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# Comprehensive case study on heat transfer enhancement using micro pore metal foams: From solar collectors to thermo electric generator applications

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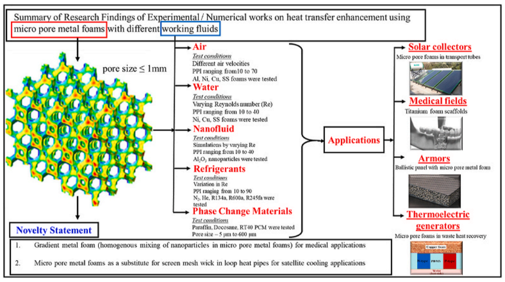
## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

Open cell metal foams also called as porous substrate, are found to be one of the best contenders for enhancing the heat transfer rate, with added advantages of light weight and compact size. The unique characteristic of metal foams that distinguishes from typical solid metals has gained significant attention and finds possibilities of using it in many industrial applications. This article addresses the summary of recent research works on the enhancement of heat transfer and improvement in effective thermal conductivity by using micro pore metal foams with pore size of ≤1 mm. In addition, the article summarizes the forced convective heat transfer studies with air, water, refrigerants and nanofluids using micro pore metal foams which have not been addressed

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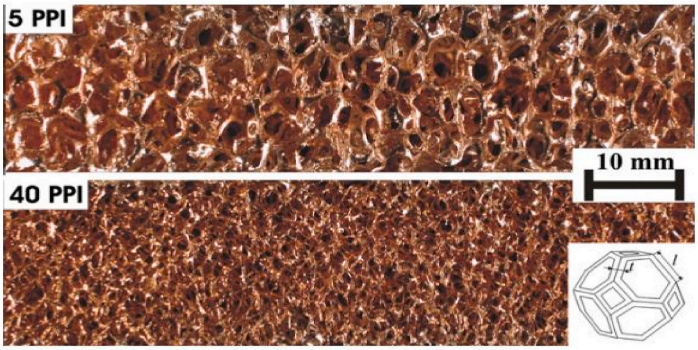
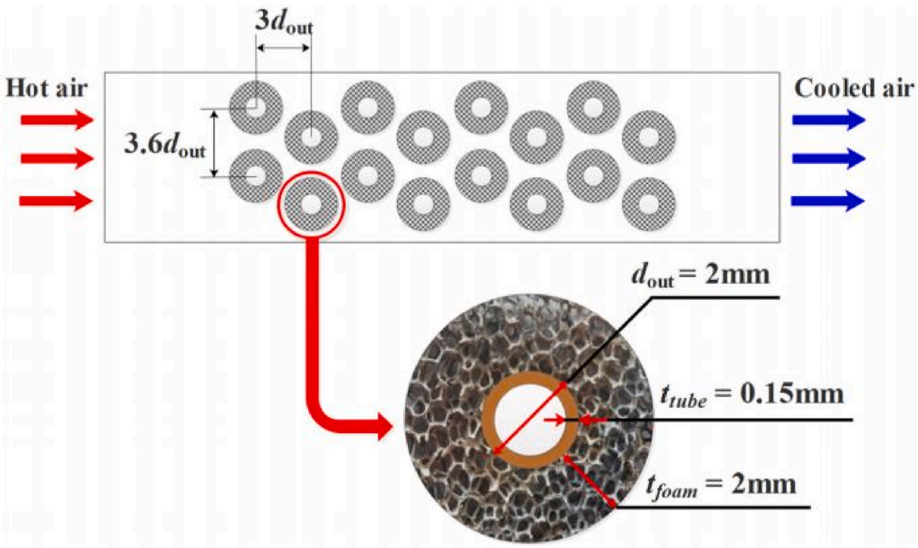
in existing literatures. Effects of porosity and pore density on heat transfer enhancement (HTE) based on experimental/numerical works are also discussed. Finally, it concludes with the applications of using metal foams in various fields and identifies the opportunities and challenges for future research.

## 1. Introduction

The need of removing heat per unit volume of modern miniaturized electronic devices has been a demanding field. Developments involving heat transfer has covered many areas such as heat removal from processors [1–3], automotive sectors specifically in radiators [4], cooling of circuit boards, de-icing systems in aerospace field and wind turbines [5], chemical processing industries [6], waste heat recovery systems [7] and condenser sections. The enhancement in heat transfer by convection became very essential in the existing thermal systems. Conventional heat transfer methods such as heat sinks, finned systems, thermoelectric cooling etc. do not satisfy the present cooling requirements [8]. Moreover, an exponential growth in miniaturization of modern electronic devices resulted in higher order of heat rejection rates [9]. Thus, the expectation in reducing the dimensions routinely makes the researchers to indulge in finding an appropriate solution for extracting the generated heat, thereby increasing the reliability of the product's profile. It is well known




(a)




(b)

**Fig. 1.** (a) Copper metal foams with pore density of 5 PPI and 40 PPI [From Mancin et al. [18], with permission from Elsevier] (b) Dimension of Aluminium foam bundles [From Chen et al. [27], with permission from Elsevier].

that, increase in surface area consequently leads to higher heat transfer [10–15]. Thus, one method of achieving higher heat transfer is with the use of porous media. The development of porous section has now moved towards metal foams in order to efficiently resolve thermal management problems [16]. Many experimental and numerical studies were carried out to understand the heat transfer characteristics and pressure drop (ΔP) of working fluid by using metal foams. Incorporating metal foam increases the ΔP and proved to be significant one to transfer heat from the heat source. This is due to the higher surface-volume ratio of metal foams that ranges from 500 to 3000 $m^2/m^3$ when compared to fins whose value is found to be 250 $m^2/m^3$.

Metal foams that are developed for structural applications, has been majorly used now a days for thermal management problems. Copper, Aluminium and Nickel due to higher thermal conductivity, their existence became an essential one for efficient heat transfer. Rather utilizing it as a single bulk material, for the requirement of less weight and more surface area density, these metals were reformed in to foams depending on major influencing parameters such as porosity, pore size, cell size and fiber thickness. With an aid of technological advancement such as intrinsic blowing agent, high pressure foaming technique and foam control by mechanical pressure handling, micro pores metal foams with relatively less density and pore size (pore diameter) below a millimeter are developed [17]. As pores of these micro pore metal foams are highly organized and interconnected, they are found to be good substitute in some applications like heat exchangers, high temperature filters etc. Initial studies have been carried out with foams by concentrating on pore size ranging from 5 to 30 PPI in the areas of refrigeration systems, where flow boiling heat transfer occurs in evaporator section in mini channels. Recent research works have covered the convective heat transfer characteristics of micro pore sized foams made of high conductivity metals. Assessment in convective heat transfer with micro pore sized foams became a valid research in modern times.

This article summarizes the recent research of using metal foams for the HTE using different working fluids such as water, air, refrigerants and nanofluids. Moreover, enhancement in storing thermal energy with the combination of PCM and foams are also discussed. In addition, the practical applications of metal foams in medical fields, armor sectors, solar collectors and thermo electric power generation have also been covered in this comprehensive review. Also, this article addresses the prospects of future works thereby to develop an efficient method to satisfy the present and future cooling requirements.

