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NUMERICAL ANALYSIS OF A PARTIALLY FILLED HEAT EXCHANGER'S THERMAL AND FLUID KINETIC BEHAVIOR WITH METAL FOAM

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ABSTRACT

A computational fluid dynamics analysis of forced convective heat transfer has been conducted numerically on the hydrodynamic and heat transfer of airflow through vertical channel. The effects of airflow Reynolds number, metal foam porosity and thermal conductivity on the overall Nusselt number, pressure drop, maximum temperature and temperature distribution were considered. The novelty of the present study is the use of metal foams in a two-sided vertical channel and the quantification of the heat transfer enhancement compared to an empty channel for different foam material. Based on the generated results, it is observed that the heat transfer rate from the heated plate is the same for aluminium foam (porosity of 0.948) and copper foam (porosity of 0.877) against equal velocity range and heat flux conditions. Furthermore, it is noted that increasing the airflow velocity reduces the maximum temperature; however, the decrement is not linear. Results obtained from the proposed model were successfully compared with experimental data found in the literature for rectangular metal foam heat exchangers.

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

1. INTRODUCTION

The industrial world pays particular attention to new techniques that can guarantee an increase in the efficiency of several plants. At the same time, the research is being carried out so that these new techniques cannot increase the risks for the world reducing their negative effects on the environment. Recently, applications of metal foams are employed to improve the heat transfer and consequently energy efficiency of the components. In fact, these materials are generally applied in many industrial fields such as heat exchangers [1], fuel cells, solar power systems [2], heat sinks [3], automotive thermoelectric generator [4], liquefied natural gas system [5], latent thermal energy storage [6].

A review of the literature on heat transfer improvement due to the use of metal foams in a heat exchanger was accomplished by Mahjoob and Vafai [1]. The foam’s morphology influences the thermal and fluid dynamic performance of metal foam heat exchangers, as demonstrated by Huisseune et al. [7].

Recently, there has been an increasing focus on new class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties. Metal foams, which are a class of cellular materials improve efficiency and minimize the required weight and volume in energy producing or transferring systems. Due to their forms that have great strength to weight ratio, they are used in different engineering applications ranging from mechanical to thermal.

The porous media have been studied using also analytical solutions. Xu et al. [11] carried out an analytical study about the local thermal equilibrium (LTE) model and the local thermal non equilibrium (LTNE) model. The results showed that the heat transfer coefficient in LTE hypothesis is greater than that of LTNE model; furthermore, LTNE model becomes more important when the porosity is low, the difference between the thermal conductivity of the fluid and solid phases is large and the PPI is low. The thermal and fluid dynamic performance of parallel-plate heat exchangers partially filled with foams was analyzed by Lu et al. [12] analytically. The effects of different parameters- such as porosity, pore density, thickness of metal foams- on the system behavior were studied.

The need to have more and more information about the behavior of heat exchangers comes from their numerous applications such as energy conservation and conversion. Several numerical investigations were accomplished in order to estimate the effects of metal foams presence in heat exchange system. Odabaee et al. [13] carried out a numerical study to evaluate the heat transfer efficiency of a cylinder wrapped by metal foam in cross-flow. A comparison was carried out respect to a finned-tube heat exchanger; the results demonstrated that the metal foam cylinder was characterized by a higher heat transfer with an adequate excess of pressure drop. A heat exchanger with porous graphite foam for vehicle cooling was numerically investigated by Lin et al. [14]. Four different arrangements of foams were analyzed in order to evaluate the thermal and fluid dynamic behavior. The results demonstrated that the best configuration was the one with wavy corrugated characterized by a low pressure drop and a high thermal efficiency. A numerical study on heat transfer inside a metal foam was conducted by Zafari et al. [15]. A real geometry was used for the construction of the computational mesh. The results demonstrated that the pressure drop decreased with increasing of the porosity; moreover, the thermal equilibrium between fluid and the solid phases existed for a little size of the porous media.

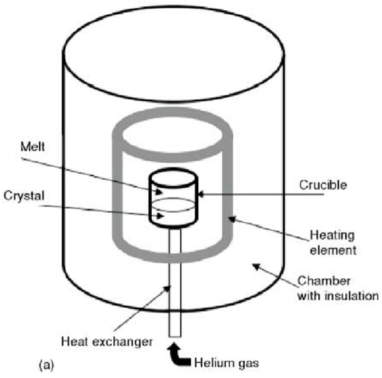
Alhusseny et al. [16] investigated numerically a double-pipe heat exchanger partially filled with high porosity metal foam and rotating coaxially. The heat transfer improvement was obtained by an active method and a passive method. The active method was the use of a secondary flow near to the surface with metal foam guiding vanes; on the other hand; the passive method was the cover by metal foam of the conducting surface. Several parameters were considered to evaluate the system, like the operating conditions, the arrangement of the guiding vanes, and the geometrical and thermal characteristics of the foam. The rotating porous vanes caused the vortex and so the fluid particles swirled. For this reason, the heat exchange surface changed continually; moreover, the boundary layer became thinner near to the conducting surface. A new Kelvin-cell-based metal foam (KMF) with elliptical struts was analyzed by Moon et al. [17] to estimate the thermal and fluid dynamic behavior of a heat exchanger with metal foam. The authors examined five KMFs with different struts. The results demonstrated that the scheme with the same cross-sectional area had a better behavior than the configuration with the same circumference; in fact, an elliptical KMF with the same cross-section area was characterized by 32% less pumping power than a KMF with circular struts. Alvandifar et al. [18] accomplished a numerical investigation on a heat exchanger with a bank of five rows of tubes wrapped by partially metal foam layers. The arrangement with partially wrapped tubes caused the same heat transfer rate respect to the system totally filled;

