektronik ekipmanların boyutlarındaki küçülmelere rağmen işlevlerinin artmasından kaynaklı birim hacim ısı yükleri sürekli bir artış göstermektedir. Artan ısı yüklerine bağlı olarak soğutma performanslarının iyileştirilmesi önem kazanmaktadır. Metal süngerler çok yüksek yüzey/hacim oranları ile ısı transferini iyileştirmede kullanılabilen yöntemler arasında öne çıkan uygulamalardan biridir. Yüksek porozite, su gibi ısı transfer özellikleri yüksek bir akışkan için ısının metal süngerin yüksekliği boyunca iletiminin sağlanmasında sorun teşkil etmektedir. Bu sebeple metal süngerin yüksekliği boyunca ısı iletiminin sağlanması ve ısıtılan yüzeyin Nu sayısının yükseltilebilmesi için metal süngerlerin kanatlarla birleştirilmesi literatürde incelenmiştir. Bu çalışmanın literatürdeki çalışmalarından farkı metal sünger ile kanatçık kullanımının etkisinin büyük ısı iletkenliğe sahip bir akışkan (su) ve küçük ısı iletkenliğe sahip bir akışkan (hava) ile ayrı ayrı kullanılmış olmasıdır. Metal süngerler Hesaplamalı Akışkanlar Dinamiği (HAD) yazılımlarında poroz ortam parametreleri kullanılarak modellenmektedir. Metal sünger alüminyum malzemeden üretilmiş olup yüksek poroziteye (%90) sahiptir. Çalışmada kanat sayısı da bir parametre olarak incelenmiş olup, kanat sayısının bu iki sıvının ısı tanımlanan yüzeydeki Nu sayısını nasıl etkilediği ANSYS Fluent yazılımı ile incelenmiştir. Çalışmada akışkan hava olduğu durumda kanat eklenmesinin verimliliği artan hava hızı ile artarken duvardaki sıcaklık artışı %43'e kadar, akışkan su olduğu durumda ise kanat eklenmesinin verimliliği artan su hızı ile azalırken duvardaki sıcaklık artışı %48'e kadar azaltılabildiği gözlemlenmiştir.

Keywords: Solar air collector, conical spring, fuzzy logic, modeling, outlet temperature, thermal efficiency.

1. INTRODUCTION

Electronic components are structures that perform their functions through the electric current passing through them. As a result, they emit heat to the surroundings.

With advancing technology, it is a well-known fact that the heat loads of electronic components have increased. Despite the high heat loads, there are no radical changes in the operating temperature limits of the components.

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Traditional cooling methods are insufficient to meet the rising power dissipation capacities of new electronic components, leading to reduced performance and shortened operational lifespans due to high operating temperatures. Methods that can be considered to improve heat transfer from electronic components include using a different coolant, using a coolant at a lower temperature, increasing the coolant flow rate, or increasing the heat transfer surface area.

When considering the methods mentioned above, using a coolant at a lower temperature is often not feasible, as the coolant is typically either ambient air or derived from a cooling system. While increasing the coolant flow rate is somewhat possible, it is generally not preferred because it usually results in system expansion. Increasing the heat transfer surface area appears to be the best option. One of the best methods for enhancing the surface area of heat transfer is the use of metal foams. Because of their surface area-to-volume ratio, which can reach up to $10,000 \text{ m}^2/\text{m}^3$, metal foams have significant potential for improving heat transfer. Additionally, because of their structure, metal foams can cause turbulence by mixing the flow, which can increase the heat transfer coefficient. Metal foams can be soldered to cooling surfaces to minimize thermal contact resistance while not significantly increasing weight due to their high porosity.

Metal foams' high porosity and light structure give them a high surface area-to-volume ratio, but they also make it challenging to transport heat from the heat source along the foam's height. In this research, after validating the numerical modeling of metal foams with experimental studies from the literature, the effect of metal fins in mitigating the mentioned disadvantage of metal foams was examined for cases where water and air were used as the cooling fluids.

1.1. Literature Review

Numerous studies have shown that metal foams, together with their great surface-to-volume ratios, considerably improve heat transfer. Both experimental and numerical techniques have been used to investigate how metal foam parameters affect heat transfer. This section discusses a few of these studies.

Hunt and Tien [1] examined the thermal dispersion effects during forced convection in fibrous materials and discovered that the heat transfer coefficient was enhanced with flow rate. The study further demonstrated that the thermal dispersion effect becomes much more pronounced in flows with high Peclet numbers. Additionally, they provided an empirical expression for the thermal dispersion coefficient.

Calmidi's doctoral thesis [2] assessed the flow and heat transfer capabilities of highly porous metal foams both experimentally and numerically. The study examined how metal foams' cell size and porosity (85–97%) affected both heat transfer and flow resistance. Empirical equations were proposed for parameters such as effective thermal conductivity, solid-liquid interface heat transfer coefficient, surface area density, form coefficient, and

permeability, which are required for the usage of metal foams in porous media modeling. Additionally, the study includes a section where the metal foams use with fins is evaluated numerically.

