Review of Fluid Flow and Heat Transfer through Porous Media Heat Exchangers

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Abstract- Latest developments in the manufacturing technology have led to development of advance lightweight materials for thermal applications. Investigation of thermal properties for such materials is desirable. On the other hand, it is recognized that there are different thermal management issues. Heat transfer through porous materials has gained significance in industrial applications based research. In this paper the research on heat transfer through porous material, mostly metal foam heat exchanger, has been reviewed. This paper aims to acquire state of the art knowledge and information in the field of porous materials as well as various research carried out on heat transfer and fluid flow through porous materials. The forced convection has been reviewed extensively. At the end, aspects which require further research have been identified.

Keywords: Forced Convection, Porous Media, Porosity, Permeability, Heat Transfer.

1. INTRODUCTION

The use of porous materials as efficient and compact heat exchangers for heat dissipation is under extensive research. Amongst these, high porosity, open cell metal foams shown in Fig.1 has emerged as one of the most promising materials for thermal management applications where a large amount of heat needs to be transferred over a small volume. This is attributed to the high surface area to volume ratio as well as enhanced flow mixing (convection) due to the tortuosity of metal foams Fig. 2. The surface area to density ratio of metal foams is roughly 1000–3000 m2/m3. So far the louvered fin compact heat exchanger is known to be the most efficient and is widely used in automotive and aircraft air-cooled systems [1]. The louvered fin has a same level of the surface area density as the uncompressed metal foams. However, the manufacturing process of a louvered fin is very complicated and is costly as compared to the metal foams. Furthermore, the mechanical strength of the louvered fin is less than that of the metal foams. Therefore, there is a demand to make highly efficient compact heat exchanger by using metal foams which have a high heat transfer rate and structural strength as well as a low-cost manufacturing process. Some metal foam heat exchangers are shown in Fig. 3. In the past investigations have been carried out for heat transfer in metal foams for practical applications, including compact heat exchangers. [2].

Fig. 1 Heat transfer applications of metal foam [3]

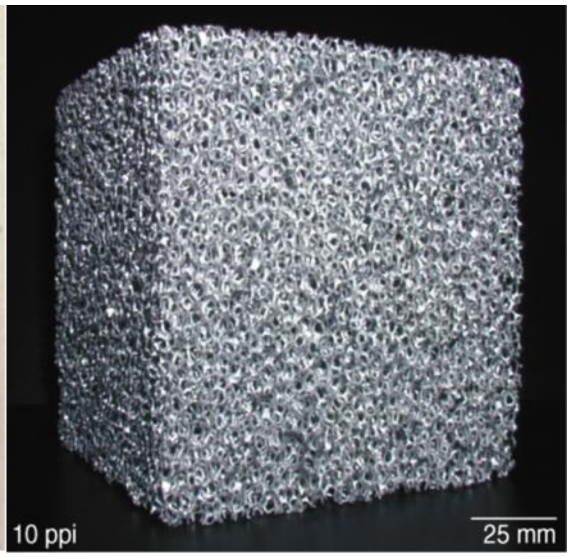

Fig. 2. A Foam sample manufactured by sintering route[2]

Nomenclature

A	surface area	k_{se}	effective thermal conductivity of solid
C_i	inertial coefficient	K	permeability
Cp	specific heat capacity	Nu	overall Nusselt number
C_{sf}	a constant of Rohsenow correlation	p	pressure
D_a	Darcy number	Pr	Prandtl number
g	gravitational acceleration	q_{Load}	heat flux at the evaporator
H	channel height	T	temperature
h_{fg}	enthalpy of vapourization	u	velocity
k	thermal conductivity	X, Y, Z	Cartesian coordinates
k_c	effective solid thermal conductivity due to pure conduction		Greek symbols
k_e	effective thermal conductivity of metal foam	α	absorption coefficient
k_f	thermal conductivity of fluid	ε	porosity
k_{fe}	effective thermal conductivity of fluid	μ_f	viscosity of fluid
k_s	thermal conductivity of solid	ρ	density of fluid

In order to enhance the convective heat transfer rate, metal foams can be used for making advance compact heat exchangers, because of the high surface area to volume ratio as well as enhanced flow mixing. Therefore, it is believed that the overall performance of a thermal system can be enhanced by using metal foams as a heat exchanger. From the heat transfer point of view, metal foams can be considered as one type of porous media, so that the study on metal foams can be classified as heat transfer in porous media.

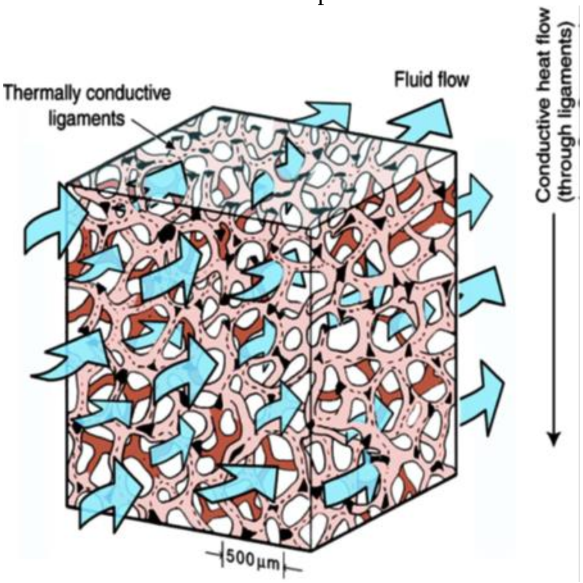

Fig. 3 Forced convection in metal foam [2]

The initial investigation of fluid flow through a porous medium can be traced back to the nineteenth century. Darcy was the first to perform recorded experiments and to produce formulations pertaining to a porous medium. He discovered that the area-averaged fluid velocity through porous material is proportional to the pressure gradient and inversely proportional to the viscosity (μ) of the fluid flowing through the porous material, represented by the Darcy flow law as follows:

$$u = \frac{K}{\mu}\left(-\frac{dP}{dx}\right) \qquad (1)$$

Where, K is material constant called permeability.

The Darcy flow model has subsequently been employed in numerous engineering applications related to fluid flow and heat transfer in porous materials. However, although the Darcy model is popular in porous medium convective heat transfer investigations, it neglects several physical effects of importance. Thorough understanding of the fluid flow and heat transfer characteristics in porous medium is a challenging task [2].

II. APPLICATIONS OF POROUS MATERIAL'S

Forced convection heat transfer in porous media is a rapidly growing branch of thermal science. Several thermal engineering applications can benefit from a better understanding of convection through porous materials such as geothermal systems, thermal insulations, microelectronic cooling system, filtering devices and products manufactured in the chemical industry.