## 2. Forced convection heat transfer through micro pore metal foams

### *2.1. Air/water/nanofluid flow through micro pore metal foams*

Convective heat transfer studies with relatively higher thermal conductivity metal foams with pure fluids and water based nanofluids have become a significant research in the field of thermal management. Particularly in the field of electronic cooling, heat sinks with micro pore metal foams were developed in recent times and have been employed in real applications. The following research works deal with some of the most productive works on the forced convective heat transfer study through micro pore metal foams. Mancin et al. [18] experimentally analyzed the HTP of copper foams (40 PPI) by varying the frontal velocity of air from 2.5 to 5 m/s and stated that the inlet air velocity determines the interstitial and overall heat transfer coefficient of copper foam whereas heat flux has no significant influence. Also, decrease in the heat transfer performance was observed for increase in pore density of foams. The copper foam with 5 PPI and 40 PPI is shown in Fig. 1(a). Shih et al. [19] experimentally analyzed the HTC of Al foams with solid aluminium core by varying the contact ratio ($\alpha$=0 to 0.013) and height to diameter ratio (h/d=0.15 to 0.92) at constant inlet air velocity. Increase in Nusselt number was observed for the minimum h/d ratio as the cooling air is forced to move towards the heated surface thereby providing effective cooling. The effect of varying the contact ratio was also stated to be a significant factor for the heat transfer enhancement. Hamadouche et al. [20] explored the possibilities of improving the heat transfer by conducting experiments on turbulent forced convection through Aluminium foams placed as baffles. A detailed study was carried out by analyzing the foam height, pore density and porosity. Turbulence on air flow and higher permeability of Al foams were noted to be the reason for the HTC when compared to solid baffles and foamless channels. Lai et al. [21] experimentally analyzed the effect of porosity ($\phi$=0.85–0.95) and pore density (5–40 PPI) of copper metal foam under dehumidifying conditions. Initially, the HTC increases for less air humidity but then decreases for further increase in the humidity level. The condensing droplets from air on to the metal foam increases for higher PPI foam and block the path of flowing air which was found to be the major reason for decrease in HTC. To overcome this, an experimental work with lower PPI copper foams under dehumidifying conditions was carried out by Hu et al. [22]. The irregularity and complexity of the metal foam structure and higher relative humidity of air, increases the nucleation site density of foam, leading to higher heat transfer enhancement effect. However, increase in cooling water temperature reduces the degree of sub cooling which was observed to be major reason for decrease in latent and sensible heat transfer. Nawaz et al. [23] experimentally studied the thermo-hydraulic performance using Aluminium foam under dry air flow conditions and also developed a model to predict its performance. Based on the results, increase in frictional pressure drop and HTC was observed for the maximum pore density foam (40 PPI). The calculated values of friction and Colburn factor were found to be in good agreement to prediction with a deviation of ±14.86% and ±4% respectively. Also, it was suggested to have more than one unit scale to accurately predict the ΔP and heat transfer rate (HTR) of high pore density foams. Wang and Guo [24] conducted experiments on the heat transfer performance of Stainless Steel foam filled tubes under convective boundary conditions. At constant porosity ($\phi$=0.93), the effect of pore density (10, 30 and 70 PPI) and inlet air velocity ($V_{in}$=7–26 m/s) on heat transfer and ΔP at the exit of foam was studied. Nusselt number (Nu) was observed to be higher for high pore density foam as the convective HTR between foam fiber and air increases. Also, the ΔP characteristics were discussed clearly by stating the effect of viscous and inertial drag of air flowing at different velocities. Feng et al. [25] experimentally investigated natural convection through metal foams by varying the slot widths (0–20 mm) and foam height (10–80 mm). Enhancement of 38.2% in HTC was observed for the optimum slot width ranging from 5 to 8 mm and foam height of 80 mm. However, the HTC was found to have less significance for smaller height metal foam. Also the authors stated that, the heat permeation through foams was the key factor for the HTC for a natural convection process. Huisseune et al. [26] conducted numerical analysis by comparing metal foam (10–45 PPI) inserted heat exchanger with foamless tube heat exchanger. This work was mainly focused on low Reynolds number (Re) applications and the authors used cylindrical heat exchangers which is mainly applicable for air conditioning systems and heat pumps. The HTR of Aluminium foam with 45 PPI was found to be 6 times higher when compared to foamless tubes. However, the variation was found to be less when compared with louvered fin type and further increase in the pore density of foam was suggested to enhance the heat transfer performance of metal foam inserted heat exchanger. Chen et al. [27] conducted experiments to determine the HTP of nickel foam with different PPI (20–80 PPI) as shown in Fig. 1(b). At low Re, a flow resistance phenomenon called “thermal insulation effect” was stated to occur for higher PPI foam. This was due to the decrease in permeability of the working fluid leading to low velocity flow through foams. However, for higher Re flow, the Nusselt number and pressure drop were observed to be higher for the maximum pore density foam. Bai and Chung [28] carried out a computational analysis on heat transfer and ΔP by focusing only a single cell in metal foams (10, 20 and 40 PPI) due to its repetitive cell structure. It was stated that, the ΔP across the metal is the only function of velocity, when porosity, pore density and the properties of foam are kept constant. In addition, intensification of turbulence due to the micro-filaments in high pore density foam is found to be the reason for less velocity gradient and thin boundary layer. Moreover, the HTR and ΔP of foamed channel was observed to be higher than the open micro channel. Dukhan and Suleiman [29] conducted simulation to analyze the thermal flow development in open metal foam (20 PPI) place between two semi-infinite parallel plates. The inlet air velocity was considered as the varying parameter from which thermal entry length was determined. The estimated Nu was then correlated with Re based on the diameter of the cell fiber. It was observed that for increase in Re the Nu for a fully developed region, showed a different response for both Darcy (decreasing trend) and Forchheimer (increasing trend) regimes. Moon et al. [30] performed a three dimensional numerical analysis with Weaire-Phelan model to study the effect of ligament hollowness of copper metal foams (30 PPI) as shown in Fig. 2.

Based on the numerical results, increase in ligament hollowness was was stated to be responsible for the decrease in HTR and Nu as higher number of pores in the ligament fiber reduces the surface area and conduction effect of metal foam. Orihuela et al. [31] conducted an experimental and numerical study of forced convection through Aluminium metal foam. Effect of flow rates (20, 85,150 LPM) and pore density (5 and 20 PPI) on heat transfer performance of foam was analyzed. Thermal entry length was suggested to consider as a main criteria in designing the heat exchanger either with fully or partially filled metal foams. The effect of residence time on exit air temperature for different flow rates was also stated clearly. Xu et al. [32,33] carried out numerical investigation on fully developed convective heat transfer sintered with two pore density foams stacked together (5&40 PPI) using Brinkman extended Darcy model and LTNE method. The influence of interfacial radius on Nu, Re and flow velocity were clearly discussed. Moreover, increase in

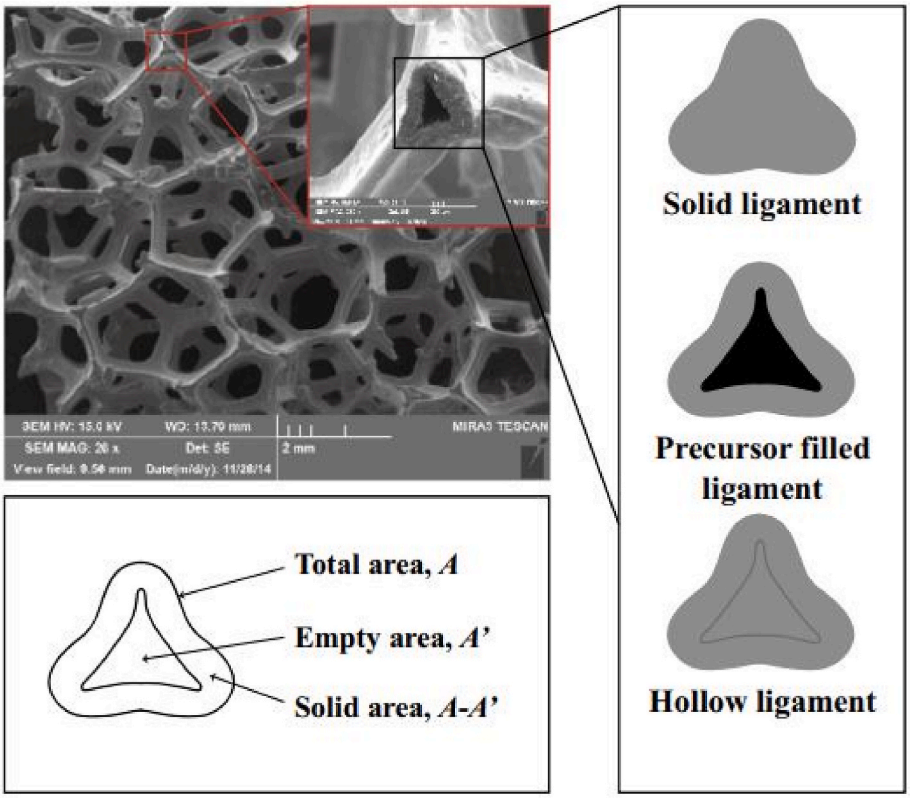



Fig. 2. Cross sectional geometry of foam ligament [From Moon et al.[30], with permission from Elsevier].

velocity gradient was observed from wall to the tube centre as the pore density of foam decreases from 40 PPI to 5 PPI. Ghafarian et al. [34] proposed a numerical work on an oscillating flow through a channel filled with Aluminium metal foam (10, 20 and 40 PPI). Computational analysis was done using Darcy-Brinkman-Forchheimer model to determine the heat transfer rate by conduction (through ligaments of foam) and convection (from ligament to working fluid). Due to the existence of two thermal entry regions, the enhancement in Nusselt number (170-20) was stated to be less significant for increase in velocity amplitude (1.8–2.6) for an oscillating flow. Torabi et al. [34] proposed a numerical study on thermodynamic perspective to analyze the entropy generation inside the gradient metal foams. Circular and square shaped foam were used for the analysis across which the working fluid was made to flow. Local entropy generation was observed to be higher at the entry section and at the centre for low and high Reynolds number. In addition, it was stated that, square section of foam had better outcome on heat transfer rate for different Reynolds number and at constant porosity.

Bayomy et al. [35] investigated the HTC of Aluminium foam (40 PPI) heat sink tested under uniform heat flux (13.8 W/cm$^2$ to 8.5 W/cm$^2$). Based on the experimental results, increase in Nu and thermal entry length was observed for increase in Re. A correlation for Nu as a function of Re was also proposed for a non-Darcy flow regime. Moreover, the surface temperature and Nu obtained from numerical results were found to be in good agreement with the experiments with highest relative error of 0.43% and 0.83% respectively. Arbak et al. [36] developed a cylindrical shell to study the HTE using water flow through metal foam. Decrease in thermal entry length from 150 mm to 122 mm was observed for increase in pore density (10–40 PPI). In other words, when pore density value becomes higher, the length at which the HTC of water becomes steady is less. In addition, stronger inertial effects at higher fluid velocity were found to be the reason for enhanced heat transfer rate at higher pore density foam. Bagci and Dukhan [37] proposed an experimental work on ΔP in metal foams with constant porosity ($\phi$=0.88) and different pore densities (10–40 PPI). Transition of flow regimes from pre-Darcy to turbulent flow was discussed using friction factor and ΔP as a function of Re. Moreover, the friction factor was found to be independent of Re (Re close to 100) for turbulent regime and the pore size has only minor role on flow transition. Ji and Xu [38] conducted experimental and numerical analysis to determine the two phase ΔP in copper foams (30, 60 and 90 PPI) using De-ionized water (DI) by varying the mass flux ($m_{flux}$) (30–200 kg/m$^2$s) and inlet fluid temperature (40–80 °C). Increase in ΔP of 8 kPa was observed for the maximum heat flux when using 90 PPI foam. Higher bubble generation was the reason stated for the increase in total ΔP (single phase and two phase flow). A new correlation was also proposed to predict the two phase ΔP across metal foam by considering mass flux, vapor quality and pore diameter and the measured values agreed well with predicted one with the deviation of ±15%. Peng et al. [39] proposed a numerical study to investigate the effect of thermal conductivity of metal foam on Nu under constant heat flux condition (q=100 W/m$^2$). The metal foam with porosity and pore diameter of 0.95 and 0.7 mm respectively was partially filled in the core of the tube and subjected under laminar flow conditions. The existence of radial velocity towards the wall and higher velocity gradient near the tube wall was stated to be the significant mechanism responsible for the enhancement of Nu. Mahdi et al. [40] carried out numerical investigation with different geometrical shapes of Aluminium foam having different pore densities (5–40 PPI) and at inclination angles (69.44$^o$, 73.3$^o$, 77.32$^o$, 81.47$^o$, 58.71$^o$ and 90$^o$) were carried out. The governing equations such as mass, momentum and energy were solved using finite volume method. Higher *Nu* value was noted for the foam with 40 PPI and at the inclination of 90$^o$. Similarly Mahdi et al. [41] conducted numerical analysis on convection heat transfer of nanofluids using various foam (10 and 40 PPI) geometries under constant heat flux (q=300 W/m$^2$) condition. The effect of aluminium foam along with the properties of nanofluid on Nu and friction factor was analyzed. The governing equation such as continuity, momentum and energy are solved using Finite volume method. By analyzing four different geometries, decrease in the Nu value was observed for the minimum angle of foam. In addition, maximum Nu was attained for the model where the surface area of metal foam is higher.

