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NUMERICAL INVESTIGATION OF HEAT TRANSFER IN METAL FOAM HEAT SINKS EMBEDDED WITH POROUS MEDIA UNDER FORCED CONVECTION

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Keywords

Heat Transfer, Porous Media, Heat Sink, Metal Foam, Forced Convection.

Abstract

This study discusses metal foam heat sinks under forced convection using porous media. Parameters such as porosity, pore density, and Reynolds number were studied, indicating enhanced thermal performance compared to solid heat sinks due to greater surface area and turbulence. Metal foams increase heat dissipation, and hence they are suitable for cooling electronics, automotive systems, and renewable energy equipment. The results offer engineers improved design considerations for high-performance thermal management. Experimental validation of the results and the search for improvements through nano-engineered foams are recommended for future work.

1. INTRODUCTION

This article begins by reviewing secondary numerical data and methodologies used to study heat transfer in metal foam heat sinks under forced convection. It then analyzes key parameters

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influencing thermal performance and compares findings across studies. Finally, the article concludes with insights, practical implications, and recommendations for future research.

The primary aim of this article is to analyse secondary numerical data to evaluate heat transfer performance in metal foam heat sinks embedded with porous media under forced convection. The intention is to explore, utilizing secondary numerical data, the thermal performance of metal foam heat sinks with porous media under convection forced conditions. In particular, it will investigate how design factors, including porosity, pore density, and Reynolds number influence heat transfer performance and pressure drop phenomenon. Moreover, the study aims to assess their thermal performance against conventional solid and upset heat sinks. It will also identify typical numerical modelling methods and related limitations, as well as reveal any design considerations useful for future thermal management projects for high-performance applications.

2. REVIEW OF LITERATURE

Effective heat transfer management is a focal issue in electronics and thermal systems, particularly with the rise of device miniaturization and high heat fluxes that bring added operational complexity. Heat sinks are traditionally made up of metal fins and fans, which play a pivotal function in cooling CPU, GPU, power electronics, and high-performance systems (Gurav et al. 2023). Conventional designs are actually becoming ever more restricted by reduced surface area, pressure drop increase, and inefficiencies in low-localized thermal loads dissipation.

Open-cell aluminum or copper metal foams have broad applications in heat sink structures due to their elevated porosity and surface area (Li et al. 2021). Porosity is from 85–98 %, with pore densities of 5–40 PPI, having enhanced fluid mixing albeit increased pressure drop (Epple 2020). Their structure offers hundreds to thousands of m^2/m^3 surface area, ensuring intense convective interaction (Mancin et al. 2011). These foams are integrated into heat sinks and enhance turbulence, boundary layer minimization, and thermal homogeneity (Li et al. 2021).

Simulation of heat transfer in these types of systems commonly depends on extended Darcy–Brinkman–Forchheimer formulations, which supplement standard Darcy's law by adding viscous and inertial terms to account for transitional and non-linear regimes in porous media (Ranjbarzadeh and Sappa 2025). The governing momentum equation in the porous domain is usually of the form:

$$-\beta\nabla^2 u + \mu/K\, u + \rho/K_1\, |u|u = -\nabla p$$

where KKK is intrinsic permeability, K1K_1K1 is Forchheimer inertial coefficient, β\\betaβ is effective viscosity due to Brinkman correction, μ\\muμ is dynamic viscosity, ρ\\rhoρ is fluid density, and ppp is pressure. Energy transport is modeled through an energy equation—sometimes with local thermal equilibrium (LTE) or using local thermal non-equilibrium (LTNE) two phase models, which solve fluid and solid temperature fields independently for higher accuracy (Yi et al. 2021).

The principal parameters impacting forced convective heat transfer in metal foams include porosity, pore density, Reynolds number, and material thermal conductivity. Porosity (0.85–0.98) impacts fluid access and area while minimizing pathways of conductive solid material (Hassan et al. 2023). Pore density can vary with a ~10 to 40 PPI; higher PPI can increase surface area and allow for greater heat transfer, but generally a greater pressure drop will occur (Nanda et al. 2024). Reynolds number, can advance from tens to thousands, will define the flow regime and be related to Nusselt number increases, especially beyond Re ≈ 10–100 (Yi et al. 2021). A higher thermal conductivity material, such as copper, will continue to improve conduction in a foam as it can better facilitate heat spreading and minimize gradients (Amoli et al. 2022).