Thomas Fend [3], Porous solids like extruded monoliths with parallel channels and thin walls made from various oxide and non-oxide ceramics, ceramic foams and metal structures have been tested in the past with the objective of applying them as open volumetric receivers in concentrated solar radiation. In this paper, the experimental work on a variety of porous materials is reported. It also present an experimental set-up designed to investigate how the properties of the porous materials affect flow stability. Based on these results, a recommendation for the design of volumetric absorbers is given.

W.H. Hsieh [4] investigated experimentally, the effects of porosity (e), pore density (PPI) and air velocity on the heat-transfer characteristics of aluminum foam heat sinks. It is noted that temperatures of the solid and gas phases of the aluminum foam decrease as Reynolds number increases, caused by the increased convective heat-transfer rate at higher Reynolds number. The deduced temperature difference between the solid and a gas phase clearly indicates the existence of non-local thermal equilibrium condition within the aluminum foam heat sink. The increase of the porosity and the pore density enhances the phenomenon of non-local thermal equilibrium.

Tadrist et al. [5] suggested one way of increasing the exchange surface area of a conventional exchanger is to replace the fins by a porous structure. Under these conditions, the exchange surface area can reach very high values. However, this increase amplifies the pressure drop of the fluid circulating in the porous matrix. It is therefore necessary to determine the optimal parameters of the porous medium in order to maximize the heat transfer with regard to the pressure drop.

Leonardo Giani [6] determined Gas-solid heat transfer coefficients in open-celled metal foams as part of their study. Examples of such processes are found in the field of environmental catalysis, including, for example, catalytic combustion, selective catalytic reduction of NOx by NH3 (SCR-DeNOx), automotive exhaust gas after treatment, and also in the catalytic partial oxidation of hydrocarbons for syngas or H2 generation processes. In his work, foam samples made of FeCrAlloy and Cu with nominal porosities of 10 and 20 pores per inch (ppi) were characterized by performing non-steady-state cooling measurements.

T.W Clyne [7] presented a brief analysis of how heat transfer takes place in porous materials of various types. The primary aim was commonly to maximize either the thermal resistance or the rate of thermal equilibration between the material and a fluid passing through it. The main structural characteristics concern porosity (void content), anisotropy, pore connectivity and scale. There are, some complex interplays between service conditions, pore architecture/scale, fluid permeation characteristics, convective heat flow, thermal conduction and radiative heat transfer. Such interplays are illustrated with reference to three examples: (i) a thermal barrier coating in a gas turbine engine; (ii) a Space Shuttle tile; and (iii) a Stirling engine heat exchanger.

Odabaee et al. [8] examined the application of two different heat transfer augmentation techniques to improve the performance of an air-cooled heat exchanger. The conventional finned-tube design is compared with a modern technique. Both designs improve the heat transfer rate from the condensing fluid flowing in the tube bundle albeit at the expense of a higher pressure drop compared to the bare tube as our reference case. Considering the heat transfer enhancement as the benefit and the excess pressure drop as the cost, the two cases are compared against each other.

Paepe [9] Thermo hydraulically characterized open cell metal foam for use in all kinds of heat transfer applications such as automotive application, electronics cooling, heat pump, geothermal energy, in order to design heat exchanger with this material. He presented summary of past research and indicates field for further development.

C.Y. Zhao [10] investigated the feasibility of using metal foams and expanded graphite to enhance the heat transfer capability of PCMs in high temperature thermal energy storage systems. The problem of low thermal conductivity as a major issue that needs to be addressed for high temperature thermal energy storage systems. Since porous materials have high thermal conductivities and high surface areas, they can be used to form composites with PCM storage to significantly enhance heat transfer. The results show that heat transfer can be significantly enhanced by both metal foams and expanded graphite, thereby reducing the charging and discharging period.

Esfahani [11] studied the forced convection heat transfer in high porosity metal-foam filled tube heat exchangers. The Brinkman Darcy momentum model and two energy equations for both solid and fluid phases in porous media are employed. The study shows that using metal-foams can significantly improve the heat transfer in heat exchangers.

Diani et al.[12] studied the reliability of electronic equipment. The results demonstrate the interesting heat transfer capabilities of metal foams during the flow boiling heat transfer; more experimental work is needed to deeply understand the two phase heat transfer process inside these new enhanced surfaces.

Thompson [13] presented measured values of heat transfer and pressure loss for a variety of porous graphite foams in subsonic turbulent airflow. Measured maxima in the thermal performance is the ratio of heat transfer to pressure loss, was correlated. The pore structure was obtained from electron microscopy, to show a linear dependence of thermal performance on the average diameter of inter-pore windows representative of the cross-sectional area through which cooling air flows.

III. Thermal conductivity of metal foam

Metal foams can be used for low temperature applications e.g. compact heat exchangers for electronics cooling [3,4]. In all these applications, the effective thermal conductivity is always the key parameter to be solved. Similar to the definition of the solid material conductivity k, the effective thermal conductivity of a porous medium or other porous materials, ke, is defined as:

$$\mathrm{Ke}=\frac{q}{\frac{\Delta T}{H}} \qquad (2)$$

Where q is the uniform heat flux, ΔT is the temperature difference and H is the sample thickness.

It is well known that the effective thermal conductivity (ke) plays a key role for studying heat transfer mechanisms in porous media. So far, most researchers employed the effective thermal conductivity model by simply accounting for the volume fraction of each substance:

$$\mathrm{K_e} = \mathrm{K_f}(1-)\mathrm{K_s} \qquad (3)$$

K. Boomsma, D Poulikakos [14] developed a geometric thermal conductivity model of saturated porous metal foam based on the idealized three dimensional basic cell geometry of foam, the tetrakaidecahedron. This geometric shape results from filling a given space with cells of equal size yielding minimal surface energy. The foam structure was represented with cylindrical ligaments which attach to cubic modes at their centers. The relative geometry length was calibrated with experiments. It was found that the model estimated the effective thermal conductivity very well for the experimental configuration.

Bader Alazmi, Kambiz Vafai [15] analyzed boundary conditions for constant wall heat flux in the absence of local thermal equilibrium conditions. Effects of variable porosity and thermal dispersion are also analyzed. The effects of pertinent parameters such as porosity, Darcy number, Reynolds number, inertia parameter, and particle diameter and solid-to-fluid conductivity ratio were analyzed. Quantitative and qualitative interpretations of the results are utilized to investigate the prominent characteristics of the models under consideration.

