Open access • Journal Article • DOI:10.1080/01457632.2012.659613

A Review of Metal Foam and Metal Matrix Composites for Heat Exchangers and Heat Sinks — Source link

Xiao Hong Han, Qin Wang, Young-Gil Park, Christophe T'Joen ...+2 more authors

Institutions: Zhejiang University, University of Texas–Pan American, Ghent University, Miami University ...+1 more institutions

Published on: 31 Jan 2012 - Heat Transfer Engineering (Taylor & Francis Group)

Topics: Heat sink, Metal foam, Heat exchanger and Forced convection

A review of metal foam and metal matrix composites for heat exchangers and heat sinks

X. Han[1], Q. Wang[1],Y. Park[2], C. T'Joen[3], A. Sommers[4], A. Jacobi[5*]

[1] Institute of Refrigeration and Cryogenics, Department of Energy Engineering, Zhejiang University, No. 38 Zheda Road, Hangzhou 310027, PR China

[2] Department of Mechanical Engineering, University of Texas-Pan American, 1201 West University Drive, Edinburg, TX 78539, United States

[3] Department of Flow, Heat and Combustion Mechanics, Ghent University-UGent, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

[4] Department of Mechanical & Manufacturing Engineering, Miami University, 650 E. High Street, Oxford, OH 45056, United States

[5] Department of Mechanical Science and Engineering, University of Illinois, 1206 West Green Street, Urbana, IL 61801, United States

Abstract:

Recent advances in manufacturing methods open the possibility for broader use of metal foams and metal matrix composites (MMCs) for heat exchangers, and these materials can have tailored material properties. Metal foams in particular combine a number of interesting properties from a heat exchanger's point of view. In this paper, the material properties of metal foams and MMCs are surveyed, and the current state of the art is reviewed for heat exchanger applications. Four different applications are considered: liquid-liquid, liquid-gas and gas-gas heat exchangers and heat sinks. Manufacturing and implementation issues are identified and discussed, and it is concluded that these materials hold promise both for heat exchangers and heat sinks, but that some key issues still need to be solved before broad scale

* Corresponding author: Dr. Anthony M. Jacobi, Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801. Tel. 217/333-4108, Fax: 217/244-6534.

application is possible.

Introduction

Metals are commonly used in the construction of heat exchangers because they generally possess a high thermal conductivity and good mechanical properties (i.e. high ultimate tensile strength, yield strength, manufacturability, etc.). The most commonly used metals are copper, aluminum, and stainless steel. While aluminum and copper have a high thermal conductivity, they also have high coefficients of thermal expansion (CTE). Materials with low CTEs, such as copper/tungsten and copper/molybdenum, generally have thermal conductivities that are lower than that of aluminum. The best conductors are the "noble metals" which include gold, silver, and platinum. However, noble metals are very expensive, and for most applications, with possible exceptions in the aerospace industry, the noble metals are too expensive to be used for heat exchanger applications. Even the non-noble metals are relatively expensive as compared to polymers and certain non-metals. Based on the above consideration, materials with low densities are needed in weight-critical applications. As a result, metal foams and metal matrix composites (MMCs) which were developed for structural and thermal applications more than two decades ago are now being considered as solutions to many thermal management problems (Zweben [1]; Ozmat *et al.* [2]). Table 1 provides an overview of several key thermo-physical properties of various metals and metal alloys used in heat exchanger construction. (In Table1, the ‘specific thermal conductivity’ (defined by Zweben [1]) is the ratio of the thermal conductivity and the specific gravity, and as such can be used as a figure of merit to indicate which metals are better for weight sensitive applications.) In this paper, these materials are reviewed for possible use in the construction of heat exchangers for use in Heating, Ventilation, Air Conditioning, and

Refrigeration (HVAC&R) systems and other similar applications. First, the material properties are surveyed after which the current state of the art of their application in HVAC&R and related heat-exchanger applications is reviewed. Some manufacturing and implementation issues are considered, and finally the future promise of using metal foams and MMCs in HVAC&R systems and components is discussed.

