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Enhancement of heat exchangers with metal foams

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Abstract

Removal of the heat is becoming a vital issue for safer operations of today’s technological equipment. The necessity of heat exchangers is underlined at this stage for the sake of the emerging technologies, which are producing more heat than before by the increment of the higher energy demand during their operations. Several methods have been suggested to improve the efficiency of the heat exchangers in last decades by the researchers including the extension of the heat transfer surface by the larger surface areas surrounding the channels. In addition to this fundamental approach (extension of the surface area), alternate methods have been released too including the implementation of metal foams to the heat exchangers as for the extension of the surface.

Keywords: Heat exchangers, surface extension, metal foams.

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1. Introduction

Heat exchangers have a very important role for the removal of the heat from the system while it is in operation. Since almost all devices that are commonly used in our daily lives generate heat, the heat removal from all these equipment is becoming vital for the sake of their operations. In order to improve the transfer of heat to the environment, several geometries, designs, structures and working fluids have been investigated and developed so far. The surface extension is one of the widely preferred approaches among all these reported methods. Within this approach, the surface of the heat transfer region is extended by the fins in different geometries such as plain, louvered, offset, wavy and pin. Even though the present applications meet the recent requirements, the need for more heat transfer by smaller volumes or surfaces becoming important by the increasing interest in the miniaturisation of devices. The insufficiency of the recent structures or the need for better solutions leads the researchers to investigate the alternate options. At this point, the substitution of metal foams with the present fins on the heat exchangers is becoming very essential for further developments.

Metal foams, which allow to reach very high surface to volume ratios, are becoming very popular in last decades due to their unique features, which assist the engineering by different applications from varying aspects. Some of the outstanding features, mostly regarding the thermo-physical ones, can be listed below (De Schampheleire et al., 2016):

1. Their weight is very low.
2. They have very high surface area to volume ratio (range 500–10,000 m^2/m^3).
3. Their heat transfer potential is higher.
4. Their gas permeability combined with high thermal conductivity is higher.
5. They resist to thermal shock, high temperature and thermal cycling.
6. During manufacturing, their morphology control is easier.
7. Thermal insulating characteristics are very good.

The basic feature of the foam is having a sponge-like structure, which is defined as the porosity or in other word emptiness of the metal structure. And these empty spaces over the entire metal volume is a measure of metal foams porosity. Metal foams basically split into two types open-cell metal foams, where pores are connected to each other via the holes that create the pores and closed-cell metal foams, where the cells are sealed off. Even though they have varying physical features, manufacturing techniques are almost identical, and the foam structure is obtained by injecting a gas to molten metal or mixing the molten metal with a foaming agent, which is generally surfactant or blowing agent.

Metal foams are becoming very popular in last decades in the field of heat exchangers by their unique feature, which is the transport of large amount of heat over a small volume. The porous medium, which is the basic feature of the structure, is the main interest of the researchers in the reported works. The effect of the surface area density, porosity and geometry of the pores on the heat exchangers is studied from various aspects in order to understand the mechanism of the heat transfer in this particular medium better. The investigations are carried out either numerically, experimentally or analytically for the highlighted parameters. Researchers noted crucial findings as regard to their works such as the flow regime inside the medium, interfacial heat transfer, the effect of strut shape on the performance and the effect of porosity on the heat transfer. Furthermore, the comparison of the ‘recent designs’ and ‘improvement after the substitution with the metal foam’ is evaluated by the investigators as well to reveal the contribution of the porosity on the performance.

In this communication, the studies about ‘metal foams used in the heat exchangers’ that could be accessible in the open literature are investigated in detail from the perspective of ‘how they are developed, modelled and investigated by the researchers’. This review is considered as a part of an on-going project about the compact heat exchangers (CHEX) and the replacement of the fins by the metallic foams on it. The detailed presentation of the topic would be very helpful for the ones who are interested in the heat exchangers with metallic foam.

2. Heat exchangers with metal foams

Two basic approaches are widely preferred by the researchers for the evaluation and investigation of the metal foams in thermal applications, which are experimental and computational. Both approaches have either bright sides or dark sides. By the experimental approach, more reliable outcomes can be obtained in the case where the experiments conducted accurately, on the other hand, the trial of numerous cases is almost impossible when the combinations of all possible cases are considered and budgetary issues may arise to accomplish all the mentioned combinations as well. There is a large number of parameters and their combinations emerge in thermal foam applications such as type of cell (whether open or closed), type of ligament, orientation of metal foam, bonding methods, cutting methods and boundary conditions (De Schampheleire et al., 2016). Due to noted challenges that appear during the experiments, numerical studies are preferred either by the scientists. It is very important to note that both methods are connected to each other most of the time, where the numerical analysis is validated by the experimental data, and further parametric works are presented based on this validation in the computational studies. In this section, the works are presented in two subsections as correspondent of the referred approaches.

