# THERMAL PERFORMANCE AND FLUID FLOW ANALYSIS OF PARTIALLY FILLED HEAT EXCHANGERS USING METAL FOAM

[1]D.Malleswari, Associate Professor, Department of Mathematics, Government Degree College for Women (A), Nalgonda, Telangana,
[2]V.Padma Anuradha, Associate Professor, Department of Mathematics,
NTR Government Degree College for Women (A), Mahaboob Nagar, Telangana, India

**Abstract:**

A computational fluid dynamics (CFD) study was performed to numerically investigate forced convective heat transfer and the hydrodynamic behavior of airflow through a vertical channel. The effects of airflow Reynolds number, metal foam porosity, and thermal conductivity on key parameters—including the overall Nusselt number, pressure drop, maximum temperature, and temperature distribution—were analyzed. The novelty of this study lies in the use of metal foams on both sides of a vertical channel and the quantitative assessment of heat transfer enhancement compared to an empty channel for different foam materials. Results indicate that the heat transfer rate from the heated plate is comparable for aluminum foam (porosity 0.948) and copper foam (porosity 0.877) under identical velocity and heat flux conditions. Additionally, increasing the airflow velocity reduces the maximum temperature, although the reduction is nonlinear. The numerical results were successfully validated against experimental data reported in the literature for rectangular metal foam heat exchangers.

Keywords: Numerical modelling, Computational Fluid Dynamic (CFD).

## I. INTRODUCTION

The increasing demand for energy-efficient systems has driven significant research into advanced heat transfer technologies. Among these, metal foams have emerged as promising materials for enhancing thermal performance due to their high surface area, low density, and unique porous structures. These cellular materials facilitate improved convective heat transfer while maintaining a lightweight configuration, making them suitable for a wide range of engineering applications, including heat exchangers, fuel cells, solar energy systems, heat sinks, and automotive thermal management. The integration of metal foams into heat exchangers has been shown to significantly enhance heat transfer rates compared to conventional empty channels, while also influencing pressure drop and flow distribution characteristics.

Computational fluid dynamics (CFD) has become a valuable tool for investigating the thermal and hydrodynamic behavior of airflow through metal foam-filled channels. Parameters such as airflow Reynolds number, foam porosity, and thermal conductivity critically affect the overall heat transfer performance, Nusselt number, and temperature distribution. Recent studies have highlighted the importance of optimizing foam geometry and material selection to achieve a balance between enhanced heat transfer and manageable pressure drop. The present study focuses on a partially filled vertical channel with metal foams on both sides, aiming to quantify the improvement in heat transfer and understand the interplay of key fluid dynamic and thermal parameters.

## 3. LITERATURE REVIEW

The industrial sector continually seeks innovative techniques to enhance the efficiency of various plants while minimizing environmental risks. Recently, metal foams have gained attention for their ability to improve heat transfer and, consequently, the energy efficiency of engineering systems.

Mahjoob and Vafai [1] provided a comprehensive review on the heat transfer improvements achievable with metal foams in heat exchangers. Foam morphology has been shown to significantly influence both thermal and fluid dynamic performance, as demonstrated by Huisseune et al. [2]. Metal foams, as a class of low-density cellular materials, offer novel mechanical, thermal, electrical, and acoustic properties. Their high strength-to-weight ratio makes them suitable for diverse engineering applications, from mechanical structures to thermal management systems.

Porous media, including metal foams, have also been studied analytically. Xu et al. [3] compared local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) models, showing that LTE predicts higher heat transfer coefficients, while LTNE becomes significant at low porosities, large thermal conductivity differences between fluid and solid phases, and low pores per inch (PPI). Similarly, Lu et al. [4] analyzed parallel-plate heat exchangers partially filled with foams, studying the effects of porosity, pore density, and foam thickness on system performance.

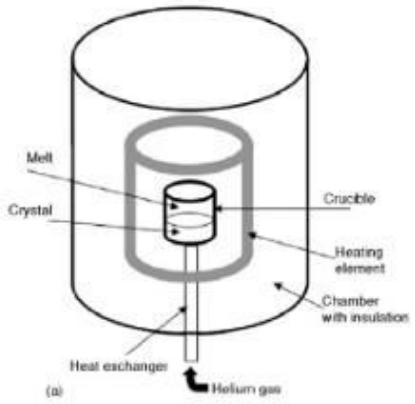
Numerical investigations have further explored the impact of metal foams on heat exchangers. Odabaee et al. [5] evaluated the heat transfer efficiency of a cylinder wrapped in metal foam under cross-flow conditions, finding higher heat transfer compared to finned-tube heat exchangers, with manageable pressure drops. Lin et al. [6] studied porous graphite foams for vehicle cooling, showing that wavy-corrugated foam arrangements offered the best thermal performance and lowest pressure drop. Zafari et al. [7] demonstrated that increasing foam porosity reduces pressure drop and achieves near thermal equilibrium between fluid and solid phases for small-scale porous media.

Alhusseny et al. [8] investigated a double-pipe heat exchanger partially filled with high-porosity rotating metal foam, employing both active (secondary flow with guiding vanes) and passive (foam-covered surfaces) methods to enhance heat transfer. Moon et al. [9] introduced a Kelvin-cell-based metal foam (KMF) with elliptical struts, showing that designs with the same cross-sectional area required 32% less pumping power than circular-strut designs. Alvandifar et al. [10] examined a heat exchanger with partially foam-wrapped tube banks, achieving the same heat transfer as fully filled systems but with a 60% lower pressure drop and 50% reduced foam usage. Chiappini et al. [11] employed a coupled lattice Boltzmann–finite volume method to investigate conjugate heat transfer in open-cell metal foam, demonstrating enhanced heat exchange and steeper temperature gradients.