In forced convection, external fans or pumps push fluid thorough or across porous media. The flow velocity and channel geometry (e.g. parallel plate, tube, slot) affects convective heat transfer rates and pressure drop trade-offs. Typical study of heat exchange in forced convection systems can be simulated using finite volume or finite element CFD codes, idealized unit cell models, or volume averaged porous media approaches to analyse temperature distribution, pressure drop, and Nusselt number variation as functions of design parameters (Lu et al. 2024).

As per Babar et al. (2023) traditional heat sinks often have limitations such as low surface area and low heat dissipation due to high thermal loads, especially in smaller electronic systems. Embedding metal foams with porous media promotes better convective heat transfer through increased surface area, turbulence, and thermal uniformity. Nevertheless, there exists a gap in the literature where comprehensive numerical studies address forced convection in hybrid porous structures, and research on parameter optimization and predictive modelling for high performance thermal management applications in electronic and energy systems has not been conducted.

The survey of literature brings to light a lack of research on hybrid porous structures integrating metal foams with nano-enhanced or graded porosity designs. Current research pertains to independent parameters (porosity, PPI, Re) and not integrated optimization. Transient thermal analysis and two-phase flow simulations are also lacking, which hinders real-life applicability. These lacunae match the use of secondary data in the methodology, where the scope for integrating experimental and numerical methods in the future lies.

3. METHODOLOGY

To study the behaviour of heat transfer in porous medium-embedded metal foam heat sinks in forced convection applications, the study has chosen a qualitative secondary research process to enhance the capability of the study. Rather than conducting primary experiments or simulations, numerical data from peer-reviewed literature have been gathered and synthesised with this research to develop meaningful discussion and key trends in the thermal performance of systems.

4. RESEARCH APPROACH

The collected and secondary research methods explore the computational and numerical simulation data of porous media and metal foam heat sinks, which have been published (Li and Yang 2023). Strikingly, it has been used very positively in analysing a very large number of academic materials, as a lot of modelling and experimentation has already occurred. This method was also very easily accessed and enabled the conceptualisation of more than one academic piece with varying configurations, materials and boundary conditions, therefore, giving a more globalised perspective with regard to the performance of the system overall. Also, this is a very cost-efficient way to start any study, provided you do not have access to any laboratory or necessary simulation software straightway. The use of good data published from reputable sources and well-thought-out literature can enhance and bolster the confidence in the conclusions drawn.

4.1 Data Collection

The information used in this study was collected from various known sources of peer-reviewed journal articles, including International Journal of Heat and Mass Transfer, Applied Thermal Engineering, and Energy Conversion and Management. The article selection process relied on an initial set of criteria. The studies must have been published between 2005 and 2025, and they assessed forced convection through porous metal foams, and they had to have utilised modelling approaches either numerically or using a computational fluid dynamics (CFD) program (Lobe et al. 2020). Relevant articles were identified through keyword searching and database filtering, mainly focused on research articles that reported numerical values from the stated parameters, which included heat transfer coefficients, Nusselt numbers, thermal conductivities and pressure drops in metal foam geometries.

4.2 Data Analysis and Thematic Framework

Thematic analysis was used to analyse and interpret the secondary data (Lochmiller 2021). Once relevant results were acknowledged, data were coded according to repeating thermal and fluidic parameters, for instance, porosity, pore density (PPI), Reynolds number, and material composition (e.g. copper versus aluminium foams). Performance measures, including Nusselt number, thermal resistance, and pressure drop, were taken as references. Overall comparative tables and graphical plots allowed trends to be seen amongst studies, as well as synthesising results into sensible design meanings. Please see the Comparisons & Analysis section for more in-depth detail.

4.3 Limitations

This investigation is limited to using secondary data, thereby limiting control over assumptions and simulation setups. There is an additional layer of variability from differences between turbulence models, geometries, and boundary conditions from one study to another that could affect both cross-comparability as well as interpretations of results.

5. FINDINGS AND ANALYSIS

5.1 Overview

The findings synthesizes a secondary data numerical study to assess the thermal performance of metal foam heat sinks with porous media under forced convection. The results are organized thematically, including comparisons of performance with traditional heat sinks, impact of porosity, pore density, and Reynolds numbers; the modelling approaches and implications for design. Diagrams are added to illustrate key trends in Nussle number, pressure drop and optimal ranges for each parameter, providing a complete picture of performance implications for applications requiring thermal management at higher performance standards.