2.1. Experimental studies on metal foams

Bhattacharyya, Calmidi and Mahajan (2002) investigated the thermo-physical properties of high porosity metal foams experimentally. The tests are performed on four different pore per inch (PPI) values (5, 10, 20 and 40) for a varying range of porosity (0.905–0.978) as shown in Figure 1.

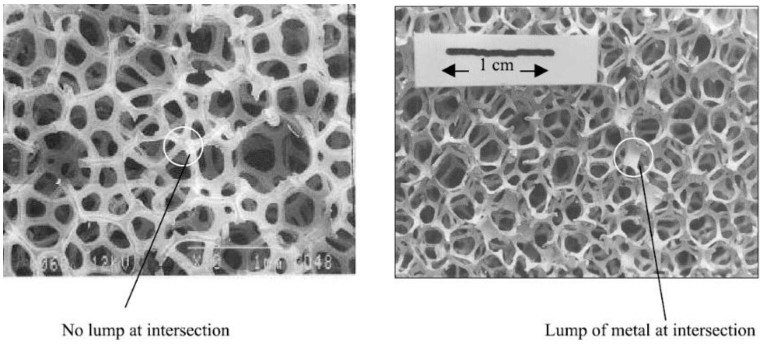

Figure 1. Samples used in the tests (Bhattacharyya et al., 2002)

In order to understand the thermal response of the porous medium, two varying fluid ambient is used such as air and water, where the effective thermal conductivity *keff* and friction factor are observed during their tests. As regards to the outcomes, when the porosity of the metal foam reduces or solid fraction increases then the *keff* increases. As for friction factor (*f*), it gains higher values as the solid fraction reduces and emptiness in the entire volume increases.

T'Joen et al. (2010) studied the thermo-hydraulic performance of a single row round tube heat exchanger, which is covered by metal foam as given in Figure 2. In their work, the effect of air velocity, tube spacing, foam height and foam type on the performance is searched. As regards to the outcomes, as the foam height on the round tube increases, the air couldn't get a chance to reach to tube surface, which makes the system inefficient and brings a pressure drop increment along with it. Another outcome is as the spacing increases the performance of the system ascends too. They noted that porosity cannot be solely considered for the evaluation of the performance, pore diameter and strut size-specific surface area considered too for better consideration.

Figure 2. Helically finned tube and metal foam covered tube (T'Joen et al., 2010)

Mancin, Zilio, Cavallini and Rossetto (2010) studied the heat transfer during air flow over aluminium foam. The tests are conducted to determine the effect of porosity, PPI and height on the performance of metal foam. The metal foams used in the experiments have varying alloys, PPI's, porosity and foam heights and effect of all these on the thermal response is investigated. According to the findings, when porosity reduces, heat transfer coefficient ascends. In addition, a better heat transfer is observed when foam height is lesser, as the foam height increases transfer ability reduces. Tadrist, Miscevic, Rahli and Topin (2004) investigated the fibrous materials as a different type of porous medium on CHEX. They tested fibrous materials composed of copper and bronze by varying porosities (in the range of 0.38–0.92) and PPI's.

Fiedler, Belova and Murch (2012) investigated thermal resistance of the copper metal foams both experimentally and numerically as shown in Figure 3. Since the identification of the resistance behaviour at the contact surface is very critical to maintain the heat transfer via extended surface from the channel where heat-carrying fluid flows, the tests apparatus is carefully designed by the researchers. During the experiments, time-dependent temperature evolution is observed for the thermal resistance or contact information. Simultaneously, the numerical analysis is accomplished either which is modelled with regard to the micro-computed tomography data. In order to calculate the resistance, an extrapolation method that benefits from both numerical and experimental analyses is used. They concluded that thermal resistance depends on sample size and particular shape of contact surface.

De Jaeger et al. (2012) worked on the contact resistance between the working fluid channel and extended surface either. They focused on more to the conditions which can effect to the resistance in the region of this contact. First of all, they investigated the effect of the cutting method of the methods before it is attached to the heat exchanger channels. They used four methods which are brand saw, circular saw, electron discharge and sawing wire method as shown in Figure 4. According to the outcomes, the sequence of resistance measured from the samples obtained by the listed methods can be written from high to low as, circular, brand saw, sawing wire and finally electron discharge. The least resistance is observed when the samples prepared by the electron discharge method while the highest one is observed for the sample cut by a circular saw. The electron discharge sample has almost 64% lower resistance than a circular saw sample. In another study, the bonding methods are compared for four different alloy foams with varying PPI and porosities. They bonded to the surface by epoxy, co-casting, pressing fitting and brazing. Among the conducted tests, the lowest contact resistance is observed for brazing (0.7 m^2K/W) while the highest one is seen at the press fitting (1.88 m^2K/W).