Park et al. [42] conducted experimental and numerical method for evaluating convective HTC for open cell metal fins at low Re. The extended surface which has a contact was considered as fins. It was observed that when equivalent diameter was taken as characteristic length, variation of Nu value seems to be less. Moreover, Nu for low velocity flow was presented in the form of Dittus-Boelter correlation. Siavashi et al. [43]. Darcy Brinkman Forchheimer relation was used for flow analysis through the annulus. It was noted that permeability reduction in metal foam causes more entropy generation. Moreover, it has been stated that there is an optimum level of metal foam thickness for each volume fraction flowing through at definite Re. Rashidi et al. [44] performed numerical analysis with square diamond shaped porous medium under the effect of magnetic field in traverse direction. It was observed that traverse magnetic field has greater effect when compared to the magnetic field input along the stream line. Mantelli [45] conducted a simulation on cross flow cooling towers with porous media and thermosyphon. The main aim of this work is to cool the hot air using ambient air, thus recovering the exhaust vapor in the form of condensate which will be released in to the atmosphere as waste heat. Entropy generation concept was discussed and it was stated that 30% of waste heat recovery was achieved from this work. Pozzobon et al. [46] in order to investigate the level of water recovery in a reduced scale cross flow cooling tower using metal foam plate heat exchangers. Stainless steel was used as a porous material and it was observed that 10% process water can be recovered.

In addition to the extensive studies on flow boiling HTC of different fluids in micro/mini channel and helical coils, heat transfer behavior of nanofluids in porous media received greater attention in solving thermal management problems. Nazari et al. [47] studied forced convective heat transfer in a pipe containing metal foams. Increase in Nu was noted when the volume fraction of nanofluids was increased. Enhancement of 300% in heat transfer performance was reported for metal foam inserted tube when compared with the foamless channel. Generally a porous medium consists of a complex structure with an appropriate pore size ranging from 0.1 to 10 μm. Of concern to many industries where nanofluids are employed, particle retention/settlement in porous media is considered as a major issue irrespective of pore size. This retention restricts further propagation of nano particle in the porous media and reduces the HTP. Therefore, a detailed study on particle motion and its settlement in porous media has become a valid research in the present context.

Nanofluids with higher stability can be achieved by using nano particles with much smaller sizes ranging from 1 to 100 nm due to which, the nanofluid flow through the porous media can be expected without any particle deposition. However, the physicochemical interaction that occurs between nanoparticles and metal foam fibers result in a significant retention which changes the wettability characteristics of porous media and also reduces its permeability [48–51]. In certain circumstances, some nanoparticles tend to block the flow channel irrespective of pore and particle size. This condition was noted due to the occurrence of nano particle agglomeration. Also, based on the open literatures, the nanoparticle settlement also depends on other factors such as fiber roughness, surface charge of nano particle/porous media, nano particle to pore size ratio, particle concentration, permeability of porous media, temperature and mass flow rate. Therefore, future research must be focused on reducing the nanoparticle settlement rate in porous media to enhance its heat transfer performance thereby providing a useful guide for the engineering design.

### *2.1.1. Inferences from forced convective heat transfer through micro pore metal foams*

The observations from previous research works on forced convective heat transfer with air/water through micro pores metal foam was discussed below. It clearly shows that the metal foam substantially increases the ΔP and heat transfer of the working fluid. Materials of good thermal conductivity like copper and Aluminium have been widely used as a foam material thereby enhancing the HTC. Based on experimental results, the porosity and pore density are the major influencing factors in which most of the comparative way of research has been carried out between foam and foamless channels. Additionally, other factors such as fiber thickness, effect of ligament hollowness, height and geometry of foams were also discussed for low and high Re applications. Also, a common conjecture was stated by the authors that, increasing the PPI with constant porosity will exceptionally enhance the HTR. However, most of the above-mentioned works either experimental or numerical, it were constrained for foams with 40 PPI and mere research were carried out for further increase in pore density irrespective of foam dimension. Despite having few numerical works on heat transfer with nanofluids and metal foams, clear explanation and comparison of numerical results with the experiments are deficient. Also, the discussion and the justification on nanoparticle settling or blocking the micro sized pores when using nanofluid to flow through the foams were not discussed in the open literatures. Due to a lack of knowledge about the thermal behavior of micro pore sized foams, experimental research on forced convective study in later days should be performed on increased PPI of micro pore metal foams. Table 1 points up the summary of some of the published experimental and numerical investigations on convective heat transfer study

**Table 1**
Summary of experimental and numerical investigations for Convection heat transfer with air/water through micro pore metal foams.

| Author | Exp/ Numerical | Foam/working fluid | Porosity of foam | Pore size/PPI | Input parameters | Results and remarks |
|---|---|---|---|---|---|---|
| Mancin et al. [18] | Exp. | Cu/air | 96.4% | 5, 10, 20, 40 | Varying $q = 25, 32.5, 40$ kW/m$^2$ | Pressure drop is higher for 40PPI. HTC depends more on mass flow rate than heat flux. |
| Hamadouche et al. [20] | Exp. | Al/air | 93.8% | 5,20,40 | Constant $q = 2$ W/cm$^2$ | Usage of foams as baffles decreases the pressure drop due to its increased permeability. |
| Lai et al. [21] | Exp. | Cu/air/water | 85%, 90%, 95% | 5 to 40 | $T_{in,\ air} = 27, 30, 32, 35\ ^\circ C$ | When ϕ increases from 85% to 95% HTC was observed to be decreased by 22.-32% |
| Nawaz et al. [23] | Exp. | Al/air/ethylene glycol | 93%–97% | 5, 10, 20, 40 | Air inlet temperature = 31–37°C, Air velocity 3–7 m/s | HTC was observed to be higher for larger pore density foam even for higher velocity of air. |
| Wang and Guo [24] | Exp. | Stainless steel/ air | 93% | 10, 30, 70 | Air velocity 7–26 m/s Constant $T_{in,\ air}$ =373.2K | *Nu* was found to be greater for 70 PPI foam with increase in Re. |
| Huisseune et al. [26] | Exp. | Al/air | 90%–95% | 10,20,30,35,40,45 | Constant $T_{in,\ air}$ =65°C | HTC was 6 times higher than foamless heat exchanger when PPI was increased to 45 PPI. |
| Bai and Chung [28] | Numerical | Al/air | 95% | 5 to 40 | $T_{in,\ air} = 27 - 35\ ^\circ C$, Constant $T_{wall} = 350K$ | HTR was twice greater for foamed channel than the micro channels. |
| Moon et al. [30] | Numerical | Cu/air | 96% | 30 | Constant $T_{in,\ air}$ 328K | Hollowness value of 0.79 reduces *Nu* to 40% that the solid fiber ligament |
| Ghafarian et al. [34] | Numerical | Al/air | 90% | 10, 20, 40 | Frequencies 0, 4, 8Hz Amplitude 1.8, 2, 2.2, 2.6 m/s | Higher amplitude and frequency value of flow increases the HT rate |
| Bayomy et al. [35] | Exp. Numerical | Al/water | 90% | 40 | Varying $q$ =8.5 and 13.8 W/cm$^2$ | Thermal entry length increases for increase in Re |
| Arbak et al. [36] | Exp. | Al/water | 88.5% | 10, 40 | Constant heat flux 15518 W/m$^2$ for lower $m_{air}$, 26865 W/m$^2$ for higher $m_{air}$ | Thermal entry length was 150 mm for 10PPI and 122 mm for 40 PPI. |
| Mahdi et al. [40] | Numerical | Al/$Al_2O_3$ nanofluid | 89%–92% | 5, 10, 20, 40 | $\phi_{np} = 1 - 4\%$ $D_{np} = 15$ nm, q =300 W/m$^2$ | Higher convection rate was observed for $\gamma = 69.44^\circ$ |
| Aghaei et al. [49] | Exp. | FeCrAl, NiCrAl, Cu/Co/$N_2$&He gas | 93%–98% | 60 to 110 | $T_{wall} = 300^\circ C$ and $500^\circ C$, $m_{f,g} = 25, 30, 35$ NI min$^{-1}$ | Higher HTC was obtained for copper foam by using $N_2$ gas. |
| Wang et al. [50] | Numerical | Ni/air | 95% | 10, 30 | | Increase in thickness of foam from 0.1 to 0.3 increases the ΔP. 10PPI with φ =95% has better HTP. |

with air/water/gas and micro metal foams.