Material properties of metal foams and metal matrix composites (MMCs)

Metal foams

Compared to ordinary metals, the notable feature of metal foams is the existence of many voids within the material. Metal foams with a cellular structure are known to have many interesting combinations of physical and mechanical properties (Liu and Liang [7]; Tang *et al.* [8]; Tuchinskiy [9]), including:

1) Low weight (composed of about 90% of air);
2) High to very high specific surface area (500 to over 10000 m^2/m^3);
3) High heat transfer potential (convection and radiation, for open-cell bodies);
4) High gas permeability combined with high thermal conductivity (for open-cell bodies);
5) Resistance to thermal shock, wear, high temperature, humidity, and thermal cycling;
6) High strength and toughness, suitable for high-pressure conditions;
7) Good impact energy absorption;
8) Easy control over material morphology (pore size and distribution);
9) Machinability and weldability, allowing for the formation of complex parts;
10) Excellent noise attenuation;

11) Thermally insulating characteristics (for closed-cell bodies);

12) Excellent fluid mixing due to the tortuous flow path within the foam.

Because of their interesting properties, open-cell metal foams are currently regarded as a highly promising material for constructing efficient compact heat exchangers (Ashby *et al.* [10]; Bastawros and Evans [11]; Kaviany [12]; Ruiz [13]; Boomsma and Poulikakos [14]; Zhao *et al.* [15]; Anthohe *et al.* [16]; Boomsma *et al.* [17]) as well as for high heat flux applications such a processor cooling. In addition, many new applications have been suggested for metal foams, such as structural elements for aerospace, automotive, and building systems, thermal management systems, filters and catalyst carriers, and others (Banhart *et al.* [18]). Indeed, metal foams have been used to produce filters (Koltsakis *et al.* [19]), catalyst supporters (Ismagilov *et al.* [20]), porous electrodes (Wilkinson and Paserin [21]), energy absorbers (Kim *et al.* [22]), pneumatic silencers (Kang *et al.* [23]), shock-absorbing buffers, electromagnetic shielding or compatible elements (Losito [24]), flame arresters, cellular scaffolds for tissue engineering (Spoerke *et al.* [25]), flow mixers (Azzi *et al.* [26]), etc. Furthermore, they can be used to produce composite materials or to serve as gaskets. Therefore, metal foams are a versatile engineering material (Liu *et al.* [27]).

Metal foams (cellular metals) can be categorized according to their structure as either (i) open- or closed-cell, and (ii) stochastic or ordered/periodic. Open-cell foam consists of cells which all are interconnected (i.e. ‘without walls’) allowing a fluid to pass through it, while in a closed-cell foam the cells constitute individual enclosures within the material (see Fig. 1). Fig. 2 shows a few examples of periodic structures (Tian *et al.* [28]) used in cellular metals. These structures are very different from the stochastic orientation of the foams in Fig.

1 and clearly demonstrate the high specific surface area (i.e. surface area which is in contact with the fluid per unit volume). Examples of periodic structures include materials made from stacked metal textiles and microtruss concepts (Wadley [29]; Wadley [30]; Evans *et al.* [31]). The open-cell systems shown in Fig. 2 compare favorably to closed-cell honeycombs when used for the cores of sandwich panels. They are therefore attracting considerable attention as multi-functional structures (Tian *et al.*[28]).

Cellular metals are often characterized by their relative density $R=\rho/\rho_s$, where ρ is the density of the cellular metal and ρ_s is the density of the solid parent material (Ashby *et al.* [10]). Certain cellular material properties such as elastic stiffness, effective thermal conductivity, and effective yield strength can be directly related to the properties of the material comprising the cell walls through the relative density (Ashby *et al.* [10]; Lu *et al.* [32]). However, the effective thermal conductivity of metal foam is not only dependent on the relative density and the thermal conductivity of the base material from which the foam is made, but it is also dependent on the actual geometry of the foam due to the conductive pathways through the porous material which are limited to the ligaments of the material (Haack *et al.* [33]; Dai *et al.* [34]). Heat conduction in porous matrices has also been summarized in a number of extensive review articles and books (Kaviany [12]; Alazmi and Vafai [35]; Hsu *et al.* [36]). Ashby *et al.* [10] conducted an experimental study and found $k_s \cdot R^{1.65} < k_{eff} < k_s \cdot R^{1.8}$, where k_s is the base metal thermal conductivity, R is the foam relative density (as defined above), and k_{eff} is the effective foam thermal conductivity. Calmidi and Mahajan [37] and Boomsma and Poulikakos [14] independently developed analytical models specifically for metallic foams saturated with a fluid utilizing a geometrical estimate