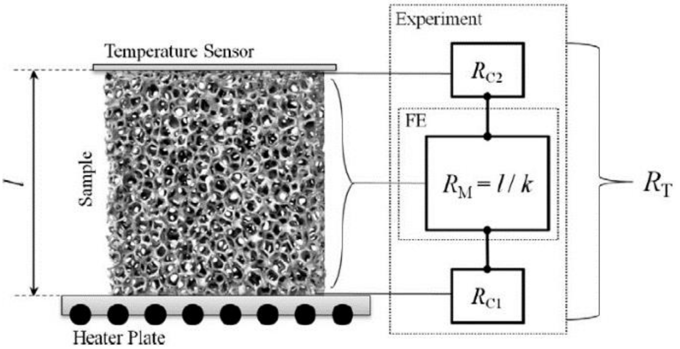

Figure 3. Thermal resistance in experimental setup and simulation (Fiedler et al., 2012)

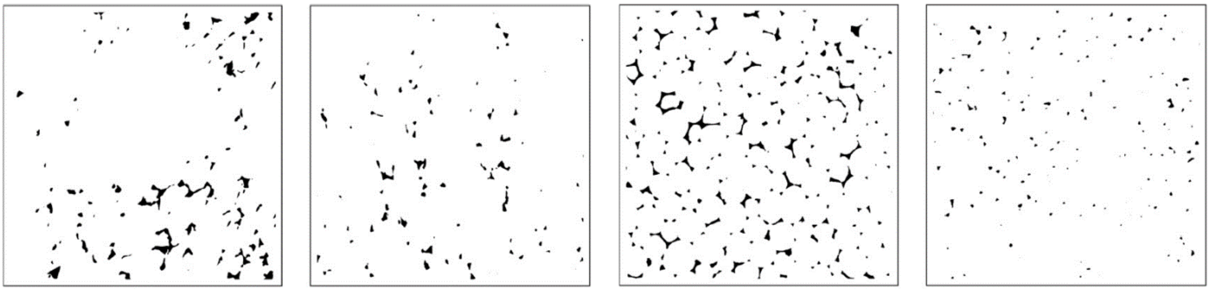

Figure 4. Contact area of the samples used in cutting method investigation (De Jaeger et al., 2012)

Boomsma, Poulikakos and Zwick (2003) studied the Al metal foams on the CHEX. They substituted the fins of the CHEX with metal foams but before they implement it, they compressed it first to 40 × 40 × 20 mm^3 volume (Fig. 5) then integrated to the CHEX. As regards to the findings, it is seen that compressed Al foams provide heat transfer enhancement, over commercially available heat exchangers under identical conditions, reduces the thermal resistance.

Son, Weibel, Kumaresan and Garimella (2017) Investigated another type of porous medium used in CHEX, in their particular case which is multifunctional lattice frame materials (LFM) (Fig. 6). It is noted that LFM's provides high porosity and area to volume fraction by their unique feature. The structure is experimented under laminar regime of air flow. According to their findings, unlike the earlier works, the *f* (friction factor) reduces as the porosity reduces and velocity of the air flow increases. Besides, higher Nu numbers are obtained when porosity descends and Re number ascends.

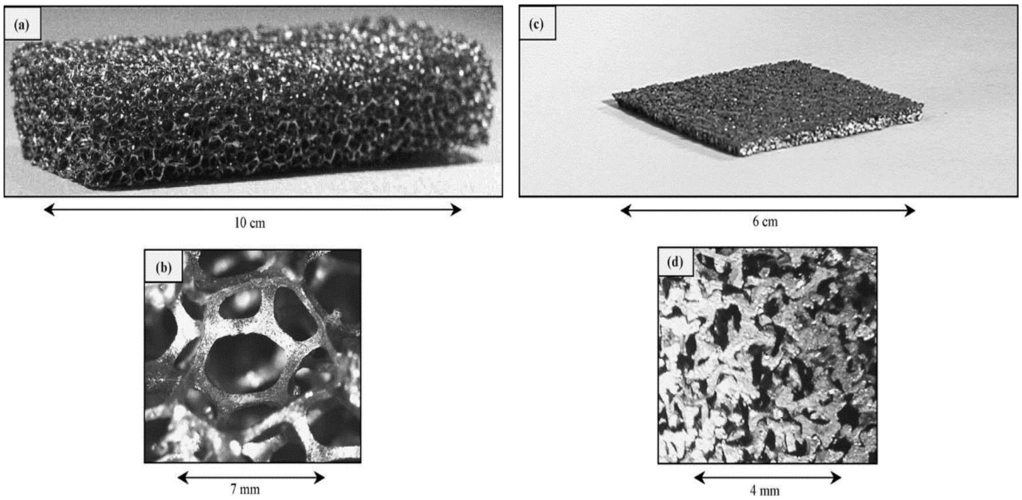

Figure 5. Compressed metal foams used in the experiments (Boomsma et al., 2003)