### 2.2. Refrigerant flow through micro pore metal foams

Conditioning air with commercial refrigerants became quite popular now-a-days as it has two advantages. It cools the air to lower temperature and it dehumidifies the atmospheric air which enters in to the room. On the other hand, flow boiling of refrigerants takes place as it absorbs the temperature of surrounding air. The following literatures reveal the potential of using micro-pore metal foams in evaporator section.

HTP for turbulent regime was also experimentally studied by Abdelmalek et al. [52] in which a clear analysis on the influence of hollow struts in FeCrAl alloy foam was carried out. Presence of hollow struts are stated to be the reason for decrease in HTP. Aghaei et al. [53] conducted experiments to determine the heat transfer on open cell metal foams with high PPI. FeCrAl alloy, NiCrAl alloy, Cobalt and copper were used with different porosities and PPI and the hollow struts in FeCrAl alloy was shown in Fig. 3. The pore diameter varies from 0.19 mm to 0.49 mm $N_2$ and He gases were used as heat transfer fluid that passes through the porous medium. Wall HTC was focused more in the study and it was stated that resistance in heat transfer due to the distance between the outer surface of metal foam and inner surface of tubular structure plays a vital role. Thus, it was suggested that higher velocities are not needed rather, good thermal conductivity working fluids are better enough for effective heat transfer. Even though most of the investigations are focused on single phase flow and boiling heat transfer, some of the researches have dealt with condensation heat transfer stating that metal foams have vast potential in making heat transfer stronger. Moreover, the HTP was good for counter flow than the con-current flow. Wang et al. [54] proposed a numerical model for comparing metal foam covered cylinders with bare cylinders. Darcy-Forchheimer-Brinkman momentum equation and local thermal non equilibrium energy equation was developed to investigate HTP and ΔP. Moreover, for foam thickness ($t_{foam}$) of 0.1 and 0.3 m the ΔP seems to be good when compared to the bare tube. Dixit and Ghosh [55] have done an experimental work on aluminium and copper metal foams in order to determine the cooling capacity of foam at constant temperature. Thermal model for analyzing radiative cooling capacity has been done. High porosity foams are used as extended surface. It was noted that the foam temperature was considerably less when the volumetric flow rate of the convective fluid was reduced. Experimental investigation with finite element analysis was carried out by Amani et al. [56]. In addition, material design optimization and flow convection were also carried out. X-ray computed tomography was used to obtain the micro structure of the metal foam and it was noted that low porosity foam shows enhanced thermal conductivity thereby resulting in good heat transfer. Li et al. [57] conducted an experimental study on the HTE of gas tube partially filled with metal foam. The efficiency of the system was determined based on PEC also called as an evaluation index. The authors concluded that for low Re, the metal foams of low porosity value and increased volume of foam will yield proficient heat transfer. Analytical model was developed to determine the HTR and CFD model with the use of Ansys Fluent was used to assess the ΔP in metal foams. Wang et al. [58] proposed an experimental work with charcoal powder as porous media in which heat and mass transfer was studied. It was observed that when the humidity level is less, the temperature gradient between inlet and outlet of humidifying gas seems to be small. Whereas for increase in humidity level, the temperature gradient seems to be more. Fouling concept was described by Hooman and Malayeri [59] in which they used metal foams as gas coolers for exhaust gas recirculation system using aluminium metal foams. Parameters such as HTC, ΔP, soot deposition, fouling resistance were discussed clearly. It was found that blockage ratio and velocity of gas flow influences more on heat transfer and fouling factor. Visualization of soot deposition on metal foam was observed for different velocity of gas. However, decrease in heat transfer was observed for higher PPI value.

Zhu et al. [60] made an experimental work in finding the HTC of oil and refrigerant inside circular tubes in which copper metal foam was inserted. The vapor quality of air (x) was varied from 0.175 to 0.775 and it was stated that the flow boiling coefficient was higher for the metal foams with higher PPI value. Similar work has been done to find the boiling HTC due to variation in tube diameter and film condensation in a circular tube using commercially available refrigerants [61]. The varying parameters in these works are mass flux, heat flux, vapor quality, pore density and porosity. In addition, empirical relation was developed to determine boiling HTC in a sub cooled flow. Abadi et al. [62] dealt with heat transfer study through different metal foams by varying the pore densities in a flat

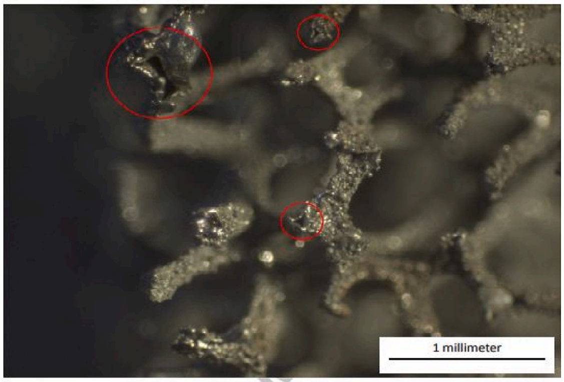



**Fig. 3.** Hollow struts in FeCrAl alloy metal foam with pore size of 1 mm [From Aghaei et al. [53], with permission from Elsevier].

plate heat exchanger. Though experimental values were collected, comparing it with numerical values in order to find the thermal hydraulic behavior is not possible as correlations for conventional heat exchanger cannot be used for the heat exchangers where refrigerants and metal foams are used. Thus authors developed new correlations to compare results which were found to have an uncertainty of 30%. For some applications, there will be a need of higher heat transfer with in a constrained size say ORC, micro power generator etc. In these cases, as obvious, metal foam's thermal conductivity should be at the higher level when compared to that of convective fluid. Abadi et al. [63] focused on heat recovery in Organic Rankine cycle system in which metal foams were inserted in the flow channel. R245fa refrigerant was used as a coolant to study both single phase and two-phase flow. It was observed that the foams of low PPI increases the overall HTC 2.3 times greater when comparing with heat exchanger where metal foams are not placed. The author stated that 10-KW capacity heat exchangers has been widely used especially in ORC's which yields around 10% efficiency and incorporating metal foams with heat exchangers will be a promising one. Similarly Abadi and Kim [64] investigated the working of phase change evaporators with zeotropic refrigerant. This work was done to evaluate the HTP of a heat exchanger using R245fa and combination of R245fa/R134a refrigerants along with copper metal foam. An improvement in overall HTP was observed by relating HTC and effectiveness. HTP for increase in mass flux is greater for combination of refrigerants than pure R245fa. The above-mentioned works dealt with heat transfer and ΔP only for larger channels and no work has been done for smaller channels. However Abadi and Kim [65] have proposed an experimental work on heat transfer and ΔP using very small tubes in a metal foam filled heat exchanger. Copper metal foams are inserted in to the tubes where constant heat flux is given outside. As correlations which have been developed by researchers are suitable for bigger channels, results for reduced test section area were not as expected. Therefore, new correlation has been developed by the authors mainly for smaller channels. Gao et al. [66] presented an experimental work on flow boiling HTC of R134a in an open-cell metal foam mini-channel evaporator. Different flow patterns were discussed in this work along with its transition as shown in Fig. 4. It was observed that for higher heat flux and quality, HTC gets increased. Moreover, nucleate boiling along with evaporation are the two main reasons for effective heat transport. The authors concluded that, HTC and pressure drop are 1.5 and 2.7 times greater for ME when compared to OMFME. Abadi et al. [67,68] conducted experiments on flow boiling visualization and heat transfer in metal foam filled mini tubes. By adding the porous material in the tube, it was observed that the improvement in heat transfer area was about 3.2 times greater when compared to the foamless tube. HTC was determined by heat flux, vapor quality and mass flux. Moreover, by increasing the quality of the vapor, there exists a noticeable change in flow pattern from intermittent flow to