at the same time, the pressure drop was reduced of 60%, the surface factor increased by 33% and the quantity of the use of foam decreased by 50%. Chiappini et al. [19] used a coupled lattice Boltzmann finite volume method in order to investigate the conjugate heat transfer in a porous medium. The system under investigation was a heat exchanger with open-cell metal foam. The results demonstrated that the metal foam allowed having temperature gradients steeper than the clean channel. In this way, a specific temperature difference was obtained by means of a reduce heat exchanger length. Furthermore, the porous medium allowed enhancing the heat exchange.

This paper is an extension of the work accomplished by Buonomo et al. [20]. In fact, the heat exchanger is analyzed with different thicknesses of the same metal foam in order to study the behavior of the partially filled system. The dimension of the heat exchanger are different respect to the work above indicated because a following study has been carried out with the aim to find the optimal configuration of the system. The results are given in terms of the heat transfer coefficient and pressure drop in order to obtain the metal foam dimension that represents a good trade-off between the improvement of the heat transfer and the increment of the pumping power.

2 NUMERICAL METHOD

The finite volume method is applied in order to obtain the solutions of the governing equations. Fluent 15.0 is used to carry out the numerical investigations. The SIMPLE algorithm is accomplished for the pressure-velocity coupling; the least square cell is used to evaluate the gradient evaluation for the spatial discretization. The pressure calculation is done by means of the PRESTO algorithm; the second order upwind scheme is used for energy and momentum equations. Convergence criteria are considered equal to 10^{-5} for the continuity and the velocity components while for the energy equal to 10^{-8}. As the computational domain is utilized half of a single tube, as represented



Computational domain

The thicknesses of metal foam have been indicated as t, as can be seen in the Figure. Their values have been obtained as ratio respect to the distance center-to-center of two consecutive tubes (I); in fact, in order to obtain the metal foam thicknesses, several ratios t/I have been considered, equal to: ¼, ½, ¾, 1.

The grid is made up of rectangular cells into the entire computational domain Three different types of grids were analysed to find an independent solution from the mesh. They are constituted by 28500 cells, 114000 cells and 456000 cells for the configuration characterized by t/I equal to ¾. In corresponding of an inlet air velocity equal 0.511 m/s (Red = 392), the evaluation of the thermal power Q˙, as showed in Table 2, highlights that the grid with 114000 cells had 0.3 % error than the mesh with 456000 cells. The grid adopted for the simulations was the one with 114000 elements because it was represented a compromise between solution accuracy and convergence. The grids for the other configurations have been made up of with the same criteria of the construction of the mesh for the ratio t/I equal to ¾.

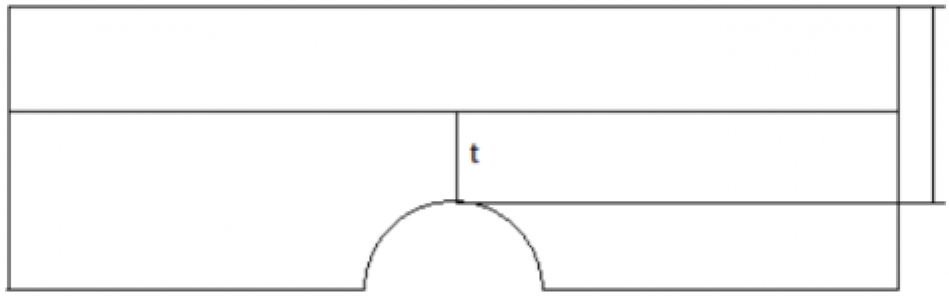


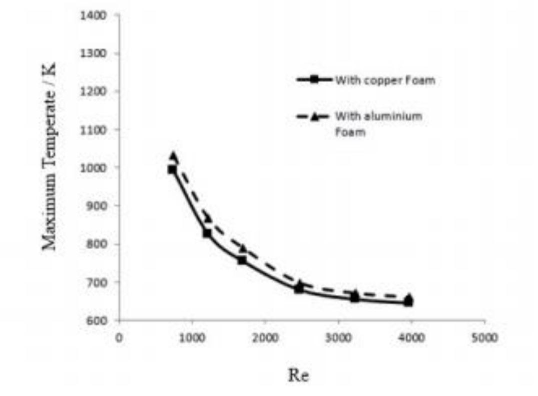
Figure. Geometrical metal foam configuration