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Theme 1: Comparative Thermal Performance of Metal Foam vs Conventional Heat Sinks

The experimental and numerical investigations invariably reveal that hybrid heat sinks based on metal foam or a combination of metal foam and fins (finned metal foam, FMF) perform better than conventional solid fin heat sinks when subjected to forced convection. In one CFD investigation of a copper foam fin heat sink, the Nusselt number was found to be raised by ~21.9% when foam thickness was increased from 10 mm to 40 mm, substantially enhancing heat transfer coefficients over corresponding conventional designs (Abdullah and Jubear 2022).

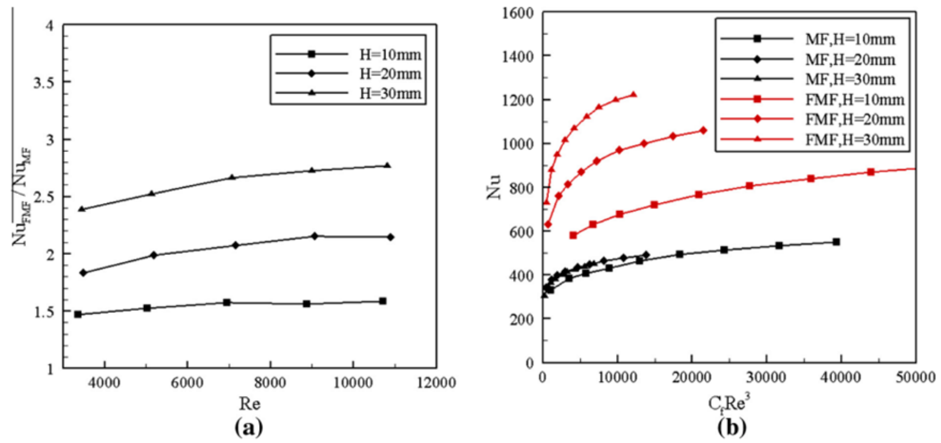

Figure 1: Comparison of thermal performance between MF and FMF heat sinks at: (a) fixed flow rate; (b) fixed pumping power (Source: Feng et al. 2014)

The experimental and numerical studies by Feng et al. (2014) revealed that finned metal foam (FMF) heat sinks had 1.5–2.8 times greater heat transfer rates than pure metal foam (MF) configurations under equivalent flow conditions, particularly with circular impinging jet cooling. The improvement comes about due to the synergy of foam-induced turbulence and fin surface area. Figure 1 illustrates the comparison between MF and FMF heat sinks and identifies the better thermal performance of FMF under both constant flow rate and pumping power constraints.

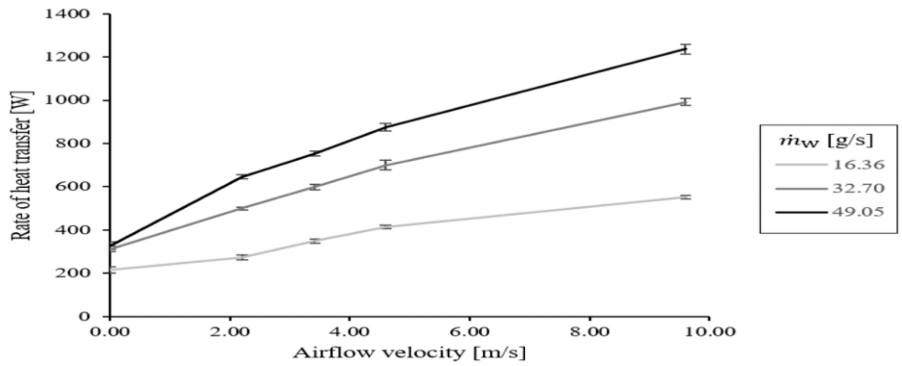

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Figure 2: Rates of heat transfer for an air-cooled aluminium-foam heat exchanger (Source: Fiedler et al. 2024)

Increased convective heat transfer in metal foam architecture is due to their high surface area, caused turbulence, and disruption of the boundary layer. Open-celled foams of ~90% porosity enhance good fluid mixing and recirculation, greatly enhancing heat exchange. Research finds 1.5–2.8× higher Nusselt numbers for finned foam heat sinks compared to foam-only architecture. Figure 2 demonstrates aluminium-foam heat exchangers performing better in heat transfer than non-foam equivalents, highlighting the impact of foam-created turbulence and enhanced contact area in favoring convective performance (Fiedler et al. 2024).