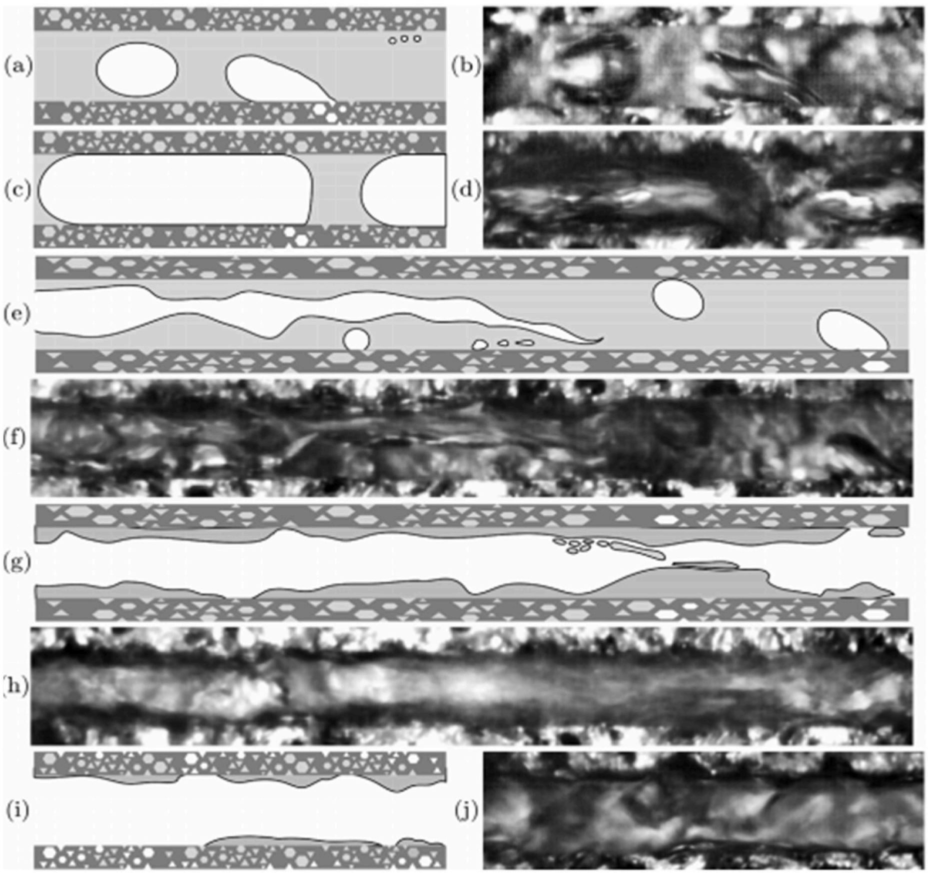



**Fig. 4.** Flow pattern between two open cell copper foams (a),(b) bubbly flow (c),(d) Slug flow (e),(f) slug-churn flow (g),(h) annular-churn flow (i), (j) annular flow [From Gao et al. [66], with permission from Elsevier].

annular flow. Thus, the enhancement in HTC due to increase in mass flux has a greater effect when compared to the enhancement due to heat flux. An extension of this work was done based in which it was stated that pressure drop occurs as a function of vapor quality and also PPI value of metal foam.

Even though the refrigerants are used in many real time applications, various attempts are carried out nowadays to enhance its thermal conductivity. As a consequence, the nano-refrigerant is one kind of nanofluid in which the base fluid is the refrigerant and high thermal conductive nano particle are suspended in it. The nano-refrigerant was noted to have higher heat transfer coefficient value when compared with the base refrigerant which can be employed to enhance the HTP of refrigeration systems. Also, the thermal conductivity of nano-refrigerant is observed to be very higher when than the conventional refrigerants. Based on the survey, the thermal conductivity of a nano-refrigerant can be enhanced by increasing the volume fraction of nano particles or by using high thermal conductivity nano particles. However, deposition and instability of nano particles can be noted when the volume concentration increases. Therefore the usage of the first method is limited and the second one becomes quite interesting.

### 2.3. Thermal enhancement of phase change material (PCM) with micro pore metal foams

Technologies involving energy storage are considered to be of great interest due to its higher potential to bridge the gap between energy demand and supply. The commercial PCMs are used as an energy storage medium and its storage capacity varies from 5 to 14 times higher than the sensible heat storage materials. However, the heat storage performance for most of the PCMs lack due to their lower thermal conductivity value. As the time for charging and discharging heat of PCM is relatively higher, enhancement in thermal conductivity of PCM with micro pore metal foams were developed and shown as one of the most effective solutions for storage enhancement [69,70]. The following research works includes some of the recent research works on enhancement in effective thermal conductivity of PCM using metal foam. Experimental study on transient performance including metal foam and PCM was conducted by Zhu et al. [71]. This work was done with an aim of achieving effective heat transfer with optimized metal foam heights. In addition, a term called filling effectiveness was introduced to analyze the improvement in performance and also for cost saving. It was observed that, partial filling is feasible and will yield higher performance even at low heat input. Zhong et al. [72] conducted experiments on high porosity graphite foams with varying pore densities from 600 μm to 200 μm. The authors stated that, by keeping the porosity fixed and reducing the pore size (200 μm) leads to higher thermal diffusivity of PCM/foam composite. Whereas, increasing the pore size (600 μm-less surface area of foam) causes more impregnation of PCM to store more latent heat. Hu and Patnaik [73,74] performed a simulation study on heat transfer with PCM infused in micro foams using ANSYS Fluent software. The details of permeability and inertial coefficient were given in Table 2. Direct numerical simulation (DNS) was used for simulation and the results were compared with volume averaged simulation to determine thermal interaction between the solid foam and PCM. Aluminium foam with docosane (PCM) was used as testing medium and size of cell and pore are 400 μm and 360 μm respectively. It was found that, when compared to DNS, volume averaged simulation predicts the heat transfer process even for complex geometry in a reasonable way when the input parameters such as effective thermal conductivity value are given. Hong and Herling [75] proposed an experimental study to determine the effective thermal conductivity of metal foam + PCM composite. It was stated that effective thermal conductivity depends on the following factors 1. Selection of PCM and metal foams based on its thermal conductivity 2. Fine thermal contact between metal foam and liquid PCM. Moreover, it was stated that, even though for same relative density, the thermal conductivity value of composite varies with respect to different surface area densities. Three models were used with more or less same porosity and with different cell sizes and the lowest was 500 μm. Lafdi et al. [76] conducted an experimental study on phase change process of PCM with high thermal conductive metal foams. Aluminium foams with different pore densities such as 10, 20 and 40 PPI were used for the experiment. It was stated that the heat transfer enhances only when the metal foam has higher porosity. Additionally, it was observed that, decrease in porosity results in lowered heater temperature as the conduction mechanism influences more. Sundarram and Li [77] proposed an analytical work on finding the effects of pore size and porosity on PCM infiltrated metal foam. Aluminium/paraffin composite were used for analysis and the main aim of this work was to determine the HTP with very less pore sized metal foams say 100 μm–25 μm. Mainly the authors insisted two things regarding HTP. Essentially lower pore size results in increased torturous path, thus the heat transfer by convection between liquid and solid PCM gets suppressed. Secondly, decreased porosity value consequently increases the relative density of foam material whereas the storage amount of PCM gets reduced. This leads to reduction in thermal energy storage of PCM infiltrated metal foam composite. Thus, it was concluded that, only conduction effect has to be focused when discussing about reduction of pore size. Moreover, optimum porosity and pore size has to be selected for applications like portable electronics where there will be an occurrence of higher heat generation. It was clearly stated that the decreased pore size of the metal foam results in higher HTR. This is due to the primacy of natural convection. As the pore size gets reduced the melting rate of PCM

**Table 2**
Calculated permeability and inertial coefficient for different porosities [From Hu et al. [74] , with permission from Elsevier].

| Porosity (ϕ) | Permeability (K) | Inertial Coefficient (F) |
|---|---|---|
| 0.7570 | $5.07765 \times 10^{-10}$ | 0.83089 |
| 0.8570 | $1.33843 \times 10^{-9}$ | 0.16874 |
| 0.9006 | $1.87374 \times 10^{-9}$ | 0.13183 |
| 0.9704 | $3.34780 \times 10^{-9}$ | 0.09103 |
| 0.9898 | $4.84120 \times 10^{-9}$ | 0.05886 |

reaches to steady state faster when compared to larger pore size. Thus, author concluded that decreased pore size is recommendable for higher HTR. Huang et al. [78] conducted an experimental study with nickel and copper foam impregnated with Myristyl alcohol (MA) to determine the HTP. The pore size selected for experiment were 40, 70, 90 PPI. It was stated that the impregnation ratio of MA in to nickel was greater when compared to that of Copper foams. This was due to the increased thermal conductivity of copper foams as the solidification rate at external surface of copper is faster than Nickel. This prevents the passage for the incoming MA to move further inside the foam. Moreover, it was mentioned that increased pore size causes reduction in thermal conductivity due to higher interfacial area and also the HTE does not influence linearly with mass ratio of metal/PCM composite as it has increasing trend only for certain range. Hong and Herling [79] experimentally studied the influence of geometrical parameters of metal foam on HTE. Tests were carried out with Aluminium 6061 foam with different cell sizes varying from 2 mm to 500 μm. Copper plate was fixed on which the metal foams with PCM has been placed. It has been observed that the time taken for the copper plate to reach the limit temperature of 100 °C was higher for copper/metal foam/PCM combination when compared with copper/metal foam and only copper plate. This happens because; as surface area density is higher there occurs larger contact area of metal foams with copper plate resulting in effective HTR. Tao et al. [80] conducted simulation on metal foams filled with PCM. Authors used lattice Boltzmann method for determining latent heat storage and heat storage density. It was observed that for higher porosity value, heat transfer was initially dominated by conduction but as the process continues, conduction diminishes whereas natural convection increases. When pore density is high, the surface area of metal foams will restrict natural convection and thus reducing the heat transfer. Zhao et al. [81] proposed a two dimensional numerical study for metal foam incorporated with phase change material using phase field method. Solid-liquid interface concept has been explained clearly using phase field method. It was found that inspite of varying the Rayleigh number, only when the porosity value is low, melting and solidification rate increases. Moreover in case of low pore densities, melting rate is faster when compared to the solidification rate. Thus, the reason for reduced natural convection not only depends on the over existence of metal foams but also it rely on the quantity of PCM. Jin et al. proposed visualized study on pore scale of copper foam filled with PCM. The authors concluded that, if effective melting rate and local thermal equilibrium are the main requirements, foams with reduced pore density will be a suitable one. Welsford et al. [82] experimentally studied the HTC of metal foams filled PCM with nanofluids. It was observed from the experimental results that nano particles enhances the HTR and addition of metal foam with combination of nano fluids reduces the surface temperature to a greater extent along with faster rate of storing heat in the PCM. Mahdi and Nsofor [83] proposed a numerical simulation in a triplex tube system aiming to decrease the melting time of PCM by adding nano particles. Copper foam of fixed pore size (40 PPI) was used for analysis with $\epsilon_f = 0.95, 0.98$ and $\phi_{np} = 0.01, 0.03, 0.05$. It has been stated that, addition of nano particles results in heat conduction dominance than convection and also decreases the total time for melting of PCM. However, in order to achieve higher thermal energy storage, foams with high porosity and lower volume fraction of nano particles were suggested. Thus, the quantity of PCM impregnation will be more followed by improvement in latent heat storage through convection. Same authors proposed a numerical work on solidification of nano PCM using ANSYS Fluent. Introducing nano particles with PCM reduces the solidification time. It was observed that less nano particle addition can result in enhancement of the thermal conductivity of PCM. Similar work has been done by Hossain et al. [84] in which copper oxide nano particles are included with Cyclohexane a PCM. Moreover, in order to enhance the heat transfer ability, Aluminium porous foam was used. It was observed that higher energy will be required for melting the PCM/foam composite having high porosity value when compared to that of low porosity (increased surface density).