C.Y. Zhaoa, T J. Lua [16] measured the effective thermal conductivity of steel alloy FeCrAlY (Fe—20 wt.% Cr—5 wt.% Al—2 wt.% Y—20wt.%) foams with a range of pore sizes and porosities between 300 and 800 K, under both vacuum and atmospheric conditions. The effective conductivity at temperature 800K can be three times higher than that at room temperature (300 K). Results obtained under vacuum conditions reveal that the effective conductivity increases with increasing pore size or decreasing porosity. The results also show that natural convection in metal foams is strongly dependent upon porosity.

Leblond [17] considered the cooling of a heat-generating surface by a stacking of porous media (e.g., metallic foam) through which fluid flows parallel to the surface. A two-temperature model is proposed to account for non-local thermal equilibrium (non-LTE). Results demonstrate that the optimized stacks do not operate in LTE. Therefore, we show that assuming LTE might result in underestimation of the hot spot temperature, and into different final designs as well.

Moran Wang [18] developed a random generation-growth method to reproduce the microstructures of open-cell foam materials via computer modeling, and then solved the energy transport equations through the complex structure by using a high-efficiency lattice Boltzmann method. The effective thermal conductivities of open-cell foam materials are thus numerically calculated and the predictions are compared with the existing experimental data. In general the effective thermal conductivity of open-cell foam materials is much higher than that of granular materials of the same components due to the enhanced heat transfer by the inner netlike morphology of the foam materials.

M. Haghighi[19] investigated thermal performance of open-cell metal foam under low Reynolds number by comparing the heat transfer coefficient and thermal conductivity for the flow through a packed channel of high porosity metal foam to that of an open channel. In the case of Al-Air at porosity 0.971, the ratio of heat transfer coefficients is estimated to be 18.5 when the thermal conductivity ratio of foam matrix to fluid conductivity is

130. DeGroot, [20] conducted numerical study on the effect of thermal contact resistance and its impact on the performance of finned aluminum foam heat sinks. Numerical results have been obtained for a wide range of contact resistances at the porous-solid interfaces, up to the limit of an effectively infinite resistance. As the contact resistance is increased to such high levels, the heat transfer is found to asymptote as conduction into the solid constituent of the foam is completely blocked. Even without conduction into the solid, a convective enhancement is obtained due to the presence of the foam material.

E Sadeghi [21] in this study, a test bed that allows the separation of effective thermal conductivity and TCR in metal foams is described. Measurements are performed in a vacuum under varying compressive loads using ERG Duocel aluminium foam samples with different porosities and pore densities. Results show that the porosity and the effective thermal conductivity remain unchanged with the variation of compression in the range 0–2MPa; but TCR decreases significantly with pressure due to an increase in the real contact area at the interface.

Chumpia [22] two types of aluminum foam-wrapped cylindrical heat exchanger, with foam layer thickness of 5mm, are being tested for heat transfer performance and pressure drop characteristics. The results show that, within the range of designated air velocity, thermal contact resistance (TCR) of HX1 is 0.015-0.001K/W larger than that of HX2; essentially constant with the air flow rate. This TCR contributes between 10%-19% of total thermal resistance of HX1, from lowest to highest air velocity. On the other hand, pressure drop results show very close figures between HX1 and HX2. They are steadily increased from 2.0 Pa at lowest air velocity to 19 Pa at highest velocity.

IV. Forced Convection

T. J. LU [23] developed an analytical model for foams with simple cubic unit cells consisting of heated slender cylinders, based on existing heat transfer data on convective cross flow through cylinder banks. A foam filled channel having constant wall temperatures is analyzed to obtain the temperature distribution inside the channel as a function of foam density, cell size and other pertinent heat transfer parameters. The overall heat transfer coefficient of the heat exchanging system is calculated, and the pressure drop experienced by the fluid flow obtained. These results are used to analyze and guide the design of optimum foam structures that would maximize heat transfer per unit pumping power.

V. V. Calmidi [24] reported experimental and numerical study of forced convection in high porosity (ε~0.89–0.97) metal foams. Experiments have been conducted with aluminum metal foams in a variety of porosities and pore densities using air as the fluid medium. Nusselt number data has been obtained as a function of the pore Reynolds number. In the numerical study, a semi-empirical volume-averaged form of the governing equations is used. The velocity profile is obtained by adapting an exact solution to the momentum equation.

Table 1 Characteristics of metal foam samples used in experimental study [24]

#	Porosity	PPI	d_f (m) Fiber Dia.	d_p (m) Pore Dia.	f	K ($*10^7$ m^2)	k_{se} (W/m-K)	k_{fe} (W/m-K)
1	0.9726	5	0.00050	0.00402	0.097	2.7	2.48	0.0256
2	0.9118	5	0.00055	0.00380	0.085	1.8	6.46	0.0237
3	0.9486	10	0.00040	0.00313	0.097	1.2	4.10	0.0248
4	0.9546	20	0.00030	0.00270	0.093	1.3	3.71	0.0250
5	0.9005	20	0.00035	0.00258	0.088	0.9	7.19	0.0233
6	0.9272	40	0.00025	0.00202	0.089	0.61	5.48	0.0242
7	0.9132	40	0.00025	0.00180	0.084	0.53	6.37	0.0237

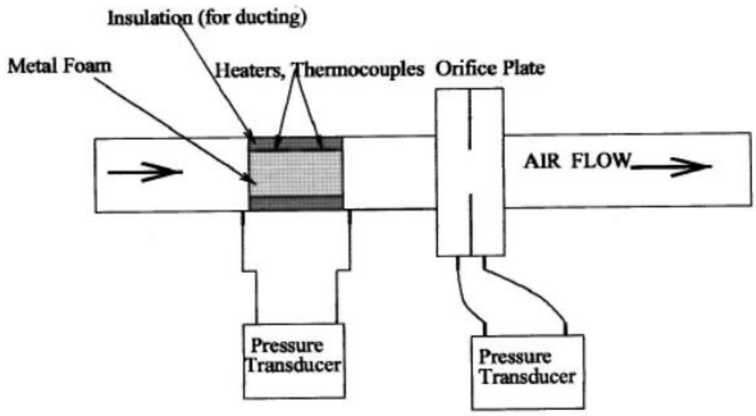

Fig. 5 Schematic of experimental setup used for forced convection experiments.[24]

The energy transport is modeled without invoking the assumption of local thermal equilibrium. Models for the thermal dispersion conductivity, kd , and the interstitial heat transfer coefficient, hsf , are postulated based on physical arguments. The empirical constants in these models are determined by matching the numerical results with the experimental data obtained in this study as well as those in the open literature. Excellent agreement is achieved in the entire range of the parameters studied, indicating that the proposed treatment is sufficient to model forced convection in metal foams for most practical applications.