The improvement in convective heat transfer is mainly contributed by higher surface area, more turbulence and boundary layer disturbance in metal foam structures. Simultaneously, the uniformity of temperature in the base of the heat sink is also enhanced—experiments revealed base plate temperatures 1–1.5 °C lower in foam embedded sinks compared to solid fin blocks at the same airflow and heat flux (Ataer et al. 2020).

Theme 2: Influence of Porosity on Heat Transfer and Pressure Drop

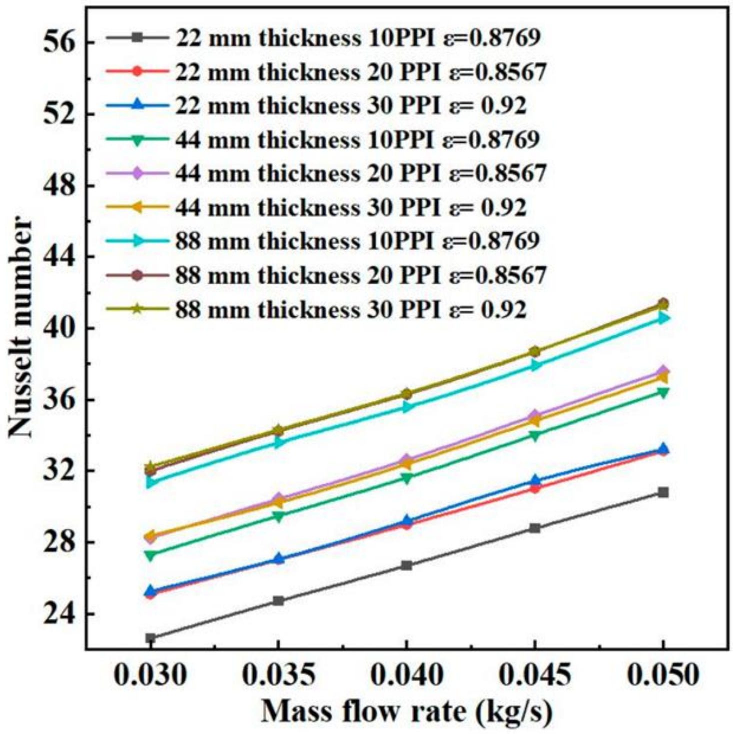

Figure 3: Variation of Nusselt number for different mass flow rates for different PPI and different thicknesses (Source: Diganjit et al. 2022)

The porosity values ranging from 0.85 to 0.98 significantly impact convective heat transfer and hydraulic resistance. In modeled solar-air heater channels, copper foam with ~0.8567 porosity exhibited better thermal-hydraulic performance—trading off high Nusselt number for moderate pressure drop—than higher-porosity configurations, particularly at moderate mass flow rates (performance factor maximized at porosity ≈ 0.8567 and 20 PPI (Diganjit et al. 2022). Likewise, panel-type radiator channel studies showed that reducing porosity (i.e. denser foam) had the effect of raising Nusselt number by 4.6–11.2%, although its impact on pressure drop differed between copper and aluminum based on changes in permeability (Si et al. 2025). Analytical modeling also proved that functionally graded foam—with decreased porosity closer to the wall and increased core porosity—maximized heat transfer at reasonable pressure penalty, achieving 20–50% improvement over uniform-porosity designs (Bai et al. 2023).

The more dense foam (lower porosity) increases the scaffold area per unit of volume, which increases interstitial turbulence and heat conduction into the fluid—while simultaneously reducing permeability and increasing hydraulic resistance. Alternatively, a high porosity will improve flow but decrease conductive paths through the solid part. The best performance will occur at moderate porosities (~very near to 0.85 - 0.90) where the thermal gain surpasses pressure drop losses. For solar-air and channel applications, porosity ranging from ~0.856 -0.90, and primarily in conjunction with moderate PPI, will keep performance efficiency consistently operating at the maximum outcome.