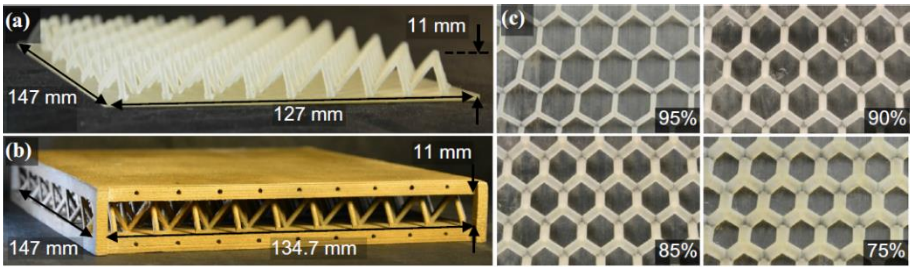

Figure 6. Multifunctional LFM used in the experiments (Son et al., 2017)

Another important topic in reported works is the comparison of metal foams with recent applications such as heat exchangers with varying fin types. Some of these comparisons can be found in the following. De Schampheleire et al. (2013) compared an air conditioner's condenser manufactured with louvered fins in real with the one substituted with Al metal foams (Fig. 7). Tests are conducted in an air tunnel in a range of air velocity (1.1–3.1 m/s). They noted that the performance of both heat exchangers is almost identical while there is great difference and is observed at higher air velocities. The HEX with louver fin shows better performance than heat exchanger with metal foams. One more item is investigated either the contact resistance impact on the overall thermal resistance is observed. It is seen that press fit one has a serious impact on the overall thermal resistance.

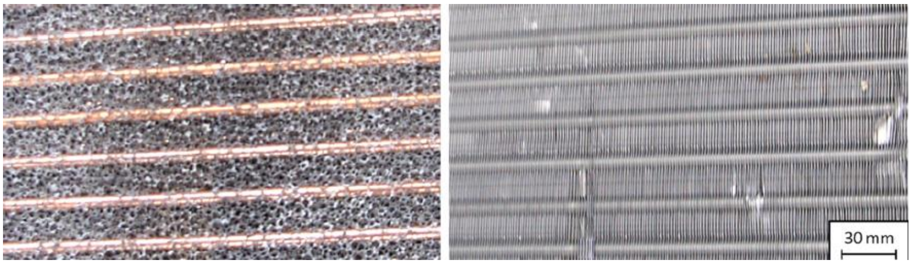

Figure 7. Heat exchanger with metal foam and louvered fins used in the experiments (De Schampheleire et al., 2013)

Riberio and Barbosa (2013) compared the miniaturised condensers with louvered fin and metal foam within a serious of experiments conducted in a wind tunnel in a velocity range of 2.1–7.7 m/s (Fig. 8). In their study, the metal foam is made of copper with varying porosity and PPI and the louvered fins made of aluminium with varying fin heights. As regards to their findings, under all tested conditions, the samples with metal foams show worse performance than with louvered fin ones. A similar comparison work (Ribeiro, Barbosa & Prata, 2012) is conducted for the condensers with Cu foam and Cu plain fin. This time the velocity range is limited in the range of 2.1–4.9 m/s. They reported that ΔP or f is indirectly proportion with pore density while they are in inverse proportion with porosity. They also noted overall thermal conductance of heat exchangers with plain fin is higher than heat exchangers with metal foam.

Sertkaya, Altinisik and Dincer (2012) worked on the comparison of the heat exchanger with metal foams and the heat exchanger with fins in real as well (Fig. 9). The thermal performance of Al winged heat exchanger and open cell Al foam heat exchangers are conducted in the same air tunnel. The Al foam tested in the experiments varies by the change of PPI and porosity while in the structure, fin intervals have changed for the same heat exchangers with a dimension of 200 × 200 × 100 mm^3. The results show that when the air velocity ascends, effective thermal conductivity falls and pressure drop ascends. Under all considered circumstances, the heat exchanger with fin shows better performance than the heat exchanger with metal foam.