T.S. Zhao [25] investigated analytically the forced convection in a saturated porous medium subjected to heating with a permeable wall perpendicular to the flow direction. It is shown that the heat transfer rate from the permeable wall to the fluid can be described by a simple equation: Nu = Pe. As compared with Nu α Pe1/2 for the case of boundary layer flow over a flat plate embedded in a porous medium, the linear relationship between Nu and Pe indicates that heat transfer can be remarkably enhanced for the case when the fluid flow direction is opposite to the heat flow direction. The analytical solution is shown to be reasonable agreement with the experimental data.

Seo Young Kim [26] investigated the impact of the presence of aluminum foam on the flow and convective heat transfer in an asymmetrically heated channel. The aluminum foams tested in this experimental investigation are made of aluminum-6101 alloy that has three different permeability at a porosity of ε= 0.92.

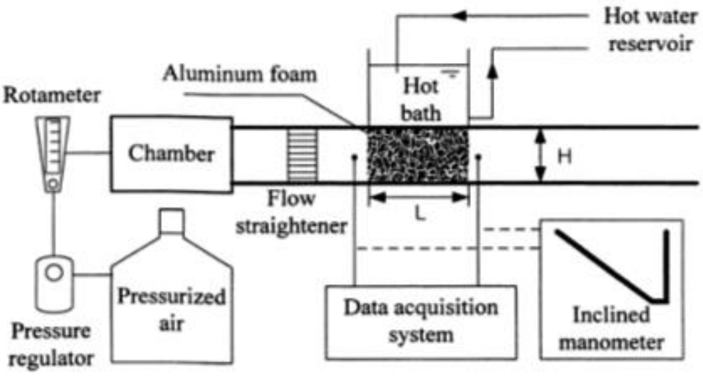

Fig. Experimental setup used by Kim [26]

$$f = \frac{1}{Re\,Da} + \frac{Ce}{Da^{\frac{1}{2}}} \quad (4)$$

$$Nu = 0.0159\,Re^{0.426}.Pr^{\frac{1}{3}}Da^{-0.787} \quad (5)$$

Aluminum foam is placed inside a channel, in which the upper wall is maintained at a constant temperature while the lower wall is thermally insulated. The simple correlation of the friction factor f and the average Nusselt number Nu of aluminum foams provide a guide in practical applications.

Pei Xue Jiang [27] experimentally investigated forced convection heat transfer of water and air in sintered porous plate channels. The effects of fluid velocity, particle diameter, type of porous media (sintered or non-sintered), and fluid properties on the convection heat transfer and heat transfer enhancement were investigated. The results showed that the convection heat transfer in the sintered porous plate channel was more intense than in the non-sintered porous plate channel due to the reduced thermal contact resistance and the reduced porosity near the wall.

Y. S. Muzychka [28] developed a new model for predicting Nusselt numbers in the combined entrance region of noncircular ducts and channels. This model predicts both local and average Nusselt numbers and is valid for both isothermal and isoflux boundary conditions. The model is developed using the asymptotic results for convection from a flat plate, thermally developing flows in non-circular ducts, and fully developed flow in non-circular ducts. Through the use of a novel characteristic length scale, the square root of cross-sectional area, the effect of duct shape on Nusselt number is minimized. Comparisons are made with several existing models for the circular tube and parallel plate channel and with numerical data for several non-circular ducts. Agreement between the proposed model and numerical data is within +15 percent or better for most duct shapes.

A J Fuller [29] presented the heat transfer characteristics of FeCrAlY (an iron-based alloy with a melting point of 1510 oC) sintered foams. The foam samples had a range of cell sizes (1–3 mm) and relative densities (4.6–12.5 per cent). Foam cores sandwiched between two conductive substrates were subjected to forced air convection with a constant input heat flux. The volumetric heat transfer coefficient is shown to depend on the effective porosity. Heat transfer is predominantly due to the increased flow mixing that the foam structure promotes. With higher-conductivity materials, the foam also acts to increase the heat transfer by providing an extended surface area, but this is not a strong effect in FeCrA1Y foams owing to the low thermal conductivity of 16 W/m K. The FeCrA1Y foam is compared with copper foam, and the latter effect is more significant.

Kouichi Kamiuto [30] derived a general correlation for volumetric heat transfer coefficient between stream of air and open-cellular porous materials by utilizing experimental data obtained by several researchers. The derived correlation is written in form of hv=(A/Ds 2-n)un. Here, hv denotes the volumetric heat transfer coefficient, A is the constant, n is the velocity exponent, u is the mean fluid velocity and Ds is the equivalent strut diameter of Dul'nev's unit cell. The parameters, A and n, were determined by a least-square fit of the expression to the above mentioned experimental data to give A=13.0 and n=0.791

Ken I. Salas [31] investigated convective heat transfer in aluminum metal foam sandwich panels with potential applications to actively cooled thermal protection systems in hypersonic and reentry vehicles. The size effects of the metal foam core are experimentally investigated and the effects of foam thickness on convective transfer are established. Four metal foam specimens are utilized with a relative density of 0.08 and pore density of 20 ppi in a range of thickness from 6.4 mm to 25.4 mm in increments of approximately 6 mm. Our experimental results indicate that larger foam thicknesses produce increased heat transfer levels in metal foams.

Tzeng [32] experimentally investigated the convective heat transfer and pressure drop in porous channels with 90-deg turned flow. Aluminum foams with a porosity of 0.93 were used. Experimental results reveal that the wall temperature was maximal at the corner under perpendicular flow entry. It fell along the channel axis until x/H was about 1.0, finally approaching a constant value. Parametric studies indicate that increasing Re increased the average Nusselt number (Nu) and the effects of Wj/H and PPI on Nu were negligible.

Sheng Chung Tzeng [33] experimentally determined the local and average heat transfer characteristics in asymmetrically heated sintered porous channels with metallic baffles. The fluid medium was air. Measurements on the test specimen of four modes, without baffles (A), with periodic baffles on the top portion (B), with periodic baffles on the bottom portion (C) and with staggered periodic baffles on both sides (D), are performed. Heat transfer enhancement was around 20-30% in mode D, around 10-20% in mode B and around 0-12% in mode C.

Frederic Topin [34] first part of his work deals with flow laws of gas, liquid and mixtures in metallic foam. Experimental work is based on the stationary pressure profile measurement in a channel filled with metallic foam of several grades or materials for several controlled flow rates. Several foam samples with different characteristics (10, 40, 60, 100 ppi) of copper and of nickel are studiedIn single phase conditions, the heat transfer coefficient was improved by two orders of magnitude with the presence of metallic foam with only a limited increase in pressure drop. In biphasic conditions, the study of convective boiling regime also showed significant heat transfer enhancement with very low-pressure drops. A simple one dimensional homogeneous model was used and allows a good description of global flow behavior across the test section.