**Table 3**
Summary of experimental and numerical investigations for thermal enhancement of PCM with metal foam.

| Author | Exp/ Numerical | Foam/PCM | Porosity of foam | Pore size/PPI | Input parameters | Results and remarks |
|---|---|---|---|---|---|---|
| Zhu et al. [67] | Exp. | Cu/RT40 | 96% | 15, 30 | Input $q = 12.6$ W/cm$^2$ and 25.3 W/cm$^2$ | 2/3rd of channel filling with metal foam was found to be economical. |
| Zhong et al. [68] | Exp. | Graphite/ Paraffin wax | 72.9%–90.5% | Pore size 200 μm–600 μm | Constant temperature of 353K | Thermal diffusivity increases to about 570 times for form with pore size 200 μm |
| Hu and Patnaik [69] | Numerical | Al/Docosane | 75.7% | Pore size 360 μm | Wall temperatures 334K, 357K, 368K | Latent heat absorption followed by phase change of PCM can be observed clearly using Volume average simulation. |
| Hong and Herling [71] | Exp. | Al/Paraffin wax | 92%, 93% | Cell size = 2 mm, 1 mm, 0.5 mm | Constant temperature of 360K | Effective thermal conductivity of composite relies on selection of both PCM and metal foam. |
| Sundarram and Li [73] | Numerical | Cu/Paraffin wax | 75%–94% | Pore size 5,10,25,50,100 μm | – | Foams with smaller pore size of 25 μm has the capability to maintain low wall temperature for a sustained period. |
| Hong and Herling [75] | Exp. | Al/Paraffin wax | 92%, 93% | Cell size = 2 mm, 1 mm, 0.5 mm | Constant temperature of 100°C | Melting and Cooling time of PCM increases for reduced cell sized foam (0.5 mm) |
| Tao et al. [76] | Numerical | Cu/Paraffin wax | 90%, 94%, 98% | 45 | Constant temperature of 104°C | Higher melting rate of 105.61% was observed by increasing the porosity from 94% to 98%. |

#### *2.3.1. Inferences from thermal enhancement of PCM with micro foams*

From the observation of above-mentioned papers, it can be clearly noted that, adding metal foams with PCM will absolutely increase the effective thermal conductivity of the metal/foam composite. Further study on the HTP was done to classify the effect of porosity and pore density of foam by which the most suitable one can be highlighted. Research works focusing on pore density and PCM has some advantages, particularly on higher PPI value, say 10 to 40PPI. As far as the porosity of foam and PCM are concerned, higher value of porosity followed by more impregnation of PCM, results in maximum HTR due to convection. However, it will be constrained when storage area and heat input are less. Thus, both the parameters are confined within certain conditions. When discussion comes under the effect of nano particles and PCM, it was stated that by addition of nano particles with PCM/foam composite, the time required for melting of PCM was less. But a contradictory result was given by Tasnim et al. [85] in which numerical work to determine the shape of the melting PCM with time was proposed. Simulation has been done to study the influence of nano particles ($\phi = 0.1\%$) in heat transfer and phase change process. It was stated that prolonged melting time of PCM was obtained in addition of nano particles. This discrepancy shows that a clear understanding on melting HTC of PCM is still inadequate. Moreover, real time experiments with higher PPI value of foams to compare the results of numerical one was not been carried out till date. Thus, a detailed investigation has to be done to have an apparent view on melting characteristics of PCM with nano particles. Table 3 lists up the summary of some published literatures on thermal enhancement of PCM with metal foams.

## 3. Applications

### *3.1. Solar collectors*

Flat plate collectors were designed initially to extract solar energy at lower cost. Due to its less efficiency and need for higher performances, later many incorporations have been done in collectors thereby acceptable results were obtained. One among them was inserting higher thermal conductivity metal foams in the solar collectors [86]. Introduction of metal foams was to enhance the energy efficiency of solar systems. The following information deals with some useful works of metal foam application in solar collectors for improving the collector efficiency.

Naphon [87] numerically studied the HTP of a D-P flat plate(FP)solar air heater by inserting a porous matrix. An average enhancement of 18.4% in heat transfer was noted for the porous matrix inserted solar air heater. In addition, 25.9% enhancement in thermal efficiency was observed for the same condition when compared with non-porous solar air heater. Chen and Huang [88] used a flat-plate solar water collector (FPSWC) to study the HTE by using metal foam blocks as shown in Fig. 5. Major influencing parameters such as Temperature difference, pressure gradient, Nu and streamlines were considered for the analysis. A correlation for Nu was developed as a function of Re, pore size, porosity and Prandtl number and found good agreement with the existing literatures with a deviation of ±15%. This study demonstrated an efficient method for enhancing the HTP of FPSWC by replacing the inner wall with metal foams and also suggested to consider a tolerance limit associated to increase in pressure gradient based on the physical properties of metal foam blocks. In addition, this numerical study was extended to analyze the HTP of FPSWC using an Aluminium foam/paraffin composite. The continuity and momentum equation for two temperature models were solved using finite volume approach with a SIMPLEC algorithm. Based on the numerical analysis, it was noted that the paraffin embedded aluminium foam enhanced the HTR and melting characteristics of paraffin due to uniform temperature distribution. Jouybari et al. [89] experimentally studied the effect of Nusselt number with metal foam inserted flat plate collector using $SiO_2$/water based nanofluid. Experimental findings showed an enhancement in performance evaluation criteria (PEC) of metal foam inserted solar collector system when mass flow rate and the nano particle concentration were increased. Furthermore, the thermal efficiency of FP collector was enhanced to about 15.7% and 16.7% when $TiO_2$/water and CuO/water nanofluids were respectively used with optimum flow rate and volume concentration of nanoparticles. Jamal-Abad et al. [90,91] investigated a solar parabolic trough in which metal foams are filled in the absorber area. Due to the presence of metallic foam, heat absorbance rate was faster. Moreover, it was observed that by increasing the value of Darcy number decreases the Nusselt number. This indicates the ratio of permeability to channel diameter as an inverse relation with Nusselt number. Overall performance of the work reduced the overall heat loss coefficient value thus increasing its efficiency than the conventional one. Ahmed and Mohammed [92] experimentally studied the performance of hybrid PV/thermal collector. This experimental work was

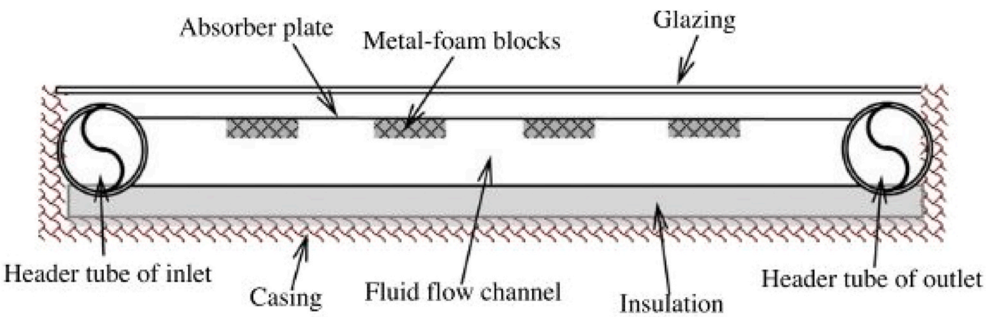



**Fig. 5.** Schematic layout of novel solar collector with metal foam inserts [From Chen and Huang [88], with permission from Elsevier].

carried out to increase the outlet temperature of air using metal foams having higher pore density. With the presence of both glass cover and metal foam, enhancement of 80.23% in thermal efficiency was noted. Moreover, by placing glass cover improvement in thermal efficiency can be obtained whereas decrease in electrical efficiency was noted. Abd-Elhady et al. [93] proposed an experimental work to determine the heating capability of evacuated tubes in a hybrid collector. Comparisons were made between evacuated tubes with oil/copper fins and with oil/foamed copper. It was found that foamed copper arrangement has higher heating efficiency and also heat storage was achieved using oil inside the evacuated tube. The maximum bulb temperature was above 200 °C for foamed section and prolonged time for cooling occurs when compared to finned type arrangement.