for the calculation of the effective thermal conductivity. For high porosity metal foams, Calmidi and Mahajan [37] presented a one dimensional heat conduction model that considered the porous medium to be a two-dimensional array of hexagonal cells, whereas Boomsma and Poulikakos [14] proposed a three dimensional model that consisted of tetrakaidecahedron cells with cubic nodes at the intersection of two fibers. This widely used model by Boomsma and Poulikakos [14] was recently shown to be erroneous, corrected and extended by Dai *et al.* [34]. These models involve a geometric parameter that was evaluated using experimental data. Bhattacharya *et al.* [38] later extended the analysis of Calmidi and Mahajan [37] with a circular intersection, which results in a six-fold rotational symmetry. Singh and Kasana [39] presented a simple semi-empirical model for the k_{eff} of metal foams which showed good agreement with experimental data. Higher base metal thermal conductivity is usually associated with a higher material density, so a significant increase in foam density also results in an increased foam thermal conductivity. On the other hand, convective heat transfer to a metal foam is enhanced by thermal dispersion (i.e. intra-cell mixing), and these dispersive effects increase with the permeability of the foam (Hunt and Tien [40]). Thus, foam that possesses high relative density usually has a high thermal conductivity, but foam structures that are more "open" are more likely to perform better in convective heat transfer. This presents an interesting trade-off for designers.

Currently, most manufactured metal foams vary in pore sizes from 5 to 60 pores per inch (ppi), in porosity from 0.85 to 0.97, and in relative density from 3 to 15%. The porosity is the fraction of void space in the material and thus is related to the relative density. The number of pores per inch (or ppi) is a standard metric used by manufactures to indicate how many pores

are present on average over a distance of one inch. Table 2 presents an overview of some thermo-physical properties of aluminum foam samples that have been previously studied. In Fig. 3, some examples are shown of Al metal foam with a constant relative density but varying ppi, providing a close up view of the internal structure of the material. The structure consists of ligaments which form a network of interconnected dodecahedral-like cells. The cells are randomly oriented and mostly homogenous in size and shape with triangular-shaped edges. Alloys and single-element metals are available for the ligaments. Common materials include copper, aluminum, stainless steel, and high temperature iron-based alloys (i.e. FeCrAlY). Some researchers (e.g. Ozmat *et al.* [2] and Boomsma *et al.* [17]) have compressed metal foams to increase the thermal conductivity. As a result, the appearance of the metal foam changes considerably (see Fig. 4). As seen in Table 2, a major limitation of metal foams arises due to the fact that they are porous structures of their parent materials. While metal foams have effective thermal conductivities that are larger than those of polymers, their conductivities are up to an order of magnitude lower than those of their parent material. Another critical limitation comes from the excessive pressure drop that a fluid experiences as it passes through the foam (as will be shown later). In the following sections, the application of metal foams to heat exchangers will be discussed.

Metal matrix composites

Metal matrix composites (MMCs) are metallic matrices reinforced with metallic or ceramic particles/fibers for increased tensile strength and stiffness, decreased CTE, improved high temperature properties, and wear resistance. Long-fiber reinforcement materials show the most significant property gains, but they are also the most expensive to produce. MMCs

with discontinuous fillers (commonly ceramic particles) are attractive for their flexibility to be manufactured into various shapes. Layered composites in the form of a matrix-filler-matrix sandwich are useful for tailoring planar components. The filler sheets are often metal alloy sheets with low CTEs.

In several reviews of packaging materials for electronic equipment, Zweben focused on the advances that have been made in composite materials with high thermal conductivity, low weight, and low coefficient of thermal expansion (Zweben [1]; Zweben [43]; Zweben [44], Zweben [45]; Zweben [46]). These composites have a very high thermal in-plane thermal conductivity (comparable to or even higher than copper), but in some cases a relatively low through-plane thermal conductivity. The through-plane values are measured in the direction perpendicular to the fiber or flake orientation, the in-plane values are measured parallel to the filler. The thermo-physical properties of some MMCs are listed in Tables 1 and 3. Chung [3] also presented a review on materials with high thermal conductivity, including MMCs. Aluminum and copper are commonly used as metal matrices, due to their high thermal conductivity. An aluminum matrix is used for both structural and electronic applications. The thermal conductivity of aluminum matrix composites depends firstly on the nature of the filler material and its volume fraction, but also the alloy matrix heat treatment and the filler-matrix interface. Silicon carbide particle-reinforced aluminum (Al/SiC) is an MMC first used in microelectronic and optoelectronic packaging by GE in the early 1980s (Zweben [45]). Both carbon and SiC suffer from the formation of a galvanic couple, which results in the aluminum matrix (anode) being corroded.