Calmidi and Mahajan [3] conducted a study to examine the effective thermal conductivity of highly porous metal foams. Their experimental investigation demonstrated that both solid material and air-filled pores influence thermal performance. Additionally, they suggested an algorithm based on the metal foam porosity to calculate the effective thermal conductivity. In another study by Calmidi and Mahajan [4], it was shown that as the flow rate increases, convective heat transfer increases significantly, albeit at the expense of higher pressure drops. They also proposed a relation for dispersion thermal conductivity in the study.

Boomsma et al. [5] examined the compact heat exchangers with metal foams in using both experimental and numerical methods, it was shown that efficient heat transfer in small volumes can be achieved thanks to their high surface area. DeCroot et al. [6] numerically analyzed metal foam heat sinks with fins and found that the addition of fins improved thermal performance under airflow.

Guarino et al. [7] had experimentally evaluated the thermal behavior of open-cell aluminum foams under air flow. They found that higher flow rates significantly increased heat transfer performance.

Ranut [8] reviews and refines empirical and analytical models for predicting the effective thermal conductivity of aluminum metal foams. The paper focuses on models for high-porosity foams (porosity > 0.89), which use water and air as working fluids and have been validated with experimental data. To improve the precision of thermal conductivity predictions, it finds flaws in the current correlations and adds calibrated empirical constants. In order to better match model predictions with experimental observations, updated mathematical formulations are also suggested. The study's conclusion, which emphasizes the importance of porosity and structural features in the thermal design of foam-based heat exchangers, is that complicated theoretical models are not always more accurate than empirical models with fitted parameters.

Mahjoob and Vafai [9] synthesized the thermal transport and fluid models of metal foam heat exchangers and demonstrated that optimizing the relationship between porosity and flow rate provides higher efficiency.

Zhao [10] made a review study examining the effects of highly porous open-cell metal foams on heat transport with liquid and gaseous fluids and emphasized that low-density foams offer energy efficiency. Mancin et al. [11] examined the effect of height difference on heat transfer of aluminum foams with a density of 20 ppi and found that convective heat transfer improved as the foam height increased.

Kim et al. [12] investigated the usage of metal foams in LNG regasification systems and demonstrated that these materials provide high performance even at low

temperatures. Bayomy et al. [13] analyzed the metal foam heat sinks performance using water flow in electronic cooling systems with experimental and numerical methods, finding that cooling efficiency was improved because of the high surface area.

Kemerli [14] investigated the heat transfer and flow performance of various cellular metallic structures, including Kagome structures, using numerical methods. In the study, which used air as the working fluid, it was proven that heat transfer performance can be increased by adding fins to metal foams. Additionally, the effects of various pore structures and flow rates on pressure drop and heat transfer were evaluated. The importance of balancing pressure drop and thermal performance enhancements in the use of cellular metal structures was highlighted in the study.

Angirasa [15] investigates forced convection numerically in metallic fiber materials used in high-performance heat spreaders. The study forecasts the effects of thermal dispersion and examines the impact of Reynolds and Darcy numbers on heat transport. The results demonstrate that the rate of heat transfer is significantly influenced by fiber thickness, with rising Reynolds numbers enhancing the heat transfer only up to a certain point.

Odabae and Hooman [16] evaluates the possible use of metal foams for thermal regulation in fuel cells. Findings demonstrate that air-cooled fuel cell systems employing metal foam heat exchangers can attain comparable heat dissipation with only half the pumping power required by water-cooled systems. The research indicates that metal foams provide structural and thermal benefits, offering lightweight and efficient fuel cell configurations.

Bhattacharya and Mahajan [17] examines buoyancy-driven convection in metal foam heat exchangers which have different pore densities. It shows that although heat transfer decreases at high pore densities because to higher air friction, it increases with increased porosity. Additionally, adding fins enhances heat transfer; however, as the number of fins increases, decreased benefits become apparent, suggesting an optimal number for efficiency.

Chen et al. [18] investigated the hydraulic and thermal performance of double-pipe heat exchangers consisting of metal foams. The use of metal foam significantly enhances heat transfer by increasing surface area and augmenting fluid mixing through tortuous flow paths. It was indicated that metal foams may lead to an increased pressure drop as a result of elevated flow resistance within the porous structure. Especially in applications with restricted pumping power or space, the authors outline that pore density is essential for maintaining a balance between heat transfer and pressure decrease.

Dai et al. [19] studied metal foam heat exchangers in comparison to conventional multilouver heat exchangers. Results of the study indicate that metal foam heat exchangers exhibit thermal performance similar to that of multilouver heat exchangers, despite their more straightforward design. Aluminum foams enhance heat

transfer efficiency by augmenting the effective surface area for heat exchange. It was stated that metal foam heat exchangers possess reduced size and weight, rendering them suitable for compact and lightweight cooling applications. The increased pressure drop through metal foam structures creates a challenge. The study indicates that high heat transfer rates can be maintained while reducing flow resistance through the use of thinner foam layers and improved pore configurations.

De Jaeger et al. [20] evaluate the effects of four bonding techniques—brazing, co-casting, epoxy bonding, and press-fit—on the thermal contact resistance (TCR) of open-cell aluminum foams. Experimental study reveals that the bonding method markedly affects thermal performance, with brazing resulting in the lowest thermal contact resistance (TCR) and press-fit yielding the greatest. The findings underscore the necessity of reducing TCR to enhance heat transfer efficiency in thermal applications.