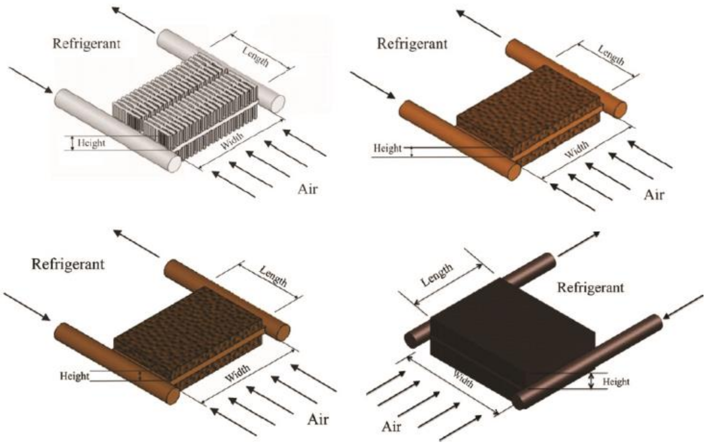

Figure 8. Miniature condenser with metal foam, louvered fin and plain fin used in the experiments (Riberio & Barbosa, 2013; Ribeiro et al., 2012)

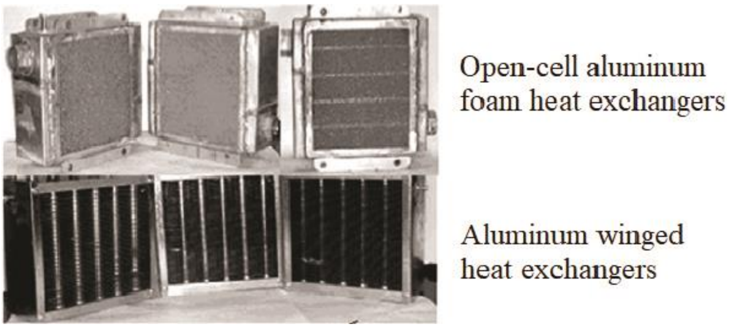

Figure 9. Heat exchangers with Al foam and Al winged (Sertkaya et al., 2012)

2.2. Numerical studies on metal foams

Numerical codes are the alternative method to determine the flow behaviour, thermal and hydraulic performance of the heat exchangers and it becomes popular with its adaptable characteristic for the parametric studies. Numerical studies make it particularly easy to calculate the surface area of the metal foam which is used for the calculation of the heat transfer coefficient of the external side of the heat exchanger. However, the determination of the thermal conductivity of metal foam is a parameter required for the calculation of the heat transfer coefficient, and it is another problem in numerical studies. In this way, some of the researchers only focus on the thermal conductivity of the metal foam. Effective thermal conductivity is calculated by considering both the thermal conductivity of metal foam and fluid which fills the porous of the foam.

Boomsma and Poulikakos (2001) used a first-order estimation method to determine the effective thermal conductivity of the metal foam (*keff*) as given in Eq. (1). The method considered the volume fraction of fluid and metal foam by taking into account their thermal conductivities (*kf* and *ks*) and the porosity of the metal foam (ε). As it is seen, the method is a simplified method by neglecting the contact resistance, natural convection and radiation effects and it can be acceptable when the porous of the foam is uniform and the thermo-physical properties of the fluid and solid are constant in the operating temperature range.

$$k_{eff} = \varepsilon k_f + (1-\varepsilon)k_s \tag{1}$$

In this study, the tetradecahedron cell, which consists of six squares and eight hexagons, was used as shown in Figure 10, and an analytical model was applied to determine the effective thermal conductivity of the cell.

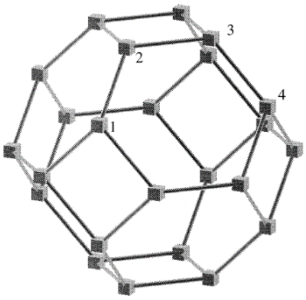

Figure 10. The tetradecahedron cell

A control volume was selected as seen in Figure 11 and the volume occupied by the solid material is calculated. Finally, the effective thermal conductivity of the fluid-filled metal foam was determined as given in Eq. (2).

$$k_{eff} = \frac{L_A + L_B + L_C + L_D}{(L_A / k_A + L_B / k_B + L_C / k_C + L_D / k_D)} \tag{2}$$