Because copper has a high density, the filler does not have to be lightweight. Thus,

metals with a low CTE but high density such as tungsten, molybdenum and Invar are often used as fillers. These metals (except Invar) have the advantage that they are quite conductive thermally and are available in both particle and sheet form. Another advantage of using metallic fillers is the improved wetting between the molten matrix metal and the metallic fillers compared to ceramic fillers, which improves the manufacturability. An advantage of copper over aluminum is its non-reactivity with carbon, making carbon highly suitable as filler for copper matrices. Carbon is light, and available both as particles and fibers. Graphitic carbon fillers have a very high thermal conductivity, which can result in a composite with a higher thermal conductivity than the matrix material (copper), as shown in Table 3.

MMCs can withstand higher temperatures than polymer matrix composites (PMCs) but in general have a higher density. The main advantages of using metals as matrix material, compared to polymers, are their high tensile strength and shear modulus, high melting point, small CTE, resistance to moisture, dimensional stability, ease of joining, high ductility, and fracture toughness. Though not as widely used as PMCs, MMCs are finding increasing application in many areas. Further development of manufacturing and processing techniques is essential to reduce production costs and accelerate the introduction of MMCs.

Applications

Liquid-to-liquid heat exchangers

Smeding *et al.* [47] and Haije *et al.* [48] studied a sandwich plate-mesh-plate structure for small-scale NH_3-H_2O/LiBr-H_2O absorption chillers used in residential and small commercial applications and for waste heat recovery. The sandwich structure consisted of two

thin flat plates (0.35 m outer diameter, 5 mm pitch) with a wire mesh in between (see Fig. 5). The junctions of the wire mesh (1 mm thick) were vacuum brazed to both plates and tested under cyclic loads. The resulting construction was able to resist high pressure differences (20 bar) from inside to outside due to the proportional distribution of the junctions. The heat transfer medium (water) flowed through the open space of the wire mesh, and heat transfer by convection occurred between the fluid and the elements of the mesh as well as the bounding plates. Especially for laminar flow conditions, good heat transfer was achieved through continuous mixing of the flow. The secondary side (outside) of the heat exchanger surface was intended to be in close contact with the H_2O/salt. Thus, surface enlarging structures such as a wire mesh and metal foam can be applied to further increase the heat transfer performance on the secondary side. The detailed structure is shown in Fig. 6, where metal foam was brazed on the outside surface to enhance the conduction of heat to the H_2O/salt.

Tadrist *et al.* [49] made a liquid-to-liquid cross-flow heat exchanger, in which U-shaped aluminum plates equipped with a 40-ppi aluminum foam were stacked and brazed. The fluids were then circulated in rectangular cross-section channels (width: 5 or 10 cm, length: 6 or 11 cm, wall thickness: 0.3 mm). For a given heat exchanger, all the channels had the same geometric characteristics; however, no comparison with a conventional heat exchanger design was presented.

Porous metals with high thermal conductivity are also used in the fabrication of heat exchangers with concentrated heat exchange (discrete type) in dilution refrigerators for obtaining super-low temperatures (Wheatley *et al.* [50]). The extended surface of a heat exchanger with a porous structure makes it possible to decrease the limiting Kapitza

resistance, a thermal resistance which gives rise to a temperature jump at the liquid-solid interface through which heat is transmitted. Such a heat exchanger consists of a block, containing two chambers, filled with a permeable material with high thermal conductivity and high specific surface area, according to Severijns [51]. Usually, both the porous matrix and the block are made of copper.

Ferrouillat *et al.* [52] considered using a tube filled with metal foam as a heat exchanger reactor, a combination of a compact heat exchanger and a chemical reactor. The idea behind this device is to exploit the large available surface area for better temperature control (extracting heat from an exothermic reaction as it is formed) during the reaction and for improved selectivity of the reaction (due a more homogeneous mixture, better temperature control and shorter residence times). To this end, Ferrouillat *et al.* [52] experimentally studied the micro-mixing behavior in a channel with 3 types of metal foam (20 ppi aluminum, 20 ppi copper, and 40 ppi copper). When comparing the results to those determined for a channel without inserts and one with different types of offset strip fins, Ferrouillat *et al.* [52] concluded that metal foams offer the best micro-mixing level for any given residence time. By using inserts in the channel the required size of the reactor can be significantly reduced, at the expense of more pressure drop. Ferrouillat *et al.* [52] also noted that these surfaces could be used as catalytic surfaces for a further benefit of integrating the heat exchanger and the reactor.