Dukhan [21] determines pressure drops in open-cell aluminum foams under varying flow conditions. It is found that foams with lower porosity exhibit superior thermal performance, which makes them more appropriate for compact heat exchangers with airflow applications, despite the fact that they result in higher pressure drops.

Feng et al. [22] investigate finned metal foam heat sinks experimentally and numerically under impinging air jet cooling. The results show that finned metal foam performs better at transferring heat than ordinary metal foam, particularly at higher Reynolds numbers.

Open-cell aluminum foams' thermal performance under forced convection with a constant heat flux was investigated by Dukhan et al. [23]. Their findings indicate that the thermal entry length within these metal foams exceeds the predictions of conventional flow models, implying that traditional approaches might undervalue the required size of heat exchangers. The study also highlights how crucial it is to take non-Darcy flow phenomena into consideration when designing metal foam heat exchangers, especially at high Reynolds numbers. Furthermore, the study shows that although open-cell aluminum foams have a higher surface area and hence provide better thermal performance, this increased heat transfer efficiency is accompanied with higher pumping power requirements.

Edouard et al. [24] provide a comprehensive review of pressure drop models in metal foams, analyzing key structural parameters including pore size, strut diameter, and porosity. The study highlights the significance of permeability in the design of foams for catalytic applications and identifies inconsistencies across existing literature. The authors argue that in order to increase foam-based system performance and optimization, improved models are required.

In metal foam strips with internal heat generation, Hetsroni et al. [25] investigate natural convection. According to their research metal foams can enhance heat transfer by a factor of up to 20 compared to flat plates,

attributed to their large surface area and improved fluid mixing. Additionally, infrared imaging reveals notable non-equilibrium effects between the solid matrix and the surrounding fluid.

In their investigation of natural convection in water-saturated copper foams, Kathare et al. [26] find that conduction is the main mechanism driving heat transfer in metal foams, with convection only becoming more significant at larger Rayleigh numbers. The study emphasizes the potential of metal foams to better thermal management through improved heat transfer mechanisms and provides insightful information on their use in energy storage system design.

Kim et al. [27] compare the performance of porous metal fins with conventional louvered fins in heat exchanger applications. Their analysis shows that while porous fins provide superior structural strength and are easier to manufacture, louvered fins result in lower pressure drops. Besides, the study provides design correlations to help optimize heat exchangers with porous fins, properly balancing pressure drop and performance constraints.

For metal foam heat exchangers, Mahjoob and Vafai [28] provide a synthesis of fluid and thermal transport models. The study looks at the relationship between overall performance and structural characteristics such as fiber diameter, pore size, and porosity. The authors also present a performance factor that maintains a compromise between pressure drop and heat transfer, showing that foam-filled heat exchangers are more efficient and compact than traditional designs.

Mancin et al. [28] examine pressure drops during airflow through six different aluminum open-cell foams with varying porosity and pore density. According to the study, increased pore densities lead to bigger pressure drops, whereas larger pore sizes improve permeability. The authors also offer a novel pressure drop model, which is validated by comparisons with experimental data and prior models.

Mancin et al. [30] investigate the thermal and hydraulic performance of aluminum open-cell foams under forced air convection. The study reveals that foams with higher pores per inch (PPI) enhance heat transfer but result in increased pressure drops, potentially raising energy consumption. Lower PPI foams, on the other hand, are better suited for applications requiring less flow resistance since they show lower pressure drops at the expense of less effective heat transmission. Furthermore, the study reveals that while raising the foam height enhances heat transfer, but the effect diminishes beyond a certain threshold.

Mancin et al. [31] investigate the effect of foam height on aluminum foam heat transfer performance. Taller foam samples improve heat transfer, but this improvement diminishes beyond a certain height, according to their findings. The study provides insightful information about how to enhance heat exchanger performance by optimizing foam height.

Noh et al. [32] evaluate non-Darcy flow and heat transmission in an annulus filled with aluminum foam.

Their results demonstrate that, within laminar flow utilizing an empty annulus, aluminum foam improves the transfer of heat. The study also provides correlations for friction factors and Nusselt numbers.

Salas and Waas [33] investigate convective heat transfer in metal foam sandwich panels, focusing on their potential applications in hypersonic and re-entry vehicles. According to the experimental findings, heat transfer is improved by increasing foam thickness, while the improvement reaches a plateau for thicker foams. Furthermore, a finite element model forecasts the panels' performance with high accuracy, which is consistent with the experimental results and confirms the model's reliability.

Sertkaya et al. [34] investigate the design and thermal performance of open-cell aluminum foam heat exchangers through Artificial Neural Network (ANN) modeling. In order to calculate key parameters such as the Reynolds number (Re), Nusselt number (Nu), pressure drop (ΔP), and friction factor, aluminum foams with pore densities of 10, 20, and 30 PPI were examined under various airflow rates. The results show that while higher PPI foams improve heat transfer, they also result in larger pressure decreases. Following training on experimental data, the ANN model showed a strong correlation ($R = 0.98614$) with the results of the experiment, demonstrating its capacity to predict performance with high accuracy. The study emphasizes the trade-off between hydraulic resistance and heat transfer efficiency. It also shows that ANN-based modeling is a useful method for improving foam heat exchanger designs without the need for extensive experimentation.