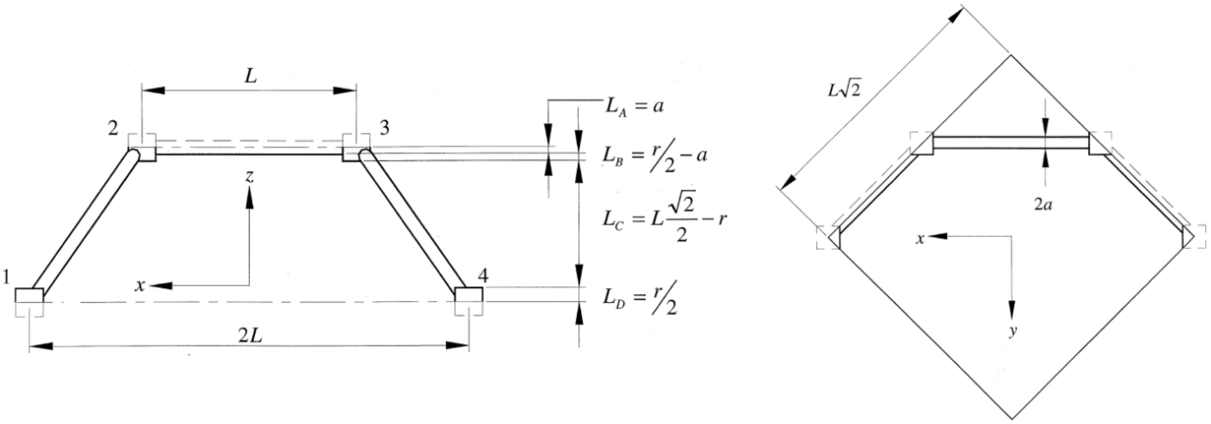

Figure 11. Control volume considered (Boomsma & Poulikakos, 2001)

The researchers reported that the model estimates the effective thermal conductivity well into applicability in lower porosity regimes and the solid part of the cell controlled the effective thermal conductivity to a large extent. The model, which was generated by Boomsma and Poulikakos (2001), has been revisited by another research group. Dai, Nawaz, Park, Bock and Jacobi (2010) reported that the Boomsma and Poulikakos (2001) model contains errors in the analytical derivation of the effective thermal conductivity of the metal foam, and the model was fully reviewed. The new model provides quite different results in terms of the harmony of the numerical and experimental results. However, the original model predicted the experimental result of Calmidi and Mahajan (2000) with relative RMS errors of about 43% for air, 31% for water and 38% of all data, and the new model was predicted even worse with an error of 70%. Wang and Pan (2008) used randomly generated open-cell foam models, which is different from the two numerical studies described above to get realistic model and results as shown in Fig*ure* 12. Additionally, the radiation effect was taken into account.

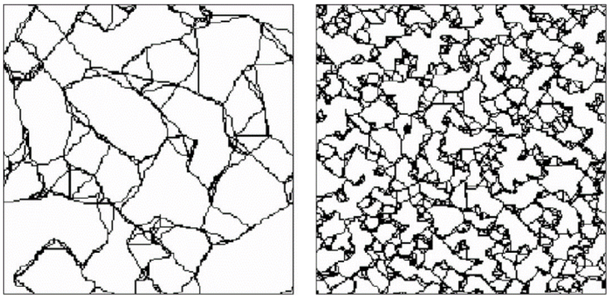

Figure 12. Two different foam model generated by Wang and Pan (2008)

By considering the radiation effect particularly in the case of low thermal conductivity of solid and high porosity mediums, the predicted results showed good agreement with the available experimental data. In another study, Kumar and Topin (2014) generated three-dimensional numerical model to predict the effective thermal conductivity. The range of solid to fluid phase conductivity was from 10 to 30,000 and for porosity range of 60%–95% was studied, and 2,000 effective thermal conductivity database was generated in the error range of 6%. Recently, the metal foams become popular with its compact structure for the heat exchangers. In many studies, open-cell metal foams are used as an alternative heat transfer enhancing application; however, it causes higher pressure drops. Lu, Zhao and Tassou (2006) investigated the application of open-cell metal foam in pipes analytically in the first of two stage work (Lu et al., 2006), and they examined the effect of microstructure of metal foams on the overall heat transfer and pressure drop. As seen in Figure 13, the pressure of a single phase flow in a pipe filled with metal foam increases with the increasing of pore density (ppi) or decreasing of pore size for all porosity values considered. When the porosity increases, which means the volume occupied by the fluid increases, as expected, the pressure drop decreases through the pipe.

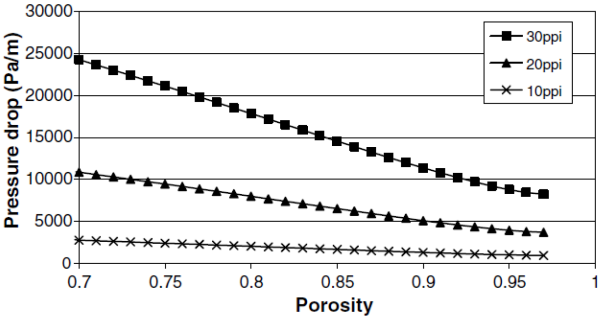

Figure 13. Effect of pore density and porosity on the pressure drop in a pipe (Lu et al., 2006)

The comparison of different pore density in terms of heat transfer performance is presented in Figure 14. As shown, when the pore density (ppi) increases, the Nusselt number increases considerably. However, the low pore size or high pore density have an advantage in terms of heat transfer performance, the pressure drop increases dramatically (Fig. 13).