Jian Yang [35] numerically studied the forced convection heat transfer in three-dimensional porous pin fin channels. The Forchheimer–Brinkman extended Darcy model and two-equation energy model are adopted to describe the flow and heat transfer in porous media. Air and water are employed as the cold fluids and the effects of Reynolds number (Re), pore density (PPI) and pin fin form are studied in detail. The results show that, with proper selection of physical parameters, significant heat transfer enhancements and pressure drop reductions can be achieved simultaneously with porous pin fins and the overall heat transfer performances in porous pin fin channels are much better than those in traditional solid pin fin channels. The effects of pore density are significant. As PPI increases, the pressure drops and heat fluxes in porous pin fin channels increase while the overall heat transfer efficiencies decrease and the maximal overall heat transfer efficiencies are obtained at PPI 20 for both air and water cases.

Horng Wen Wu [36] studied numerically the unsteady flow and convection heat transfer for a heated square porous cylinder in a channel. The general Darcy–Brinkman–Forchheimer model is adopted for the porous region. The parameters studied include porosity, Darcy number, and Reynolds number, heat transfer performance have been explored in detail. The results indicate that the average local Nusselt number is augmented as the Darcy number increases. The average local Nusselt number increases as Reynolds number increases. In contrast, the porosity has slight influence on heat transfer.

Tamayol [37] using a thermal resistance approach, forced convection heat transfer through metal foam heat exchangers is studied theoretically. The complex microstructure of metal foams is modeled as a matrix of interconnected solid ligaments forming simple cubic arrays of cylinders. The geometrical parameters are evaluated from existing correlations in the literature with the exception of ligament diameter which is calculated from a compact relationship offered in the present study. It is noted that increasing the height of the metal foam layer augments the overall heat transfer rate; however, the increment is not linear. Results obtained from the proposed model were successfully compared with experimental data found in the literature for rectangular and tubular metal foam heat exchangers.

Mohamed A. Teamah [38] investigated numerically, Laminar forced convective flow through a pipe partially filled with a porous material. The porous material has a cylindrical shape placed at Z=0.05L from the pipe inlet. The momentum equations are used for describing the fluid flow in the clear region. The Darcy-Forcheimer-

Brinkman model is adopted to describe the fluid transport in the porous region. The study covers a wide range of the dimensionless outer radius of the porous material 0 < Rp < 1 and the effect of Darcy number, 2x10-4 < Da < 2x10-1. In addition, the Reynolds number has values of 200, 400 and 600 while Prandtl number has values of 0.7, 5, 10 and 20. Through the study the ratio between pipe length to outer diameter and porosity were kept constant at 25 and 0.9 respectively.

Chen Yang [39] did heat transfer performance assessment for forced convection in a heated tube with a porous medium core and a tube with a wall covered with a porous medium layer, so as to investigate effectiveness of porous material insertion within a tube. Both local thermal and non-thermal equilibrium analyses were carried out for the two cases of partial porous medium filling, to investigate the validity of local thermal equilibrium assumption. It has been found that the local thermal non-equilibrium analysis is essential for the case of forced convection in a tube with a heated wall surface covered with a porous medium layer, whereas the local thermal equilibrium analysis suffices to capture transport phenomena for the case of forced convection in a tube with a porous medium core.

Joseph A. Attia [40] reported experimental data and scaling analysis for forced convection of foams and microfoams in laminar flow in circular and rectangular tubes as well as in tube bundles. Foams and microfoams are pseudoplastic (shear thinning) two-phase fluids consisting of tightly packed bubbles with diameters ranging from tens of microns to a few millimeters. These different microfoams were flowed in uniformly heated circular tubes of different diameter instrumented with thermocouples. Experimental data were compared with analytical and semi-empirical expressions derived and validated for single-phase power-law fluids.

Guilherme B Ribeiro [41] Experimental work was conducted to compare the thermo hydraulic performances of cross-flow microchannel condensers using louvered fins and metal foams as extended surfaces. Three copper foam surfaces with pore densities of 10 and 20 pores per inch (PPI) and porosities of 89.3 and 94.7%, and three aluminum louvered fins with lengths of 27 and 32 mm (in the flow direction) and heights of 5 and 7.5 mm were evaluated. A comparison based on the thermal conductance and air-side pumping power showed that the surfaces enhanced with louvered fins performed better than the metal foams under all conditions investigated.

Saman Rashidi [42] studied flow field and heat transfer around a cylinder embedded in a layer of homogenous porous media numerically. The range of Reynolds and Darcy numbers are chosen to be 1–40 and 1 x 10–8-1 x 10-1, respectively. A comprehensive parametric study is carried out and effects of several parameters, such as porous layer thickness and permeability as well as the Darcy and Reynolds numbers on flow-field and heat transfer characteristics. Finally an optimization process is conducted in order to determine the optimal thickness and porosity of the porous layer resulting in the lowest heat transfer from the cylinder.

Nihad Dukhan [43] Actual air temperatures were locally measured inside commercial aluminum foam cylinder heated at the wall by a constant heat flux, and cooled by forced air flow. Air speeds were in the Darcy regime. The permeability of the foam was directly determined from experimental pressure drop points that were obtained using the same experimental set-up. The experimental air temperatures are compared to their analytical counterparts. The volume-averaged analytical formulation employed the Darcy-extended Brinkman model for momentum, and the non-thermal-equilibrium two-energy-equation model for the temperatures of the solid and the fluid phases inside the foam. A comparison shows good agreement between the experimental and the analytical air temperatures, given the complexity of the foam’s morphology and the rounding nature of the volume-averaging technique. However, the analysis seems to under-predict the fluid temperature over most of the cross section.

Mohsen Nazari [44] studied the forced convective heat transfer due to flow of Al_2O_3/Water nanofluid through a circular tube filled with metal foam experimentally. An isothermal boundary condition is created and the pressure drop and the heat transfer rate are measured over a range of flow rates. The results are compared with values for water flowing through a similar tube without the metal foam insert. The experimental data indicate a significant improvement in the heat transfer rate at the cost of a pressure drop increase. Our experimental data also show a direct relationship between the Nusselt number and the volume fraction of Al_2O_3.

V. RESEARCH RELATED TO FLUID FLOW AND HEAT TRANSFER THROUGH POROUS MEDIA

K. Vafai [45] the present work analyzes the effects of a solid boundary and the inertial forces on flow and heat transfer in porous media. Specific attention is given to flow through a porous medium in the vicinity of an impermeable boundary. The local volume-averaging technique has been utilized to establish the governing equations, along with an indication of physical limitations and assumptions made in the course of this development. A numerical scheme for the governing equations has been developed to investigate the velocity and temperature fields inside a porous medium near an impermeable boundary, and a new concept of the momentum boundary layer central to the numerical routine is presented.