Theme 3: Effect of Pore Density (PPI) on Thermal-Hydraulic Behaviour (200 words)

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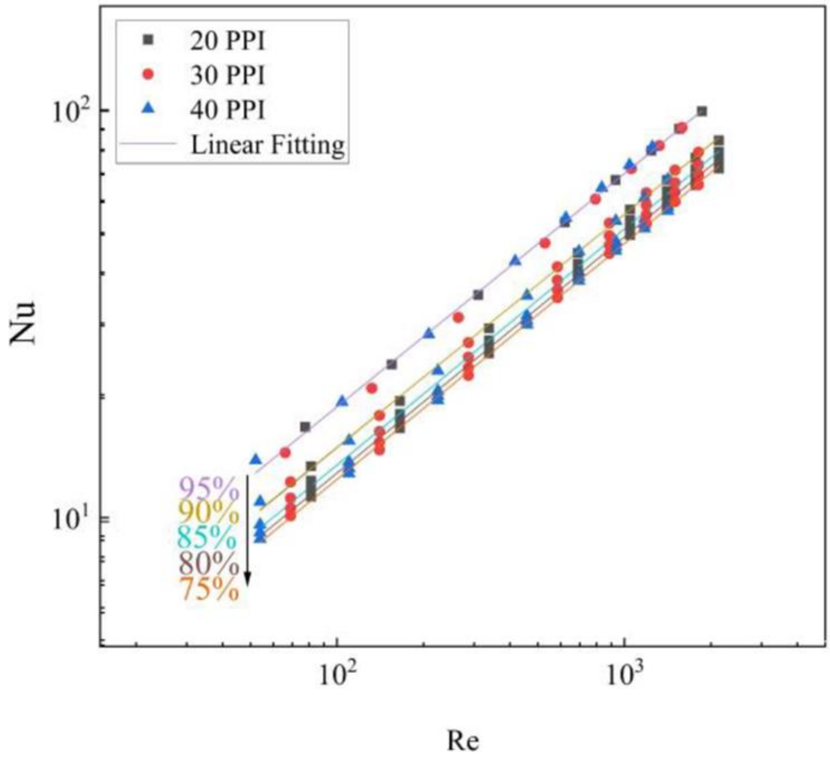

Figure 4: Variation in the Nusselt number with increasing Reynolds number for different porosities and pore densities (Source: Xu et al. 2024)

Study as per Xu et al. (2024) show that as pore density (PPI) increases, the heat transfer performance increases but the increase comes at the cost of increased pressure drop. It was determined that the metal foam with 20 PPI and 95% porosity provided the best overall convective performance, while the 40 PPI configuration provided the highest Nusselt numbers (as much as ≈110% higher than 20 PPI) but they had much larger friction and pumping requirements (Xu et al. 2024). Similar assessments with 10, 20, and 40 PPI suggested that both heat transfer and pressure drop go up with PPI: with a fixed porosity, there is greater specific surface area and turbulence with an increase PPI but the same affects occur with resistance to flow.

The low PPI (≈10) provides moderate heat transfer as well as the least pressure drop. High PPI (≈40) maximizes Nusselt enhancement, but has a high hydraulic cost. Most outcomes fall to a moderate PPI range (20–30) as the most optimal for achieving enhanced convection and moderate pressure loss.

Theme 4: Role of Reynolds Number in Forced Convection Regimes (200 words)