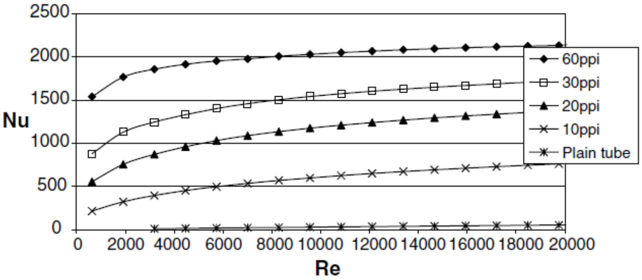

Figure 14. Effect of pore density and on the Nusselt number in a pipe (Lu et al., 2006)

In the second part, the same group (Zhao, Lu & Tassou, 2006) modelled the tube-in-tube heat exchanger analytically, and both inner section and outer annulus section were filled with metal foam. In addition to the previous study, the annulus side heat transfer performance was examined for different porosity and pores densities. As shown in Figure 15, the annulus side Nu number increases with the pore density, and when the pore size decreases (porosity increasing), the Nu number increases.

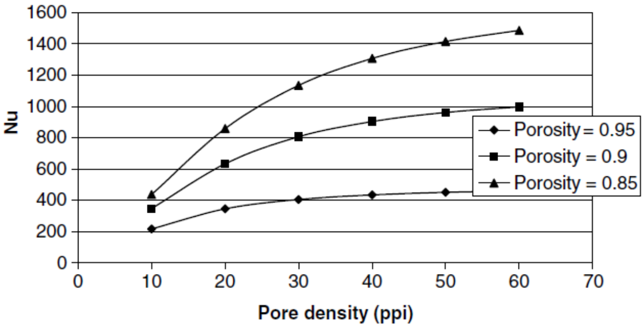

Figure 15. Effect of pore density and porosity on the pressure drop on the annulus Nusselt number (Zhao et al., 2006)

Dai, Nawaz, Park, Chen and Jacobi (2012) compared the metal foam and louvered fin heat exchanger for air-side heat transfer application. A model based on the ε-NTU method was developed, and the heat exchangers as shown in Figure 16 were compared in terms of volume, mass and cost when the heat transfer capacity was equal.

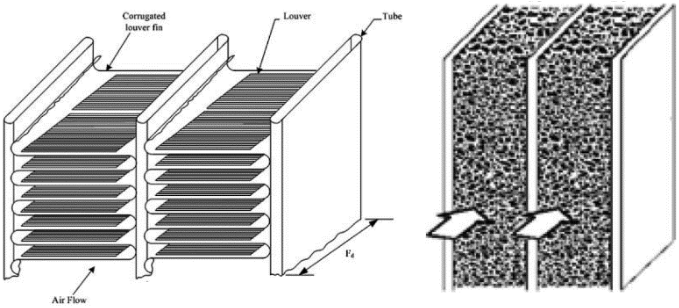

Figure 16. Louvered and metal foam heat exchangers attached on the flat tube (Dai et al., 2012)

According to the results of the study, the heat exchanger with metal foam is smaller and lighter than the heat exchanger with louvered fin for a fixed heat transfer rate and fan power; however, the cost of the metal foamed one ($174–$357) is quite high compared to the louvered one ($38).

Another numerical study to investigate the performance of a heat exchanger with metal foam was performed by Odabaee and Hooman (2012). As shown in Figure 17 that a tube bank system was considered by the authors and the effect of the characteristics of foam metal wrapped over the tubes on the thermal and hydraulic performance of the system was investigated. The performance of the tube bundle with metal foam was compared with the performance of finned tube bundle. According to the results, air side thermal resistance decreased when the tube bundle was wrapped by the metal foam instead of conventional fins. The variation in the thermal and hydraulic performance of the tube bundle was reported in terms of area goodness factor, and it was seen that the area goodness factor was five times greater when metal foam is used instead of fins.

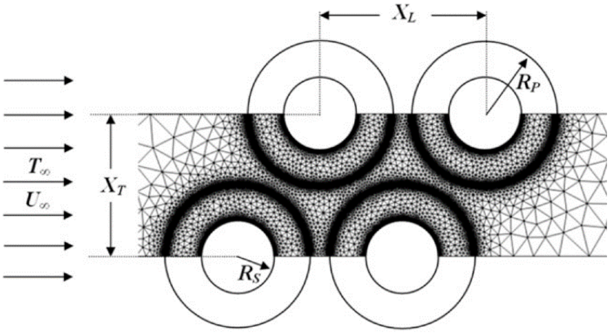

Figure 17. Representative volume of the tube bundle and the mesh structure (Odabaee & Hooman, 2012)

Huisseune, De Schampheleire, Ameel and De Paepe (2015) investigated the thermal and hydraulic performance of tube bundle type heat exchanger and compared the results with performance of the bare and louvered tube bundle. Nine different combinations of metal foam were considered during the analysis, and the comparison of pressure drop and heat transfer rate was reported in Figures 18 and 19, respectively. In the graphs, each foam sample was represented by MFxx.yyy, and xx and yyy represented the ppi and specific surface area values, respectively.