In this study, numerical investigation of the effect of using metal foam and fins on heat transfer was conducted for two fluids: a low thermal conductivity fluid (air) and a high thermal conductivity fluid (water), considering the influence of fluid velocity. To the best of the author's knowledge, there is no study in the literature that numerically or experimentally examines the use of metal foam with fins in conjunction with water as the working fluid and compares it with air.

2. METHODOLOGY

2.1. Computational Fluid Dynamics Analysis in Porous Media

Since the flow analysis within the porous medium is conducted for a single phase, the continuity equation given in Equation (1) is used.

$$\varepsilon \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

In the momentum equation used for modeling the flow within the porous medium, there are two additional source terms compared to the momentum equation used for modeling flow in a homogeneous medium. The last two terms on the right-hand side of Equation (2) are source terms.

$$\rho \left[\frac{1}{\varepsilon} \frac{\partial \vec{v}}{\partial t} + \frac{1}{\varepsilon^2} (\vec{v} \nabla \vec{v}) \right] \quad (2)$$

$$= -\nabla p + \mu_e \nabla^2 \vec{v} - \frac{\mu}{K} \vec{v} - \frac{\rho F}{\sqrt{K}} |\vec{v}| \vec{v}$$

These terms define the intrinsic, non-external effects caused by the influence of the solid part on the flow. The third term on the right-hand side of the equation corresponds to the pressure loss due to viscosity, while the fourth term represents the loss associated with inertial drag.

The commercial software ANSYS Fluent (Version 2022 R1) includes a default porous medium model. This model solves the momentum equation using the source term given in Equation (3).

$$S_i = - \left(\sum_{j=1}^3 D_{ij} \mu v_j + \sum_{j=1}^3 C_{ij} \frac{1}{2} \rho |\vec{v}| v_j \right) \quad (3)$$

The negative sign at the beginning of this equation indicates the pressure loss, and the coefficients D_{ij} and C_{ij} are calculated using $1/K$ and $2F/\sqrt{K}$ respectively.

In the ANSYS Fluent software, for modeling heat transfer in porous materials, it is possible to assume either thermal equilibrium, where the solid and fluid are at the same temperature, or thermal non-equilibrium, where the solid and fluid can be at different temperatures.

In this study, it was assumed that the solid and fluid in the porous medium would not be in thermal equilibrium, and thus the thermal non-equilibrium porous medium assumption was made. In thermal non-equilibrium porous medium modeling, using a two-equation model allows for the calculation of different solid and fluid temperatures within the same unit volume. Equations (4) and (5) are used in this modeling approach.

$$\varepsilon \rho_f c_{p_f} \left[\frac{\partial T^f}{\partial t} + \vec{v} \cdot \nabla T^f \right] \quad (4)$$

$$= \nabla k_{eff}^f \cdot \nabla T^f + h_{sf} \sigma_{sf} (T^s - T^f)$$

$$(1 - \varepsilon) \rho_s c_s \frac{\partial T^s}{\partial t} = \nabla k_{eff}^s \cdot \nabla T^s \quad (5)$$

$$- h_{sf} \sigma_{sf} (T^s - T^f)$$

In these equations, the superscript f represents the fluid, while the superscript s represents the solid. The term h_{sf} denotes the heat transfer coefficient between the fluid and the solid, and σ_{sf} indicates the surface area density.

The solid effective thermal conductivity and fluid thermal conductivity can be calculated using Equation (6) according to Calmidi and Mahajan [3]. The solid thermal conductivity has been set to zero for the fluid effective conductivity, and the fluid thermal conductivity

is adjusted to zero for the solid effective conductivity calculation. Calmidi and Mahajan [4] provide the surface area density in Equation (7).

$$k_e \quad (6)$$

$$= \left\{ \frac{2}{\sqrt{3}} \left[\frac{r \left(\frac{b}{L} \right)}{k_f + \left(1 + \frac{b}{L} \right) \frac{(k_s - k_f)}{3}} \right. \right.$$

$$+ \frac{(1-r) \left(\frac{b}{L} \right)}{k_f + \frac{2}{3} \left(\frac{b}{L} \right) (k_s - k_f)}$$

$$\left. + \frac{\frac{\sqrt{3}}{2} - \frac{b}{L}}{k_f + \frac{4r}{3\sqrt{3}} \left(\frac{b}{L} \right) (k_s - k_f)} \right\}^{-1}$$

$$\frac{b}{L} = \frac{-r + \sqrt{r^2 + \frac{2}{\sqrt{3}}(1-\varepsilon) \left[2 - r \left(1 + \frac{4}{\sqrt{3}} \right) \right]}}{\frac{2}{3} \left[2 - r \left(1 + \frac{4}{\sqrt{3}} \right) \right]}$$

here $r = 0.09$

$$\sigma_{sf} = \frac{3\pi d_f}{(0.59d_p)^2} \left[1 - e^{-(1-\varepsilon)/0.04} \right] \quad (7)$$