This study builds on the work of Buonomo et al. [12], focusing on partially filled heat exchangers with varying foam thicknesses to identify optimal configurations. Results are presented in terms of heat transfer coefficient and pressure drop, providing insight into the trade-off between enhanced heat transfer and increased pumping power.

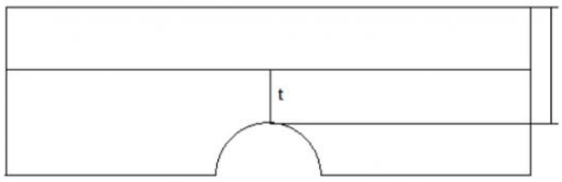
## 3. NUMERICAL METHODS

The finite volume method was employed to solve the governing equations, with numerical simulations performed using Fluent 15.0. The SIMPLE algorithm was applied for pressure-velocity coupling, and the least squares cell-based method was used for gradient evaluation in spatial discretization. Pressure was computed using the PRESTO algorithm, while a second-order upwind scheme was applied to the momentum and energy equations. Convergence criteria were set to (10^{-5}) for continuity and velocity components, and (10^{-8}) for energy.




**Computational Domain**

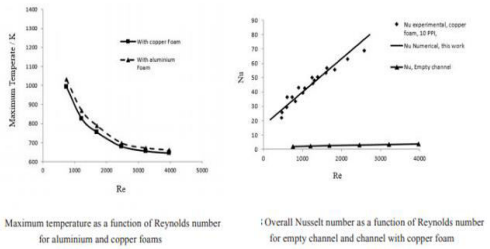
The computational domain represented half of a single tube, as illustrated in the figure. Metal foam thicknesses, denoted as (t), were expressed as a ratio to the center-to-center distance between consecutive tubes ((I)), with values of (t/I = 1/4, 1/2, 3/4,) and (1). The domain was discretized using rectangular cells, and three different mesh densities were tested to ensure mesh independence: 28,500 cells, 114,000 cells, and 456,000 cells for the configuration with (t/I = 3/4). For an inlet air velocity of 0.511 m/s (Re = 392), the thermal power evaluation (Q) showed that the 114,000-cell mesh produced only a 0.3% deviation from the 456,000-cell mesh. Therefore, the 114,000-cell grid was selected for the simulations, providing an optimal balance between accuracy and computational efficiency. Meshes for the other configurations were generated using the same approach as for (t/I = 3/4).




**Geometrical metal foam configuration**

## 4. RESULTS AND DISCUSSION

The study investigated fluid flow and heat transfer in a vertical channel, both with and without metal foams. The effect of airflow velocity on temperature distribution was analyzed for empty and foam-filled channels. For the empty channel, temperature profiles along the axial direction indicate that increasing airflow velocity reduces the thermal boundary layer thickness on the aluminum plate, enhancing heat transfer. However, the temperature in the bulk fluid decreases at higher velocities, as a significant portion of the air exits the channel without substantial temperature change.




Maximum temperature as a function of Reynolds number for aluminium and copper foams

Overall Nusselt number as a function of Reynolds number for empty channel and channel with copper foam

**Result Analysis**

For channels filled with aluminum and copper foams, the temperature distribution along the axial direction shows that heat transfer surfaces are significantly larger than in the empty channel. Metal foams increase the surface area-to-volume ratio and promote flow mixing, resulting in smoother temperature profiles and substantially lower surface temperatures on the heated plate.

The influence of thermal conductivity and Reynolds number on maximum temperature was also examined. Heat removal occurs via conduction through foam ligaments and convection within the foam. Increasing airflow velocity enhances convective heat transfer, reducing the aluminum plate temperature. Maximum temperature decreases with Reynolds number, though the reduction is nonlinear; beyond Re = 3230 (V = 2.5 m/s), further velocity increases have minimal impact. Low-conductivity foams limit heat transfer, causing heat accumulation and higher surface temperatures.

Reynolds number, foam porosity, and permeability were identified as the key factors affecting heat transfer. Overall, the Nusselt number is higher for foam-filled channels, with

maximum heat transfer at Re = 3970. Despite copper foam's higher thermal conductivity, its performance was comparable to aluminum foam (porosity 0.948) under the investigated conditions.

## CONCLUSIONS

In this study, the heat transfer enhancement of fully developed laminar flow through a two-sided vertical channel filled with aluminum and copper foams was numerically investigated. Both empty and foam-filled channels were modeled using the Darcy–Brinkman–Forchheimer and classical Navier–Stokes equations along with the corresponding energy equations. The governing equations were solved using the finite volume method, and the proposed model was successfully validated against experimental data reported for rectangular metal foam heat exchangers. The effects of Reynolds number, foam porosity, and thermal conductivity on surface temperature distribution and overall Nusselt number were analyzed. Results indicate that pressure drop increases with higher airflow velocity or lower foam porosity, while the overall Nusselt number is higher in foam-filled channels compared to empty channels, demonstrating a significant enhancement in heat transfer. Maximum temperature decreases with increasing Reynolds number, showing the dominance of convective heat transfer at high flow rates. Although copper foam has higher thermal conductivity, its performance is comparable to aluminum foam, making aluminum foam a more cost-effective choice. The proposed numerical model provides valuable insights for designing multi-channel heat transfer systems for applications ranging from electronic cooling to large-scale systems such as data centers.

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