P C Huang and I L Vafai [46] analyzed a composite system made of multiple porous block structure used for flow and heat transfer control. The primary objective of this study is to analyze the changes in the flow pattern and heat transfer characteristics due to the existence of the multiple porous block structure. A general flow model that accounts for the effects of the impermeable boundary and inertial effects is used to describe the flow inside the porous region. Solutions of the problem have been carried out using a finite difference method through the use of a stream function vorticity transformation. The Darcy number, Reynolds number, Prandtl number, the inertia parameter, as well as the effects of pertinent geometric parameters, are thoroughly explored.

R. Therrien [47] a discrete fracture, saturated-unsaturated numerical model is developed where the porous matrix is represented in three dimensions and fractures are represented by two-dimensional planes. This allows a fully three-dimensional description of the fracture network connectivity. The variably-saturated flow equation is discretized in space using a control volume finite-element technique which ensures fluid conservation both locally and globally. The use of an ILU-preconditioned ORTHOMIN solver permits the fast solution of matrix equations having tens to hundreds of thousands of unknowns. Verification examples are presented along with illustrative problems that demonstrate the complexity of variably-saturated flow and solute transport in fractured systems.

Pei-Xue Jiang [48] investigated experimentally the fluid flow and forced convection heat transfer in micro-heat-exchangers with either micro-channels or porous media. The influence of the dimensions of the micro-channels on the heat transfer performance was first analyzed numerically. Based on these computations, deep micro-channels were used for the experimental studies reported here. The measured performance of both micro-channel and porous-media micro-heat exchangers are compared with those of similar heat-exchangers tested by other researchers. It is shown that the heat transfer performance of the micro-heat-exchanger using porous media is better than that of the micro-heat-exchanger using micro-channels, but the pressure drop of the former is much larger. Considering both the heat transfer and pressure drop characteristics of these heat-exchangers, the deep micro-channel design offers a better overall performance than either the porous media or shallow micro-channel alternatives.

Bhattacharya [49] presented a comprehensive analytical and experimental investigation for the effective thermal conductivity (Ke), permeability (K) and inertial coefficient (f) of high porosity metal foams. An analysis for estimating the effective thermal conductivity is provided latter on a theoretical model is presented. It also involves determination of permeability and inertial coefficient of high porosity metal foam. A permeability model is presented in terms of porosity, pore diameter, tortuosity and is in agreement with measured data.

Despois [50] proposed a simple microstructure-based model is for the permeability of open-pore microcellular materials. The permeability of aluminium open-pore foams produced using the replication process is measured using water or glycerine as the fluid, varying the average cell size (75 and 400 μm) and the relative density from 12% to 32%. Data show the expected dependence on the square of the pore size and agree with other experimental data in the literature for coarser aluminium foams produced by a casting process. The analysis agrees well with present and published experimental data over the entire density range.

Nihad Dukhan [51] proposed that despite the geometrical differences between metal foam and traditional porous media, the Ergun correlation is a good fit for the linear pressure drop as a function of the Darcian velocity, provided that an appropriate equivalent particle diameter is used. An appropriate particle diameter considering the physics of energy dissipation, i.e. the viscous shear and the form drag is investigated. The above approach is supported by wind tunnel steady-state unidirectional pressure drop measurements for airflow through several isotropic open-cell aluminum foam samples having different porosities and pore densities. For each foam sample, the equivalent particle diameter correlated well with the surface area per unit volume of the foam.

Oliver Reutter [52] investigated air flow in metallic foams, which are produced by the slip reaction foam sintering (SRFS) process. The flow through a porous medium is analyzed by Darcy’s equation with the Dupuit-Forchheimer extension. All measurements can be described very well by this equation and permeability and inertial coefficients are obtained for a large quantity of samples with different base materials and different porosities. A threshold porosity of 70% is observed, above which the pressure loss significantly starts sinking with porosity. Additionally, it was found that the permeability was anisotropic. Permeability is lower in the direction of gravity during foaming. Scattering in the data of the permeability and inertial coefficients versus the porosity is observed and discussed.

K. Hooman [53] analytically investigated fully developed forced convection in a rectangular micro-channel filled with or without a porous medium based on the Fourier series approach. The Brinkman flow model is applied with the slip velocity being accounted for. Invoking the temperature jump equation, the H2 thermal boundary condition is investigated. Expressions are presented for the local and average velocity and temperature profiles, the friction factor, the slip coefficient, and the Nusselt number in terms of the key parameters.

Sultan et al. [54] undertook an experimental study to explore the convective heat transfer enhancement that can be achieved in an impinging airflow arrangement by bonding layers of graphitic foam to a heated metal substrate. The effects of foam protrusion, foam thickness and foam properties were explored in this study. The results show that surfaces with a layer of foam protruding upward with open edges had the highest convective enhancement over that of the bare substrate under the same conditions. For the protruding cases, convective enhancements of 30-70% were observed for airflows ranging from 7-11 m/s, for foam thicknesses in the range

2-10 mm. The highest enhancements were observed for foam specimens with the most open, interconnected void structure.

Y. S. Muzychka [55] A detailed review and analysis of the hydrodynamic characteristics of laminar developing and fully developed flows in noncircular ducts is presented. New models are proposed, which simplify the prediction of the friction factor–Reynolds, product f .Re for developing and fully developed flows in most noncircular duct geometries found in heat exchanger applications. By means of scaling analysis it is shown that complete problem may be easily analyzed by combining the asymptotic results for the short and long ducts. Through the introduction of a new characteristic length scale, the square root of cross-sectional area, the effect of duct shape has been minimized. The new model has an accuracy of +10% or better for most common duct shapes when nominal aspect ratios are used, and +3% or better when effective aspect ratios are used. Both singly and doubly connected ducts are considered.

Simone Mancin [56] investigated experimentally the pressure drop during air flow in six different aluminum open-cell foam samples with different number of pores per inch (PPI) and different porosity under a wide range of air mass flow rate. Three imposed heat fluxes are considered for each foam sample. The collected pressure drop data are analyzed with reference to models available in the literature. A new simple pressure drop model, based on present data, has then been developed.