Calmidi and Mahajan [4] have also proposed Equation (8) for the heat transfer coefficient between the fluid and the solid.

$$Nu_{sf} = \frac{h_{sf} d_f}{k_f} = C_T Re_{df}^{0.5} Pr^{0.37} \quad (8)$$

$$= 0.52 \sqrt{\frac{u d_f}{\varepsilon \nu}} Pr^{0.37}$$

In this equation, d_f represents the diameter of the metal foam fibers. Calmidi and Mahajan [4] also noted in their study that heat transfer in metal foams increases due to advection. They mentioned that this effect is negligible in flows with low Péclet numbers, whereas in flows with high Péclet numbers, the contribution of advection becomes significant. In the same study, the dispersion conductivity is provided in Equation (9), and the steady-state energy equations are given in Equations (10) and (11).

$$\frac{k_d}{k_e} = C_D (Re_K Pr_e) \frac{U}{U_0} \quad (9)$$

$$0 = \frac{\partial}{\partial x} \left(k^{se} \frac{\partial T^s}{\partial x} \right) + \frac{\partial}{\partial y} \left(k^{se} \frac{\partial T^s}{\partial y} \right) - h_{sf} \sigma_{sf} (T^s - T^f) \quad (10)$$

$$(\rho C_p)^f \frac{\partial T^f}{\partial x} = \frac{\partial}{\partial x} \left((k^{fe} + k^d) \frac{\partial T^s}{\partial x} \right) \quad (11)$$

$$+ \frac{\partial}{\partial y} \left((k^{fe} + k^d) \frac{\partial T^s}{\partial y} \right)$$

$$+ h_{sf} \sigma_{sf} (T^s - T^f)$$

2.2. Validation Study

In this study, a validation effort was first conducted to compare the results obtained from the ANSYS software simulation of flow within metal foam. For validation purposes, the test setup shown in Figure 1, established in Kemerli U.'s doctoral thesis [14], was modeled using ANSYS software. As specified in the referenced study, the channel height was taken as 45 mm, the width as 63 mm, and the length where heat flux was applied as 114 mm. There is a metal foam section 55 mm before and 27 mm after the region where the heat flux is applied. Additionally, to avoid inlet-outlet effects that could occur before and after the metal foam section, the computational domain was extended by 40 mm on both sides.

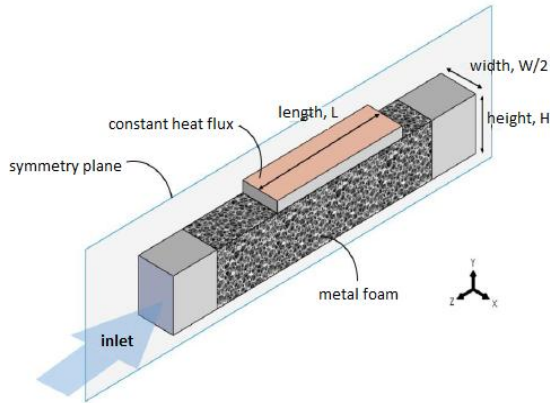


Figure 1. Test setup referenced in the validation study [14]

In the prepared validation model, a constant heat flux of 1500 W/m² was applied from the top of the plate over the metal foam in accordance with the reference study, while the remaining areas were assumed to be adiabatic. The thickness of the plate where the heat flux was applied was selected as 9.5 mm to ensure compatibility with the experimental study. The inlet air temperature was set at 30°C, and its specific heat capacity was 1006 J/kg·K, density was 1.1649 kg/m³, viscosity was 1.868e-5 kg/m.s, and thermal conductivity was 0.026341 W/m·K. As in the reference study, aluminum was used as the material for the metal foam and the channel, with a thermal conductivity of 218 W/m·K.

There are 2.63 million mesh elements in the test setup's mesh structure, as seen in Figure 2. The mesh's maximum aspect ratio was 21 and its minimum orthogonal quality was 0.10.

In the analysis, the fluid velocity was characterized as rising in increments of 0.25 m/s from 0.5 m/s to 5 m/s.

Table 1 lists the characteristics of the metal foams utilized in the reference study. Figure 3 shows the Fluent software interface's specification of the metal foam qualities.

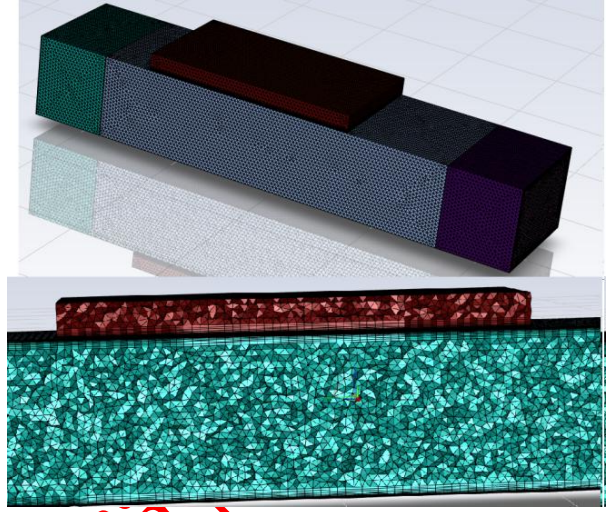


Figure 2. Mesh structure of the modeled test setup

Table 1. Properties of metal foam provided in the study by [2]

Porosity	PPI	Fiber Diameter (mm)	Pore Diameter (mm)	F	K (10 ⁷ m ²)
0.9005	20	0.35	2.58	0.088	0.9

Figure 3 demonstrates the process of inputting the D_{ij} and C_{ij} coefficients derived from Equation (3), the α_{sf} coefficient from Equation (7), the h_{sf} coefficient from Equation (8), along with the porosity of the metal foam, into the Fluent software interface for porous media modeling.