Boomsma *et al.* [14] used compressed Al foams to manufacture heat sinks. The foams were brazed onto a heat spreader plate, and water was pumped through them. The heat sinks filled the entire channel. They studied the impact of the compression on the resulting

thermo-hydraulics and found that increasing the compression rate resulted in both a larger pressure drop and heat transfer. In order to evaluate the heat exchanger performance, they compared the required pumping power to the thermal resistance. They found that using the metal foam heat exchangers results in a reduction of the thermal resistance R_{th} by up to 50% for the same conditions. Boomsma *et al.* [17] also found that, although compressing the metal foams increases heat transfer rate, compressing them too much will worsen the overall performance due to the very sharp increase in pressure drop.

Kang *et al.* [23] used an aluminum open-cell foam to construct an electric water heater. They reported the temperature rise of the water at various set points but the results were not compared to other types of heat exchangers.

Liquid-to-gas heat exchangers

Klein and Whiteside [53] studied cross-flow glycol/water-air heat exchangers, as shown in Fig. 7. The liquid was circulated through flat multiport tubes, and the air was passed through a one inch thick layer of compressed aluminum foam, which was brazed between the tubes. They stated that these metal foam heat exchangers offer the potential to be lighter, smaller, more easily integrated into existing avionics components and less expensive than a conventional redesign of existing systems in aircrafts. Tadrist *et al.* [49] studied glycol/water-air cross-flow heat exchangers consisting of flat tubes with aluminum foam brazed in between. Three types of foam (10, 20, and 40 ppi) were used in these exchanger prototypes. The tubes were also spaced at two different distances (2.5 mm and 5.3 mm) in order to study the efficiency of the exchange surfaces. They reported no noticeable differences

between the various surfaces in the Colburn *j*-factors, even though their graph suggests the 40 ppi foam results in a lower Colburn *j*-factor. Further technical details for the heat exchangers and uncertainty analysis may allow a better evaluation of the data.

In order to face increasing challenges in thermal management, efforts are underway to improve heat pipe technology. One performance limitation in heat pipes is the so-called "capillary limit," which is determined by the liquid-pumping capacity of the wicking structure. A recently developed open-cell copper foam ([54]) has been claimed to raise the capillary limit of heat pipes, and it was proposed for applications in vapor chambers, and cylindrical, flat, and loop heat pipes. Current technology uses sintered metal powders as wick material. This technology allows for manufacturing porous structures in complex shapes with precisely controlled porosity. Sintering provides structural strength and good thermal conduction paths. In order to understand the structure of powder metal wicks, imagine a container containing nearly uniform spheres which are then pressed together. The space between the spheres forms an interconnected pore structure, a flow path determined by the size and uniformity of the powder metal grains. The advantages of the copper foam compared to sintered metal powders may be due to the small-diameter windows (as low as 40 μm) in the foam microstructure which enhance capillary forces; and due to the higher porosity (between 0.60 and 0.75), which leads to high permeability increasing capillary pumping. In preliminary experiments on copper-water heat pipes, the evaporator was heated while the other end of the heat pipe was cooled by natural convection. Heating power was limited by a maximum evaporator temperature of 100ºC. The prototype using foam transferred 11 W while a particular commercial screen mesh heat pipe transferred 6 W. A proof of concept of the vapor chamber

using this copper foam was found to have a thermal resistance of 0.07°C/W (at 200 W) with no dry-out appearing below 200 W and a uniform temperature profile. On top of the vapor chamber, a heat sink was mounted with fins which were cooled using forced convection. The large surface to volume ratio of metal foams promotes nucleate boiling, an important advantage for heat pipes. Metafoam® [54] reports a value > 20.000 m^2/m^3 for their copper form; however, these results were preliminary. Queheillalt *et al.* [55] studied a multifunctional heat pipe sandwich structure, combining the mechanical properties of the classic honeycomb structure with the thermal benefits of an internal heat pipe (made using Ni foam) such as thermal spreading.