Akhilesh P Rallabandi[57] measured heat transsfer and ressure drop characteristics of a high aspct ratio duct under both jet impingment and channel flow conditions, respectively. For both cases, roughness elements in consideration are stggered and inline axial ribs. The spacing (P) to height (e) ratios studied are P/e = 2 and p/e=4; the rib height (e) to channel height (H) ratio is 0.125. Also studied is an alumnium foam roughness with a porosity of 92% and a height to channel height ratio of 0.15. Reynaulds number considered for the channel flow case(based on the hydraulic diameter) range from 10,000-40,000. Results report a 50-90% increase in heat transfer due to the use of axial ribs in both , impingement and channel flow cases. The porous foam show a more significant icrease in hear transfer cooefcient for both channel flow an impingement cases.

Simone Mancin [58] measured heat transfer coefficients during air flow heating in seven different aluminum open-cell foam samples with different number of pores per inch (PPI), porosity and foam core height under a wide range of air mass velocity. Three imposed heat fluxes are considered for each foam sample: 25.0, 32.5 and 40.0 kW/ m2. The collected heat transfer data are analyzed to obtain the global heat transfer coefficient and the normalized mean wall temperature.

H.Y. Li, K.C. Leong [59] investigated the flow boiling characteristics of water and FC-72 in aluminum foams. For the experiments, the heat transfer processes prior to nucleate boiling, the onset of nucleate boiling and the hysteresis effect were studied. Simone Mancin [60] presented experimental heat transfer coefficient and pressure drop measurements carried out during air forced convection through five different copper foam samples. The collected heat transfer and pressure drop data were analyzed to obtain the global heat transfer coefficient, the normalized mean wall temperature, the pressure gradient, permeability, inertia coefficient, and drag coefficient. The experimental heat transfer measurements reported in the present work increase the knowledge in heat transfer and fluid flow in metal foams.

Nihad Dukhan [61] Momentum transport in porous media is solved analytically in a cylindrical system, employing an existing fully-developed boundary-layer concept particular to porous media flows. The volume-averaged velocity increases as the distance from the boundary increases reaching a maximum at the center. The friction factor is defined based on the mean velocity and is found to be inversely proportional to the Reynolds number, the Darcy number, and the mean velocity.

Ahmet Ali Sertkaya [62] investigated one dimensional heat transfer of open cell aluminum metal foams is both experimentally and by using numerical methods as well. Steady heat flux was maintained electrically. Temperature distributions were measured with the thermocouples located on the aluminum foams. With the help of the recorded temperatures from the tests the graphs were plotted. The fastest drop in temperature close to the heater was observed at the foam with 10 PPI while the lowest falling rate took place at the foam with 30 PPI pore density. At an interval of three aluminum foams, the temperature difference was found to be higher near the heater and lower away from the heater. It was found that both experimental and numerical results are closely related.

Chanhee Moon [63] conducted a numerical simulation and an experiment for heat transfer of filled and hollow metal foam ligaments. the heat transfer characteristics between hollow and filled ligaments of metal foam was observed and the Nusselt number obtained with filled ligament shows higher than that obtained with hollow ligaments. The used metal foam in experiment is 40PPI and Weaire Phelan model is applied to metal foam geometry for numerical simulation.

Nihad Dukhan [64] Experimental heat transfer data for water flow in commercial open-cell aluminum foam cylinder heated at the wall by a constant heat flux, is presented. The foam had 20 pores per inch (ppi) and a porosity of 87%. The measurements included wall temperature along flow direction as well as average inlet and outlet temperatures of the water. The behavior of the wall temperature clearly shows thermal fully-developed conditions. The experimental Nusselt number is presented as a function of axial distance in flow direction, and showed what seemed to be a periodic development.

6.0 Literature related to Modeling of fluid flow and heat transfer.

Amhalhel [65] presents an up-to-date overview of the theoretical and the engineering application aspects of the porous media. Problems which arise in modeling the flow and heat transfer phenomena by momentum and energy equations, and which are not present in the corresponding free-fluid flow, are discussed in more detail. The channeling phenomenon caused by the non homogeneity of porosity near the wall is presented and models which approximate the porosity variation are demonstrated.

Wirtz [66] A semi-empirical model for conduction/convection in a thin "fin-like" porous wall of arbitrary composition and thickness is developed. The model assumes one-dimensional conduction in the porous matrix and one-dimensional flow of the coolant through the wall. Analysis shows that the equivalent unit surface conductance and the effectiveness of the porous wall are always maximum, when it is operated with the number of transfer units of the porous matrix greater than two (ntu > 2). Furthermore, if the porous matrix is composed of a packed bed of spherical particles, it is found that, for a given coolant flow rate, the pressure drop across the porous matrix is minimum when ntu < 2. This suggest that for many design requirements, the porous media exchanger should be operated at ntu = 2.

Culham [67] presented analytical models for determining laminar, forced convection heat transfer from isothermal cuboids. The models can be used over a range of Reynolds number, including at the diffusive limit where the Reynolds number goes to zero, and for a range of cuboid aspect ratios from a cube to a flat plate. The models provide a simple, convenient method for calculating an average Nusselt number based on cuboid dimensions, thermophysical properties and the approach velocity. In comparisons with numerical simulations, the models are shown to be within +6 percent over the range of $0<Re\sqrt{A}<5000$ and aspect ratios between 0 and 1.

Raffray [68] proposed an innovative technique using porous metal heat transfer in a media infiltrated by the coolant. A particularly difficult heat transfer problem exists with gas coolants, due to their inherently low heat capacity and heat transfer coefficient. The general design strategy is to minimize the coolant flow path length in contact with the porous medium, and to minimize the friction factor in that zone while simultaneously maximizing the heat transfer coefficient. A improved phenomenological thermal-hydraulic models was developed in order to assess and to help optimize the heat transfer coefficient while minimizing the associated fluid friction in innovative design concepts.

Boomsma [69] presented a new approach in modeling the flow through a porous medium with a well defined structure. To model an infinitely large matrix, periodic boundary conditions were set on the walls parallel to the flow direction, while a pseudo-periodic boundary condition with a prescribed volumetric flow rate was set over the inlet–outlet pair of the unit cell. The pressure drop data of the flow through the cellular unit were then compared on a length-normalized basis against experimental data. The increase in the pressure drop from wall effects in the simulation was quantified.

Jeng [70] a novel semi-empirical model with an improved single blow method for exploring the heat transfer performance of porous aluminum-foam heat sinks in a channel has been successfully developed. The influencing parameters such as the steady-state air preheating temperature ratio, Reynolds number and medium porosity on local and average heat transfer behavior of porous aluminum-foam heat sinks in a channel are explored.

Nihad Dukhan [71] presented a one dimensional heat transfer model for open-cell metal foam. The model combines the conduction in the ligaments and the convection to the coolant in the pores. The approach avoids a complete three-dimensional modeling of the complex flow and heat transfer inside the foam. The temperature along the foam decayed exponentially with the distance from the heated base. The model and the one-dimensional assumption were verified by direct experiment on a thin aluminum foam sample of ten pores per inch for a range of pore Reynolds number. Good agreement was found between the analytical and the experimental results.