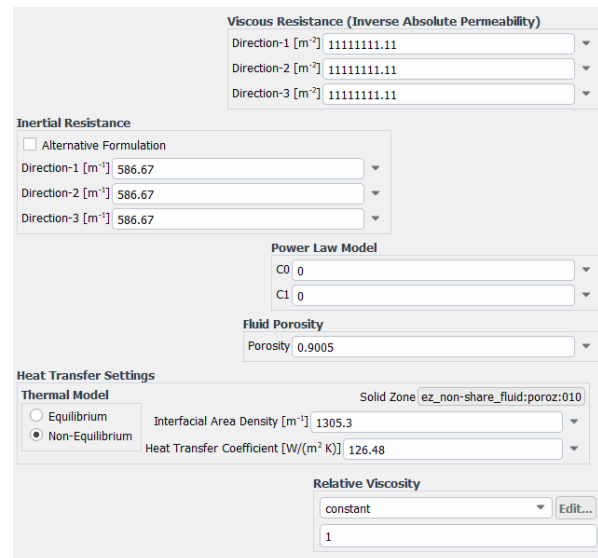


Figure 3. Fluent parameters for refrigerant at 0.5 m/s air

Along with the "Coupled" method for pressure-velocity coupling and a second-order discretization technique for the discretization of momentum, energy, k , and epsilon equations, the Realizable k -epsilon turbulence model and for walls Enhanced Wall Treatment were employed. Adiabatic boundary conditions were applied to all external walls except the wall where the heating load is defined.

The Nusselt numbers obtained from the analyses conducted with different air velocities were compared with the values from the study by Calmidi and Mahajan [4]. The Nusselt number here was calculated along the length of the porous medium, and the effective thermal conductivity calculated using Equation 6 was taken as the thermal conductivity. When calculating the Reynolds number, the square root of the permeability was used as the characteristic length. Figure 4 shows the comparison of the experimental and numerical results of Calmidi and Mahajan [4] with the results obtained in this study.

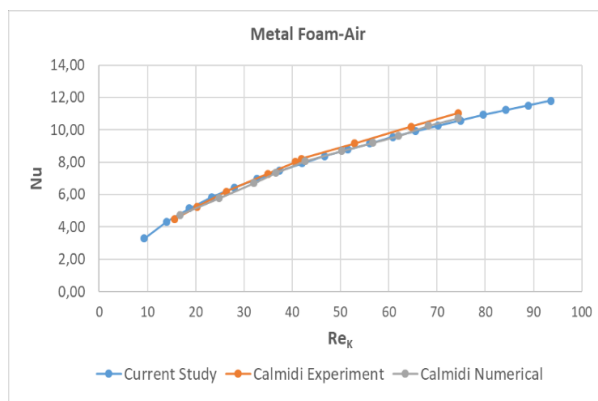


Figure 4. Comparison of analysis results with [5] - For air

Calmidi did not conduct experiments with water in his study [2], but developed the correlation in Equation 9 for dispersion conductivity using the data from the study by Hunt and Tien [1]. Figure 5 shows the comparison of the analysis results obtained for the H4 metal foam with the experimental results of Hunt and Tien [1] and the numerical results of Calmidi [2].

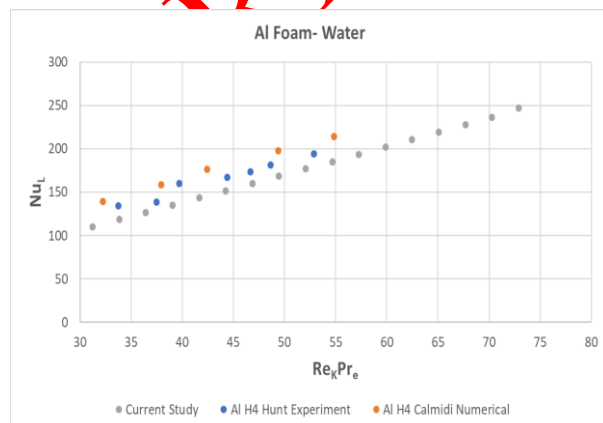


Figure 5. Comparison of analysis results for metal foam H4 with the experimental results of [1] and the numerical results of [2] - For water

2.3. Use of Metal Foams with Fins

In the study by Calmidi [4], empirical equations to determine the parameters of metal foams were proposed by conducting experiments with metal foams and air. In this study, based on Calmidi's work, the test setup which used in the study was modeled, and one of the metal foams used in that study, with a porosity of 0.9005 and a pore density of 20 PPI, was selected for use in this research. The metal foam was placed in a channel with a width of 40 mm, a height of 25 mm, and a length of 80 mm for validation purposes. A 100 mm gap was left at both the inlet and outlet of the foam to allow for flow development in the model. The heat load was defined as 50 W when air was used as the coolant, and 250 W when water was used. As shown in Figure 6, one to four fins were attached to the metal foam to enhance its heat transfer capability. The thickness of each fin was set to 2 mm.