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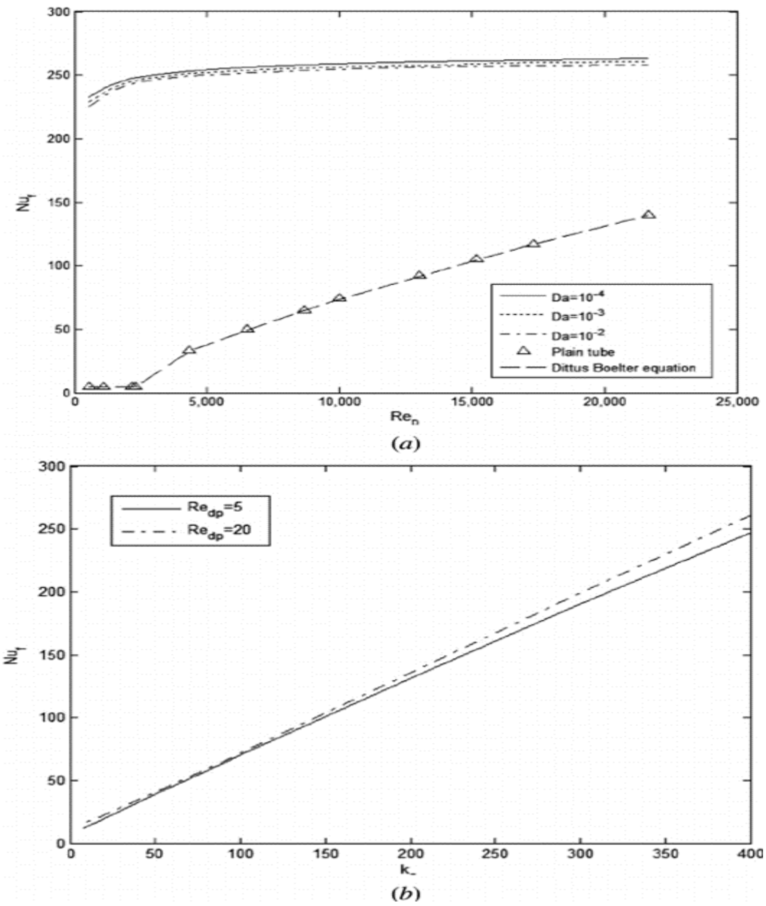

Figure 5: Effect of Reynolds number, Darcy number, and thermal conductivity variation in Nusselt number for a metal foam-filled pipe: (a) effect of Re D and Da variation, (b) effect of k s variation.(Source: Chen et al. 2015)

The increasing Reynolds number improves convective heat transfer in metal foams, and the Reynolds number increases pressure drop as well. When Re is low (~20), flow is in the Darcy regime, and viscous forces dominate. The Forchheimer regime follows, where inertial effects and drag forces begin to dominate flow resistance (Chen et al. 2015). In a foam, turbulent wakes behind the foam ligaments allow mixing to occur along with convective heat transfer, with improvements in Nusselt numbers reported to have increases of 50x over a plain pipe. Performance can vary in an application based on the relationship between permeability and porosity of the foam material, but there is generally an increase in performance at transitional-to-moderate Reynolds number ranges that will maximize thermal improvement while limiting hydraulic losses.

The heat transfer in porous metal foams is limited (as indicated by Nusselt numbers generally below 10) at Reynolds numbers below 20 because the convection is laminar-like Darcy flow. As

Reynolds number is increased into the range of 20-1000, the effect of inertia dominates and begins to create transition to turbulence, which also enhances mixing, and begins to support much larger Nusselt numbers. However, once in the turbulent range, increased Reynolds numbers lead to diminishing returns due to turbulence saturation and increased pressure losses. Thus, thermal-hydraulic performance is maximized at transitional to moderate Reynolds numbers, where really meaningful convective gains exist without severely penalizing the pumping power.

Theme 5: Design Implications for High-Performance Applications

Combining metal foam and porous media in heat sink design provides an opportunity for thermal management in high-performance applications such as electronics cooling, automotive systems, and renewable energy devices (Liaw et al. 2023). Additional numerical analysis findings suggest that the ideal design is a function of total porosity, pore density (PPI), and tuning the flow characteristics (Reynolds number), which ultimately determines the compromise between improved heat transfer and an acceptable pressure drop (Moghimi et al. 2022).

In electronics cooling applications where the restriction of space is an issue along with large heat flux, the use of metal foams, with mean porosity between moderate (like 0.90 - 0.95) and PPI 20-40, will provide superior surface area and turbulence, which is a better rate of heat removal, with low pressure losses (Narkhede and Gnanasekaran 2024). This applies best to CPU/GPU heat sinks, power electronics and miniaturised battery packs.