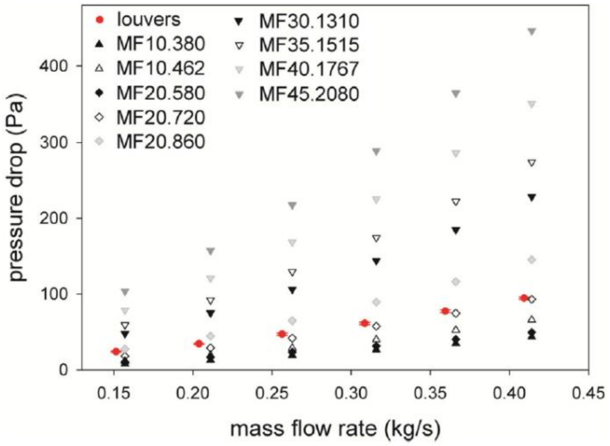

Figure 18. Comparison of pressure drops with respect to mass flow rate (Huisseune et al., 2015)

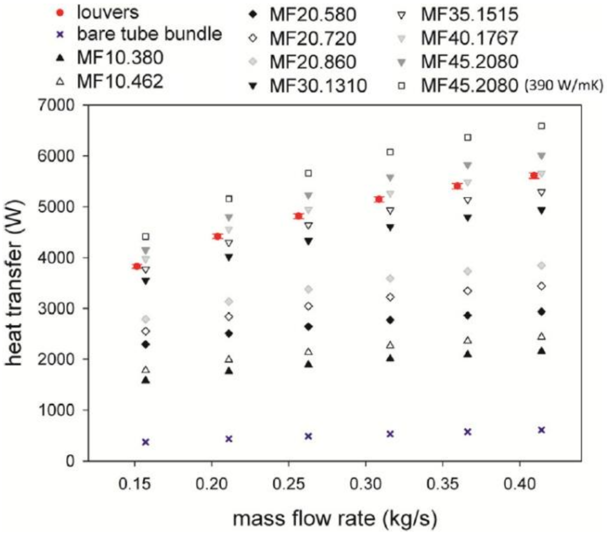

Figure 19. Comparison of heat transfer rate with respect to mass flow rate (Huisseune et al., 2015)

As shown in Figure 18, the pressure drop is increased considerably with the increase of pore density (ppi). For a fixed pore density, the pressure drop is increased with an increment of specific surface area as expected since the surface area increase causes more resistance against the flow. The louvered tube bundle had smaller pressure drops than the tube bundle with metal foam when the pore density was equal and greater than 30 ppi. Figure 18 showed the comparison of heat transfer rate of the considered heat exchanger configurations. As expected that the bare tube bundle has the poorest performance with its low heat transfer area. The one with louvered fin transfers more heat than the heat exchangers with metal foam when the pore density is lower than 40 ppi. The 45 ppi metal foam configurations stand out as the best in terms of heat transfer.

3. Conclusion

Metal foams became very popular in last decades due to their unique feature such as low weight, high surface to volume ratio and insulation characteristics. Some of these outstanding features let them to be considered in heat exchanger applications. Numerous publications reported in last decades by the researchers in this particular topic. Researches mostly based on two basic approaches which are experimental and numerical. Since the effect of the metal foams on the performance of the heat exchangers depends on numerous parameters, the investigations mostly focus on the identification of how these parameters have an impact on it. The scientists who are seeking more reliable outcomes conduct investigations experimentally while the scientists who are chasing more parameters effect either solely or combined choose the numerical or computational investigation path.

In this particular work, the ultimate goal is to provide information from a wider perspective for the reported metal foam works regarding the heat exchangers that could be addressed in the open literature. Effect of different characteristics of the metal foams such as pore density, porosity, type of foam material and type of heat exchangers on the performance of the considered systems is summarised in the previous sections in detail. Furthermore, the studies that compare heat exchangers with and without metal foams, either experimental or numerical, are presented in the mentioned sections to give a better perspective for the considered topic. The communication would help to see the overall picture of the recent status of the metal foam heat exchanger works so far.

Nomenclature

a	foam ligament radius (m)
k	thermal conductivity (Wm^{-1}K^{-1})
$keff$	effective thermal conductivity (Wm^{-1}K^{-1})
kf	thermal conductivity of the fluid (Wm^{-1}K^{-1})
ks	thermal conductivity of the solid (Wm^{-1}K^{-1})
L	ligament length (m)
Nu	Nusselt number
Rp	radius of the tube with metal foam (m)
Rs	radius of the tube (m)
r	cubic node length (m)
Rp	temperature of free flow stream (K)
$U\infty$	velocity of free flow stream (m/s)
XL	longitudinal tube pitch (m)
Xt	transverse tube pitch (m)
ε	porosity

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