The application of metal foam has also covered tubular and volumetric solar receivers. Lim et al. [94] numerically studied the effect of porosity, pore density and length of the porous matrix on the optimized design of the tubular solar receiver (TSR) to provide a useful guideline for present solar collector manufacturing industries. Based on the analysis, it was inferred that, the highest temperature of TSR was strongly associated with thermal conductivity of the porous matrix. Moreover, an average increase of 13 °C in outlet temperature of TSR was noted when compared with non-porous solar collector system. Numerical study on enhancement in collection efficiency of receiver using high thermal conductivity porous disc was carried out by Reddy et al. [94]. The analysis showed a reduction in thermal gradient between the collector surface and the working fluid (7.19 °C) for porous disc inserted receiver when compared with the conventional TSR (14.07 °C). Wu et al. [95] studied the experimental pressure drop and heat transfer by using ceramic foam and stated that the $\Delta P$ has an inverse proportion with the porosity and pore density. The model is generated with a tetrakaidecahedron cell and bunch of cells were joined to form a ceramic foam structure as shown in Fig. 6. The authors suggested Ergun's equation to predict the $\Delta P$ in fluid flow through porous media. Michailidis et al. [96] experimentally studied the pressure drop with Nickel foam inserted in the VSR and compared the HTP with the conventional solar collectors under steady flow condition. It was noted that, the collection efficiency was greatly affected by material property and fluid flow. Also, Nickel foam exhibited less resistance towards corrosion at higher temperatures for which a protective oxidation coating using slurry aluminization was carried out on the porous substrate. Huang et al. [97] performed an experimental study to determine the heat transfer performance of metal foam attached receiver plate under pulsating flow conditions. It was observed that, the HTE is associated with increase in pore density, amplitude/pulsating frequency and Reynolds number. Moreover, the Nu majorly depends on axial inlet velocity of fluid flow which is result of higher pulsating amplitude. Even though pulsating flow significantly enhanced the heat transfer, an additional pumping energy for the fluid flow has to be given to satisfy the higher $\Delta P$. Based on the above mentioned literatures, the inclusion of metal foam will significantly enhance the heat transfer. However, the concept is only applicable for the fluid flow in a straight duct and it was noted to be different for curved ducts. Rabadi and Mismar [98] conducted experiments to enhance the solar energy collection efficiency by using curved flow technology. Coarse of Aluminium chips with 0.1453 porosity was filled throughout the curved channel.

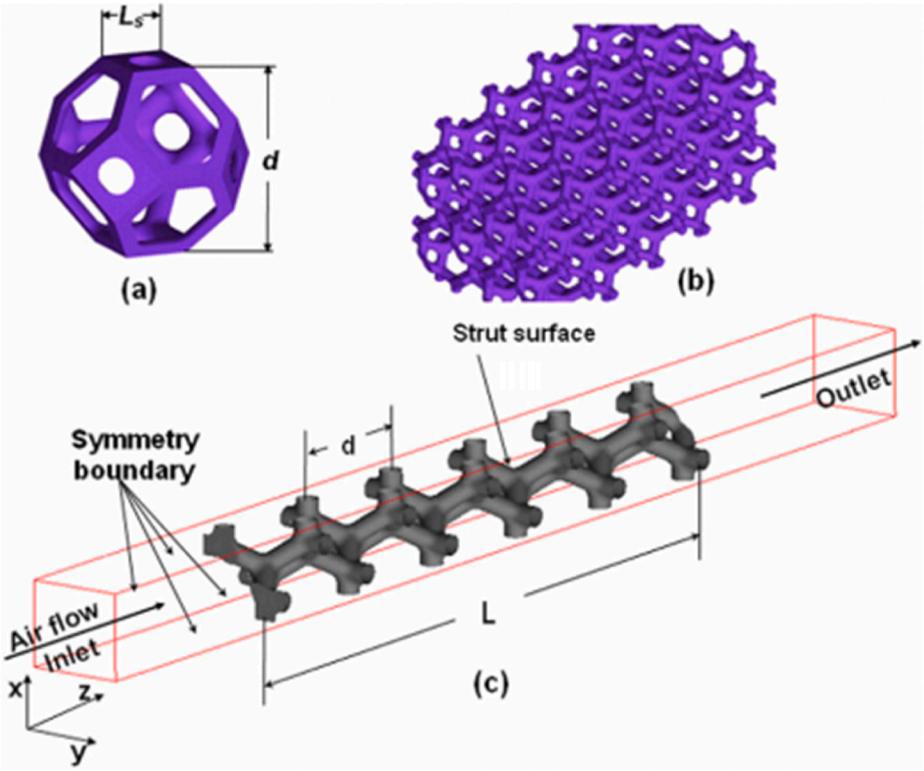



**Fig. 6.** (a) Single unit of tetrakaidecahedron cell (b) Bulk foam formed by assembling tetrakaidecahedron cells (c) Computational domain and constraints [From Wu et al. [95], with permission from Elsevier].

Experiments were carried out for different mass flow rates (300 and 200 l/h) and it was noted that the collection efficiency of foam inserted channel was less (59% and 54%) when compared to the foamless channel (60% and 56%) for two different flow rates respectively. Based on the existing literatures, a general conclusion can be taken that; the HTE in solar collectors can be achieved by inserting a porous matrix. In addition, the solar collection efficiency can be improved further by using relatively high thermal conductivity metal foams. However, due to the existence of indiscrepancy in the experimental results provided in the open literatures, a detailed analysis has to be carried out by studying the effect of porosity, pore density of metal foams on HTE particularly in the curved channels. As metal foams will provide an insight for the future research works particularly on solar collectors due to its higher thermal characteristics, more number of researches should be carried out to understand its impact in near future.

### *3.2. Medical applications*

Tissue engineering is one of the key factors in developing the scaffolds using porous structure. Replacement with scaffolds not only gives a support, but also creates an environment for the bones and tissues to grow faster. Even though high porosity foams enhance the cell proliferation, their drawback in developing these porous structures that relies on their mechanical strength was proposed by Wang et al. [99]. Bone scaffolds and orthopedic implants developed using additive manufacturing is shown in Fig. 7. Kashef et al. [100] proposed an experimental work to determine the failure behavior of Titanium foams which are used as an implant material for bones. Fatigue crack propagation test was carried out both for solid coated (solid material coated on surface) and non-coated Titanium foams. It was observed that solid coated Titanium foams with 60% porosity has less crack growth than the non-coated one. The author suggested that Titanium foams with relatively higher porosities can be a substitute for cancellous bones and also in dental applications. However, increase in metal foam's mechanical properties depends on the purity of the powder and the fabrication method of foam. Orinak et al. [100] conducted experiments to study the degradation rate of iron foam samples immersing in Hank's solution for 8 weeks. Comparison was made between CNT/Mg, Fe/Mg and Fe/CNT. It was observed that highest degradation rate was occurred in CNT/Mg whereas fewer rates were noted in Fe/CNT sample. However, for cellular applications Fe/Mg sample with highest haemolysis value of 2% seems to be a good one. As it was found that the Young's modulus value of cortical and cancellous bones is 17.6–31.2 GPa and 1.5–4.5 GPa respectively, replacement with implants were developed by satisfying the above criteria. Andani et al. [101] proposed NiTi alloy and Magnesium alloy foams as good implants as they have Yong's modulus value of 48 GPa and 45 GPa respectively. It was stated that super elastic NiTi alloy can be used due its good modulus of elasticity and also for its higher reversible transformation. Moreover, methods for manufacturing the NiTi alloy foams with optimum porosity were clearly explained. Also, details on some of the commercial used biomedical alloys with young's modulus value were presented by the authors as shown in Fig. 8. Jurczyk et al. [102] studied the corrosion, structure and biological properties of titanium with bio glass nano composite scaffolds. Due to its less density and with pore size of 400–800 μm, titanium with 10%wt bio glass scaffolds performed well and provided good compatibility when compared to crystalline titanium. The authors suggested that this titanium-based foam is being a promising one and can help bones and tissues in growth thus providing biological anchorage. Similar study on corrosive property was studied recently in which porous steel foams with pore size up to 450 μm were developed. Powdered metallurgy technique was used whereas; ammonium carbonate and

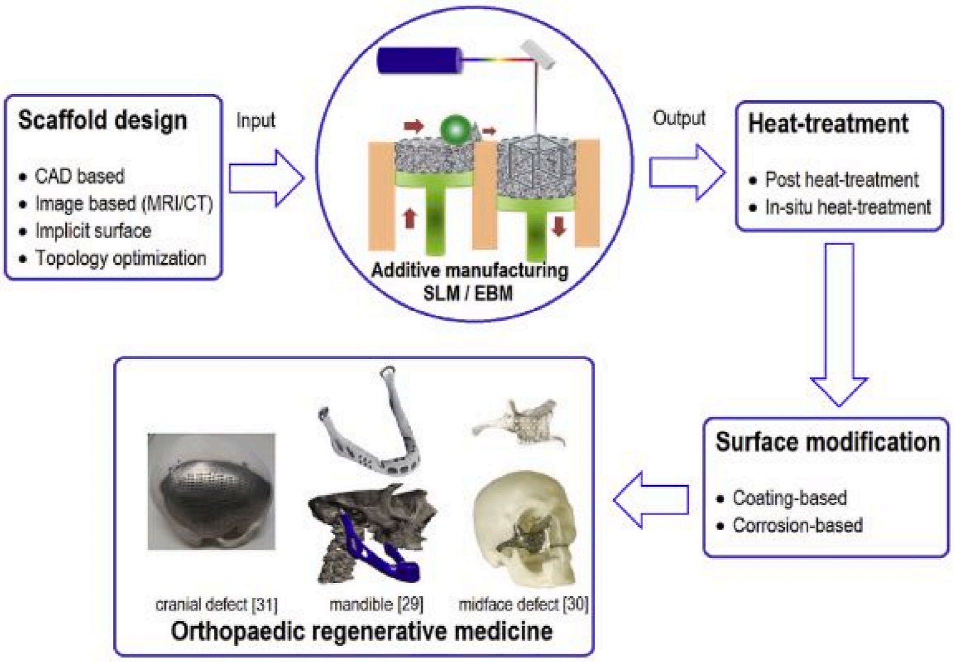



**Fig. 7.** Methodology of using porous foam in latest orthopedic regenerative medicine [From Wang et al. [99], with permission from Elsevier].