Application	Optimal Porosity	Optimal PPI
Electronics Cooling	0.90 – 0.95	20 – 40 PPI
Automotive Systems	0.92 – 0.97	10 – 20 PPI
Energy Systems	0.90 – 0.96	15 – 30 PPI

In thermal systems for internal combustion engine and exhaust gas recirculation EGR cooler applications, lower PPI foams (10–20 PPI) with higher porosity are helpful because these foams provide low resistance to fluid flow and sufficient heat exchange properties for high flow rates of fluid (Aboujafari et al. 2022). Alternatively, in solar thermal and energy storage systems, where thermal spreading must be consistent, combinations of reasonably moderate Reynolds numbers and structured porous inserts typically result in sufficient thermal spreading and fluid mixing.

Design optimisation must consider application-specific limitations and seek to utilise designs that improve the thermal performance factor (TPF), a shortening of the optimised configuration between the benefits of enhancing heat transfer and the subsequent pressure drop involved (Jadhao et al. 2025). The choice of geometry, material (copper versus aluminium), and flow control elements is part of bringing these benefits into practice.

Theme 6: Synthesis of Findings and Future Directions

The reviewed body of literature as a whole emphasises the importance of obtaining thermal performance improvement and a pressure drop penalty with porous media heat sinks. It has been found that high porosity metal foams (90-98%) at a pore density of between 10 and 40 PPI have much greater potential for augmenting convective heat transfer due to the increased turbulence as well as significant surface area advantages (Shbailat et al. 2023). However, typically enhancements in thermal performance come with increased losses due to pressure and decreased fluid velocity, hence the importance of balancing design parameters based on application needs.

In high-performance applications, such as power electronics or electric vehicle cooling, there is a trade-off between a higher Nusselt number and acceptable pressure drop (Basnet 2025). Critical assumptions have to be made cautiously, providing a clear direction. Copper foams demonstrate higher thermal conductivity with reduced density and increased cost, so depending on the application, material selection is important when understanding thermal and economic boundaries. The relationship among Reynolds number, porosity, and PPI is the centre of design optimisation, guiding engineers to design heat sink configurations for a specific operating regime.

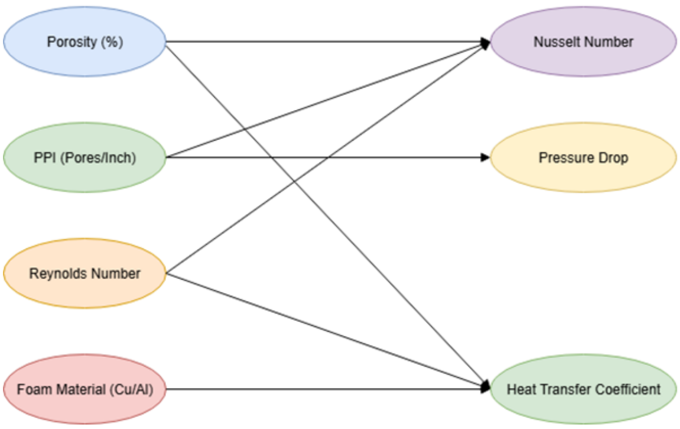

Figure 6: Influencing Parameters and Their Impact on Thermal Performance

Nano-engineered metal foams are surely the area to work into the future, where coatings or embedded nanostructures could result in a significant enhancement in heat transfer rates with very little impact on permeability, there could be possibilities with combinations of hybrid porous materials, i.e., metal foam, PCM composites to mitigate transient heat spikes in battery packs or energy storage systems. Also, deterministic CFD simulations with transient thermal loads, two-phase flow and anisotropic foam structures could result in improved engineering predictions and performance dependability for thermal systems under actual operating conditions (Kemerli et al. 2025). These paths will all push the limits of porous heat sink development.

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6. CONCLUSION

This research examined secondary data on the performance of metal foam heat sinks during forced convection, finding that the metal foam heat sinks improved heat transfer performance by increasing surface area and creating turbulence. Metal foams with porosity between and including .85 - .90 and pore density between and including 20-30 PPI and moderate Reynolds numbers or conditions minimizes the performance vs pressure drop balance. Limitations of this study stem from relying on numerical data; future work should utilize experiments and nano-engineered foams for potential real-world applications.

7. AUTHOR(S) CONTRIBUTION

The writers affirm that they have no connections to, or engagement with, any group or body that provides financial or non-financial assistance for the topics or resources covered in this manuscript.

8. CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

9. PLAGIARISM POLICY

All authors declare that any kind of violation of plagiarism, copyright and ethical matters will take care by all authors. Journal and editors are not liable for aforesaid matters.

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