3. RESULTS AND DISCUSSION

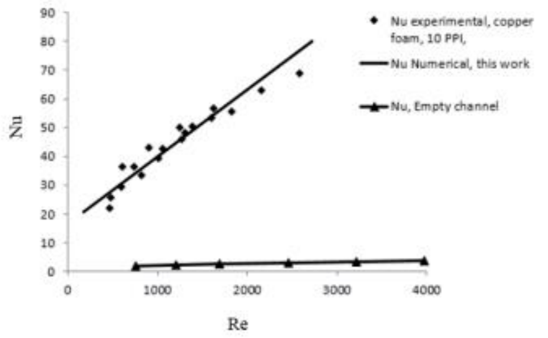
The study was conducted to discuss fluid flow and heat transfer in a channel with and without of metal foams. Effect of velocity on temperature distribution through empty and metal foam filled channels Figure presents temperature distribution of an empty channel along axial direction versus different inlet velocity. As the airflow velocity increases, the thermal boundary layer thickness on the aluminum plate decreases and the heat transfer from aluminum plate increases. However, the temperature distribution was decreased in the fluid region due to high velocity. It shows that, a large amount of air leaves channel without temperature change. present temperature distribution of filled channel along axial direction versus different airflow velocity for both aluminium and copper foams. This is obvious that heat transfer surface in the filled channel is much higher than empty channel. This is one of the advantages of employing metal foams that can provide a large surface area to volume ratio and it can intense mixing of flow through metal foam in the heat transfer systems. By using of metal foams, the surface temperature of the heated plate is significantly lower than that in the empty channel and temperature distribution gets smoother

3.1 Effect of thermal conductivity of metal foams and Reynolds number on maximum temperature The heat removal mechanism from the heater plate is conduction through the foam ligaments and convection through the foam. With increasing the airflow velocity, convective heat transfer rate increases and aluminium plate temperature decreases. Maximum temperature decreases with increasing airflow velocity and consequently, Reynolds number as shown. However, the decrement is not linear. As can be seen, after Re = 3230 (V = 2.5 m/s), temperature change is negligible and further increasing of velocity does not have a significant effect on the heat transfer rate. It is evident that by using of metal foam with low thermal conductivity, the heated plate cannot transfer heat well to metal foam and heat accumulation in the plate leads to increase surface temperature.

3.2. Effect of Reynolds number on the overall Nusselt number The most important parameters affecting the heat transfer from heater are Reynolds number, porosity and permeability of metal foams. It can be observed from that metal foams led to heat transfer enhancement. Overall Nusselt number for filled channel is higher than empty channel for both investigated cases. The maximum heat transfer rate was observed at Re=3970, which was significantly more than empty channel. The heat transfer performance of aluminium and copper foams is compared in The higher thermal conductivity of copper foam did not contribute significantly to increase heat transfer compared to aluminium foam. Consequently, copper foam with porosity of 0.877 and aluminium foam with porosity of 0.948 gave the same heat transfer performance for the investigated airflow velocity range and uniform heat flux conditions.



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

4 CONCLUSIONS

In the present work, heat transfer enhancement of fully developed laminar flow through a two-sided vertical channel which is filled with aluminium and copper foams is numerically investigated. The channel with and without metal foams were modelled using Darcy-Brinkman-Forchheimer, classical Navier-Stokes equations and corresponding energy equations. A finite volume method was utilized to solve the governing equations. The proposed model were successfully validated with experimental data found in the literature for rectangular metal foam heat exchangers. The effect of Reynolds number, porosity and thermal conductivity on surface temperature distribution and overall Nusselt number had been analysed. Based on the results, the pressure drop increased by either increasing the airflow velocity or decreasing the metal foam porosity. The heat transfer factors, overall Nusselt number in the channel filled with metal foams are higher than empty channel. Therefore, a significant increase in heat transfer is obtained in two-sided channel filled with metal foams. Maximum temperature decreased with increasing of Reynolds number. It is shown that at high Reynolds numbers, the convection heat transfer has been dominated.

Moreover, the heat transfer enhancement through a metal foam filled channel increases with inlet velocity for studied ranges. Although, copper foam has higher thermal conductivity, but it could not contribute significantly to increase the heat transfer compared to aluminium foam. It is recommended that aluminium foam is better than the more expensive copper foam with similar PPI in this system. It is revealed that the proposed numerical model can efficiently provide useful information for design of multi-channel heat transfer system for a velocity range usually encountered in electronic cooling such as tall printed circuit boards and for large-scale applications like data centers.

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