Betchen et al.[72] presented a mathematical and numerical model for the treatment of conjugate fluid flow and heat transfer problems in domains containing pure fluid, porous, and pure solid regions. The model is developed for implementation on a simple collocated finite-volume grid. Special attention is given to the matching of the interfacial heat flux, the approximation of advected variables at the interface between pure fluid and porous regions, the pressure–velocity coupling at such an interface, and the estimation of pressure values at the interface.

Khan [73] investigated heat transfer from tube banks in cross flow under isothermal boundary condition. An integral method of boundary layer analysis is employed to derive closed form expressions for the calculation of average heat transfer from the tubes of a bank, that can be used for a wide range of parameters including longitudinal pitch, transverse pitch, Reynolds and Prandtl numbers. The models for in-line and staggered arrangements are applicable for use over a wide range of parameters when determining heat transfer from tube banks.

Hayes [74] investigated Heat transfer and fluid flow characteristics through a porous medium using numerical simulations and experiment. For the numerical simulations two models were created: a two-dimensional numerical model and a Fluent™ computational fluid dynamics (CFD) porous media model. The experimental investigation consisted of a flow channel with a porous medium section that was heated from below by a heat source. The results of the numerical models were compared to the experimental data in order to determine the accuracy of the models. The numerical model was then modified to better simulate a matrix heat exchanger. This numerical model then generated temperature profiles that were used to calculate the heat transfer coefficient of the matrix heat exchanger and develop a correlation between the Nusselt number and the Reynolds number.

Shadi Mahjoob [75] discussed the effects of micro structural metal foam properties, such as porosity, pore and fiber diameters, tortuosity, pore density, and relative density, on the heat exchanger performance. The pertinent correlations in the literature for flow and thermal transport in metal foam heat exchangers are categorized and investigated. To investigate the performance of the foam filled heat exchangers in comparison with the plain ones, the required pumping power to overcome the pressure drop and heat transfer rate of foam filled and plain heat exchangers are studied and compared. A performance factor is introduced which includes the effects of both heat transfer rate and pressure drop after inclusion of the metal foam. The results indicate that the performance will be improved substantially when metal foam is inserted in the tube/channel.

Ghosh [76] has developed heat transfer correlation, assuming a simple cubic model of open cell foam. The cross-linked porous structure is equivalent to a bundle of independent, slender tubes with protrusions. It may be presumed that the projected struts either cause an increase in heat transfer coefficient or they act as extended surfaces or fins. The effect of these protruded filaments has been judiciously integrated within the empirical correlation for cross-convective flow over the bank of smooth tubes. An augmentation in foam heat transfer coefficient has occurred due to cross-connections in struts. An excellent agreement has been observed between the predicted correlations and the existing ones which have been established through experimental data.

Yang [77] carried out numerical simulations to investigate the turbulent heat transfer enhancement in the pipe filled with porous media. Two-dimensional axisymmetric numerical simulations using the k–ε turbulent model is used to calculate the fluid flow and heat transfer characteristics in a pipe filled with porous media. The parameters studied include the Reynolds number (Re = 5000–15,000), the Darcy number (Da = 10-1–10-6), and the porous radius ratio (e = 0.0–1.0). The numerical results show that the flow field can be adjusted and the thickness of boundary layer can be decreased by the inserted porous medium so that the heat transfer can be enhanced in the pipe.

K.C. Leong [78] studied forced convection heat transfer in a channel with different configurations of graphite foams experimentally and numerically. The physical properties of graphite foams such as the porosity, pore diameter, density, permeability and Forchheimer coefficient are determined experimentally. The local temperatures at the surface of the heat source and the pressure drops across different configurations of graphite foams are measured. In the numerical simulations, the Navier–Stokes and Brinkman–Forchheimer equations are used to model the fluid flow in the open and porous regions, respectively. The local thermal non-equilibrium model is adopted in the energy equations to evaluate the solid and fluid temperatures. Comparisons are made between the experimental and simulation results. The results showed that the solid block foam has the best heat transfer performance at the expense of high pressure drop.

Mujeebu [79] provides an exhaustive review of the fundamental aspects and emerging trends in numerical modeling of gas combustion in porous media Extensive experimental and numerical works were carried out and are still underway, to explore the feasibility of Porous media combustion for practical applications. For this purpose, numerical modeling plays a crucial role in the design and development of promising PMC systems.

Kaneda [80] numerically studied heat and Fluid flow through infinite porous media. The heat and fluid flow simulations are carried out separately by the lattice Boltzmann method (LBM). It is confirmed that the LBM can simulate them properly and the permeability depends on the pore structure compared at the same porosity. The heat transfer coefficient is found to be affected not only by the permeability but also the pore structure. That is, even at the same permeability, the Nusselt number depends on the structure.

F. Kuwahara [81] introduced an effective porosity concept to account for the effects of tortuosity and thermal dispersion on the individual effective thermal conductivities of the solid and fluid phases in a fluid-saturated porous medium. Using this effective porosity concept, a thermal nonequilibrium model has been proposed to attack locally thermal nonequilibrium problems associated with convection within a fluid-saturated porous medium. Exact solutions are obtained, assuming a plug flow, for the two cases of thermally fully developed convective flows through a channel, namely, the case of isothermal hot and cold walls and the case of constant heat flux walls. These exact solutions for the cases of metal foam and air combination reveal that the local thermal equilibrium assumption may hold for the case of isothermal hot and cold walls, but may fail for the case of constant heat flux walls.

Trifale [82] proposed an optimization of porous medium heat sinks with respect to the heat transfer rate, mass, and pumping power. These are functions of the simplest geometric parameters, i.e. porosity, pore density, and length of the porous medium. The optimization is performed for a specific value of porosity and length of the heat sink. The model considers the effect of flow through the porous medium and the effective thermal conduction as a function of combined conductivity of the solid ligaments and the fluid in pores. An optimum coefficient of performance (COP) is found at over 90% of porosity for minimum mass, pumping work and maximum heat transfer. This mathematical expression of the model will give a quantifiable figure-of-merit to take into account the impact of the mass and the pumping power on the performance to cost ratio.

VI. CONCLUSION

Research work related to the Heat transfer in open celled metal foams is reviewed. The forced convection has been extensively investigated, it is observed that few researchers have carried out research about porous fin tube heat exchanger with configuration similar to conventional fin tube heat exchanger, involving forced convection between hot fluid as water and cold fluid as air, and hence there is scope of research in such heat exchangers.

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