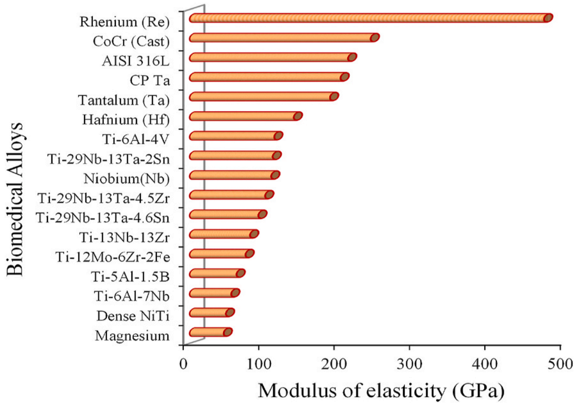



**Fig. 8.** Different biomedical alloys used for bone tissue engineering [From Andani et al. [101], with permission from Elsevier].

bicarbonate were used as space holders.

### *3.3. Armor applications*

High performance ballistic protection consists of several layers for absorbing the projectile energy. Fiber reinforced back covers and ceramic plate as a strike surface were generally been developed for ballistic panels. As metal foams have a greater energy absorption potential under static and dynamic loading conditions, research works were carried out focusing on developing a modified ballistic panel by incorporating metal foams. Some of the useful works are discussed as follows.

Plessis et al. [103] conducted experiments with Titanium alloy foam to determine the strength and energy absorption using force-displacement curve. Laser powder bed fusion technique was used to fabricate the composite foam. It was stated that, addition of foam increases the overall strength whereas, the level of energy absorption depends on the shell thickness. When the shell size becomes denser, formation of cracks in the internal lattice can be observed which leads to less energy absorption. Armor unit with 0.5 mm thickness and 80% porosity was found to be optimum for good performance. Gamache and Roland [104] presented a patent on porous refractory substrate, to reduce the effect of compressive waves on the ceramic front face. The authors stated that inclusion of the porous substrates considerably increases the strength by reducing the tensile waves thereby increasing the life of the armor material. In addition to armor applications, metal foam has greater advantage in using as a shielding material. For an instance, neutron shielding materials generally have less gamma shielding ability and also, they exhibit poor mechanical properties. Zhang et al. [105] experiments to improve the mechanical properties by using Nickel foam/paraffin composite. Static compression test was done from which the compressive strength of the composite was increased 0.4 times when compared to nickel foam. Moreover, the authors suggested that the gamma ray shielding ability can be made better by increasing the metal foam's relative density.

### *3.4. Thermoelectric generators (TEG)*

Conversion of heat to electricity using thermoelectric generators by efficiently extracting heat from the exhaust systems can definitely improve the fuel economy thereby reducing the greenhouse gas emissions. Based on the statistical report, 20–50% of energy input in transportation, residential sectors and industries are wasted in the form of heat. As metal foams are much lighter and showed better HTP, research works on incorporating both TEG and metal foams to enhance the heat absorption rate were initiated in recent years. Some of the significant works on power generation using micro pore metal foam inserted TEG system are discussed as follows. Li et al. [106] proposed an experimental study focusing on power generation using thermo electric generator which works on seeback effect. Different pore densities and filling ratio has been attempted and HTP was evaluated. It was observed that, for low pore densities the power generation value seems to be more or less same irrespective of the metal foam filling ratios and for higher pore density foam there is an increasing trend in power generation. Authors concluded that by addition of metal foam, the $\Delta P$ increases double the time when compared to normal process and also HTC gets enhanced. Nithyanandam et al. [107] conducted numerical study to determine the thermal efficiency involving thermo electric generator along with metal foam. It was observed that by increasing the flow rate of working fluid, the power generation gets increased especially for larger pore density. Increase in PPI results in greater drag force when the flow takes place through the tortuous path. In addition, the author also suggested that there should be an optimum flow through the metal foam where the thermal efficiency attains a peak value when compared to the flow through normal channel, beyond which the thermal efficiency decreases. Bai et al. [108] conducted an experimental work which involves thermo electric power generation utilizing metal foam and the experimental layout. Metal foams were sandwiched between hot side and cold side flow. It was stated that, the metal foams not only enhance the heat transfer but also it acts as a sound reducer. Moreover, increase in the thickness of the metal foam, will consequently increase the output power generated by TEG module. Wang et al. [109] proposed a waste heat recovery system achieved using thermo electric generators in which the flow channels are filled with metal foams. Heat exchanger effectiveness and HTE were experimental studied. Results reveals that insertion of metal foam leads to better heat exchanger effectiveness and progression of heat transfer occurs when pore density is increased.

## 4. Outlooks and future challenges

Based on the above-mentioned literatures, it is clear that the use of high thermal conductivity metal foams enhances the heat transfer performance of thermal systems. Even though many experimental and numerical studies were conducted on metal foams, research works on enhancing the HTP of a thermal system using micro pore sized metal foams were recently initiated. The use of micro pore sized metal foams in various applications seems to be promising. However, the development of this field is hindered by lack of agreement in experimental and numerical results. Therefore, extensive research on forced convective study in later days should be performed on increased pore density. This article also concludes by outlining the major parameters such as porosity, foam height, pore density and fiber length that influences more on the HTP of different working fluids using metal foam. In addition, most of the experiments approached only single-phase heat transfer and mere researches were carried out on two phase flow. Thus, future research must focus on two phase flow HTC of different working fluids. Moreover, there appears to be hardly any research work on gradient metal foams by homogenous mixing of pure metallic nanoparticles in the micro sized foam fibers. The suspension of metallic nanoparticles on micro fiber will definitely enhance the HTP of gradient (composite) metal foams. Despite proving the significance of composites in structural and thermal applications [110–119] the feasibility of using composites in developing a metal foam will be a valid research in near future. Also, the concept of employing metal foams in two phase closed thermosyphon (TPCT) as a substitute for capillary wick heat pipe to enhance the boiling and condensation rate at a particular heat load will also be a valid research to be carried out in the following years.

Even though extensive researches have been carried out with nanofluids in porous media, the concept of using nano particle suspended refrigerants (nano-refrigerants), to enhance the HTP is still lacking in the open literatures. Previous research works have proved the significance of nano refrigerants particularly in the refrigeration system. This creates a room for further experimental study to determine the HTP of high thermal conductive nano-refrigerants with metal foam having different PPI.

## 5. Conclusion

The present review is a comprehensive outlook on the progress made in convective heat transfer enhancement of different fluids using metal foams. An overall conclusion made from the mentioned literatures is that, study on HTE using micro pore sized metal foams will be one of the most promising alternatives for efficient thermal management in modern electronic devices. Moreover, based on the experimental results, it can be clearly noted that the metal foam cooling technology will be a practical solution for many industrial applications. This offers many researchers to develop their knowledge on handling metal foams in various cooling applications. The main reason for the heat transfer enhancement in different fields are due to increased surface area which results in uniform temperature distribution, promotes heat transfer by conduction/convection and increases the thermal diffusivity of metal/foam composite. Moreover, the structural strength of metal foams increases when different composites [120–128] are added to form a gradient metal foam. When considering the thermal enhancement of PCM with metal foams, contradictory results indicates that the understanding on melting characteristics of PCM is still inadequate and clear analysis on the effect of porosity and high pore density foams over the melting characteristics of PCM is required. Moreover, the numerical studies on metal foams used complex theoretical approach and have not produced accurate results. Thus, extensive numerical research on heat transfer study with different working fluids using micro pore metal foams must be performed. Also, mere research works on metal foams having the pore density higher than 40 PPI were noticed in the existing literatures and the surface wettability on HTP by using higher PPI foa ms were not addressed which can be a useful guide for future engineering design.

The achievements in employing metal foams in medical sciences, armor and solar applications were found to be much significant. However, in electronic cooling applications, the advanced theory and experimental results describing the implementation of micro pore sized metal foams in heat pipe technology is still lacking. Thus, future studies must focus on this area, thereby to have a clear understanding on the heat transfer enhancement and two-phase heat transfer mechanisms by using micro pore sized foams. Applied research on high thermal conductivity micro pore metal foams in electronic cooling applications will define its significance as it is expected to emerge in near future.

## CRediT authorship contribution statement

**Jefferson Raja Bose:** Data curation, Writing – original draft. **Stephen Manova:** Conceptualization, Writing – review & editing. **Lazarus Godson Asirvatham:** Supervision, Formal analysis, Investigation, Writing – review & editing. **Somchai Wongwises:** Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Nomenclature

h= height (m)
d= diameter (m)
t= thickness (m)
T= Temperature ($^{o}$C)
D= Diameter of the nanoparticle (m)
x= vapor quality
V= Velocity (m/s)
q= heat flux (W/m$^{2}$)
m= mass flow rate (kg/s)
PPI= Pores Per Inch
LPM= Litres Per Minute
MA= Myristyl alcohol
HTC= Heat transfer coefficient (W/m$^{2}$K)
ORC= Organic Rankine cycle
TPCT= Two phase closed thermosyphon
DNS= Direct Numerical Simulation
TEG= Thermoelectric generator
MEPCM= Micro-encapsulated phase change material

*Greek symbols*
$\phi$= porosity of foam
$\phi$= weight concentration of nanoparticle

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