Figure 7 shows the temperature difference between the heater surface and the coolant inlet for configurations with no fins, one fin, two fins, three fins, and four fins, using air as the coolant. The results indicate that at low Reynolds numbers, the impact of fin usage is minimal. However, as air velocity increases, the fins' efficiency becomes more evident. Adding a second fin increases the heat transfer of the metal foam, though its effect is less significant than the first fin. The addition of a third and fourth fin yields diminishing improvements, with little noticeable difference between the two.

Figure 8 shows the ratio of heat transferred from the heater surface to the metal foam relative to the total heat when air is used as the coolant. In the absence of fins, nearly all the heat is transferred directly to the metal foam and then dissipated to the air. When fins are added, a portion of the heat is transferred to the metal foam via the fins.

Figure 9 presents the temperature differences when water is used as the coolant. In this case, the effect of fin usage is more significant at low Reynolds numbers, but diminishes as water velocity increases. The addition of a second fin enhances the performance of the metal foam, but its effect is less significant than the first fin. The addition of a third and fourth fin results in diminishing returns, similar to the air-cooled case.

Figure 10 shows that the amount of heat transferred from the base increases as water velocity increases. Figure 11 demonstrates that the amount of heat transferred from the base to the metal foam decreases with increasing water velocity, and the rate of this decrease becomes steeper with fewer fins.

Figure 12 displays the ratio of heat dissipated via the base and fins through the metal foam. These results indicate that as water velocity increases, the advection effect allows the heat to be transferred directly to the water without being conducted through the metal foam. Additionally, despite a reduction in the amount of heat transferred to the metal foam at the same water velocity with added fins, the base temperature is observed to decrease. This suggests that the fins not only transfer heat

to the water but also allow for more efficient conduction throughout the height of the metal foam.

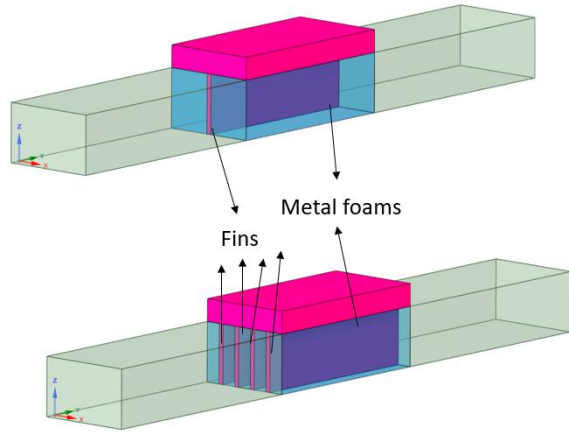


Figure 6. Addition of 1 fin and 4 fins to the metal foam

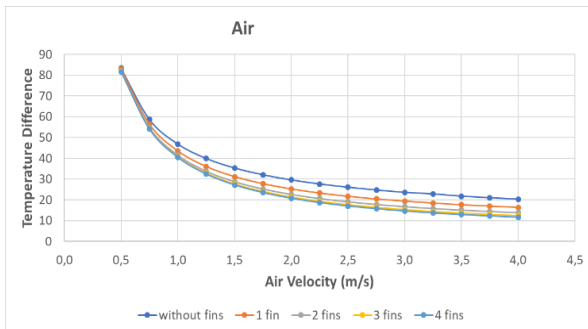


Figure 7. Temperature difference with addition of 1, 2, 3, and 4 fins to the metal foam – air

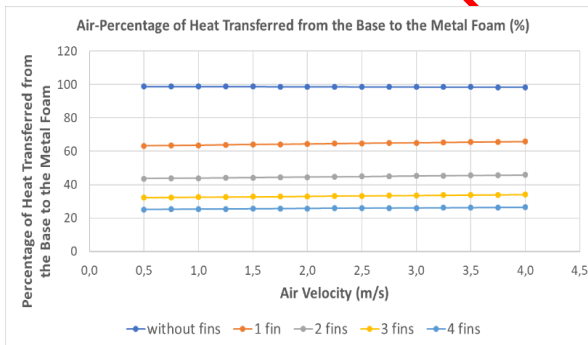


Figure 8. Percentage of heat transferred from the base to the metal foam with 1, 2, 3, and 4 fins added – air

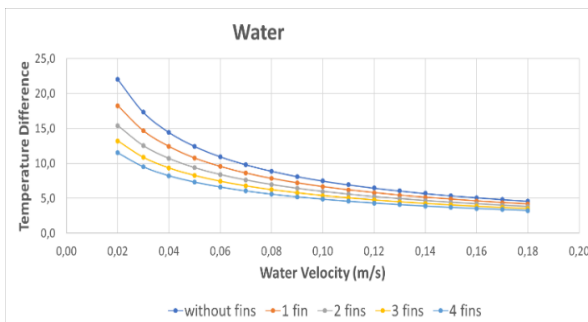


Figure 9. Temperature difference with 1, 2, 3, and 4 fins added to the metal foam - water

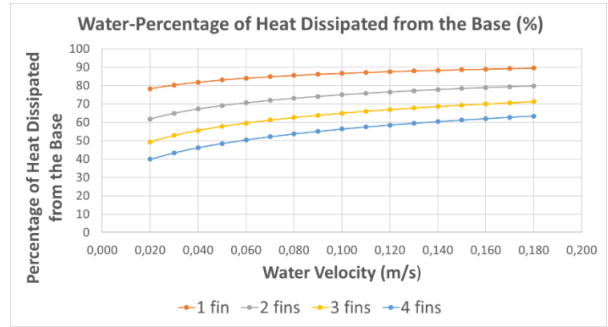


Figure 10. Percentage of heat dissipated from the base for metal foam with 1, 2, 3, and 4 fins added - water

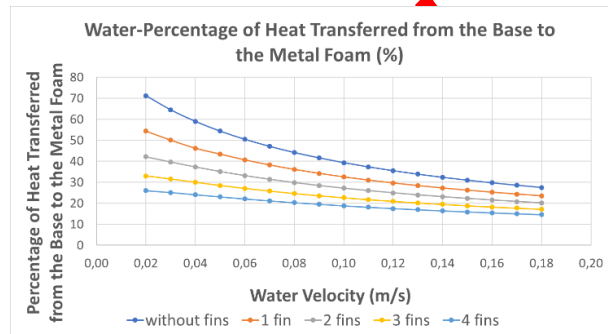


Figure 11. Percentage of heat transferred from the base to the metal foam with 1, 2, 3, and 4 fins added – water

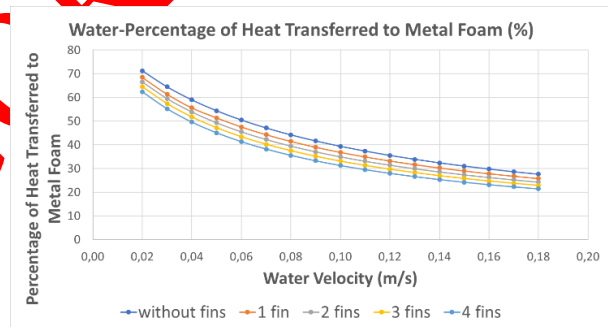


Figure 12. Percentage of heat transferred to metal foam with 1, 2, 3, and 4 fins added-water

3. RESULTS AND DISCUSSION

The small weight and high surface-to-volume ratios of metal foams with high porosity offer great promise for enhancing heat transfer. This study examined the heat transfer performance of metal foams separately for situations in which fins were utilized with air and water as the working fluids.

The results indicate that in cases where the fluid is air, adding fins provides the lowest performance enhancement at low air velocities, while as the air velocity increases, the addition of fins significantly enhances the rate of heat transfer. Conversely, when water is used as the working fluid, adding fins enables a higher rate of heat transfer at low water velocities, although this rate of increase diminishes as the water velocity rises.

The concept of using fins with metal foams arises from the inability of the foams to effectively transmit the heat they draw from the heat source over their height. At low

air velocities, heat cannot be effectively extracted through the metal foam fibers, allowing the foam to transport the heat it receives more efficiently along its height. Therefore, it is assessed that the use of fins would be less beneficial at low air velocities. As the air velocity increases, more heat will be drawn through the fibers, which will then be less effective in transmitting heat over the height of the foam. In such scenarios, the use of fins contributes to the transmission of heat drawn from the heat source along the height of the metal foam. Hence, as air velocities increase, it becomes possible to achieve more effective heat transfer through the use of fins.

In cases where water is used as the working fluid, the metal foam can only transport the heat it receives from the source over very short distances due to the small fiber diameters. In other words, a significant portion of the height of the metal foam remains unused. As a result, the use of fins at low velocities facilitates a higher rate of heat transfer, enabling improvement. However, as water velocities increase, the effectiveness of the fins decreases because the thickness of the fins begins to become insufficient to carry the heat further.

SYMBOLS

d_f	Fiber diameter [m]
d_p	Pore diameter [m]
h_{sf}	Solid-fluid interfacial heat transfer coefficient [W/mK]
F	Form factor
k_f	Thermal conductivity coefficient of fluid [W/mK]
k_s	Thermal conductivity coefficient of solid [W/mK]
k_e	Effective thermal conductivity coefficient [W/mK]
K	Permeability [m ²]
Nu_{sf}	Nusselt number between solid and fluid
Pr_e	Effective Prandtl number [$\mu_p k_e$]
Re_K	Reynolds number [$\sqrt{V\rho K/\mu}$]
ε	Porosity
ρ	Density [kg/m ³]
μ	Dynamic viscosity [kg/ms]
σ_{sf}	Surface area per unit volume [m ⁻¹]

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Orkun DOĞU: Contributed to the numerical analysis, data collection, and writing of the article.

Abdullah Berkan ERDOĞMUŞ: Contributed to defining the content of the study, drafting the outline, and evaluating the results.

İlhami HORUZ: Contributed to defining the content of the study, drafting the outline, and evaluating the results

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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