Li and van der Meer [56] numerically studied the heat transfer from a wall covered with Ni and Al foam (porosity varying from 0.89 to 0.94) to air (low velocity). A constant wall temperature boundary condition was used at the wall, thus the studied element can be seen as part of a liquid-to-gas heat exchanger. They concluded that the flow was fully three dimensional with stagnant and recirculation zones behind the filaments. The pressure drop of a channel filled with metal foam is much higher than that of an empty channel. The heat transfer process is dominated by the heat transfer from the foam to the fluid which is 10 times larger than that of the wall to the fluid. This is due to the very thin boundary layer forming on the filaments as well as the strong mixing in the flow. The flow within the foam is fully developed after a few cells in the mean flow direction. Similar findings were reported by Calmidi and Mahajan [37]. Ejlali *et al.* [57] conducted a numerical study to investigate the fluid flow and heat transfer of an air-cooled metal foam heat exchanger under a high speed laminar jet confined by two parallel walls for which the range of the Reynolds number is

600–1000. They considered two different metal foam heat exchangers samples, intended for use in a geothermal power plant, and compared the results to a reference pin fin heat sink. As the jet velocity increased, the higher mass flow rate caused more air to enter the porous region which resulted in better heat transfer and mixing at the interface between clear fluid and the porous medium. The results showed that metal foam heat exchangers are superior compared to conventional finned surfaces at no excess cost (material weight and/or pressure drop). In their simulations they considered thermal dispersion, local thermal non-equilibrium, and non-Darcy effects.

Giani *et al.* [58] experimentally determined a heat transfer correlation for metal foams. They placed FeCr alloy foams in a channel to be used as a catalyst carrier (i.e. catalytic combustion) and used a transient method to determine the heat transfer coefficient. The results agreed well with an earlier work (Giani *et al.* [59]) in which they had determined mass transfer coefficients for these samples. This study showed that decreasing the pore size increased the mass (heat) transfer coefficient. They also found that at low fluid velocities the metal foam reactors performed much better than packed beds of spheres. A honeycomb structure performed even better than the metal foam, but when compactness was also considered, it was shown that the metal foams result in a smaller reactor than when honeycomb structures are used. Groppi *et al.* [60] further expanded the correlation to include ceramic foams (lower porosity values) and reported that, in agreement with earlier modeling work, the flow behavior is similar to the flow across a bundle of tubes. The Reynolds number was based on the strut diameter and the mean flow velocity in the minimal free area.

Kim *et al.* [42] experimentally studied the heat transfer and pressure drop of a metal

foam placed between two flat tubes at constant temperature (representing a small section of a water-air heat exchanger). Six types of foam were considered with varying porosity (0.89 - 0.96) and varying ppi (10 - 40). A standard louvered fin heat exchanger was used as a reference. The results indicated that the friction factor is much lower for the fins with a high ppi value (40), despite the lower permeability, due to relatively larger surface area. For a constant ppi value (20), increasing the porosity resulted in a higher friction factor. (Even though the dimensional pressure drop decreased, the friction factor increased due to the sharp drop in surface area for higher porosities). The louvered fin exhibited slightly higher friction factor values than that of the porous fins at low Reynolds numbers. When the Reynolds number was high, however, the porous fins showed much higher friction factors compared to the louvered fin. The modified *j*-factors (i.e. Colburn *j*-factor multiplied by the surface efficiency) of the porous fins decreased as the pore density increased or as the porosity decreased. It should be noted that these porous fins had a similar thermal performance compared to the conventional louvered fin; however, the louvered fin showed a little better performance in terms of pressure drop. This was demonstrated using the volume goodness approach (see Fig. 8). It was also found that porous fins with a high ppi value and low porosity are preferred for the compactness of plate-porous fin heat exchangers.

Mancin *et al.* [61, 62] recently presented both heat transfer and pressure drop data for foam filled channels heated on one side by a uniform heat flux. This configuration mimics a liquid-to-gas heat exchanger. Different types of foam were studied with varying porosity and pore density (ppi) and only mechanical contact was present between the base wall and the foam.. They presented their results as heat transfer coefficients (related to the base surface

area on which the foam was mounted), indicating that for a constant ppi value a lower porosity results in a higher heat transfer coefficient, and that at higher air velocities a smaller foam height (2 cm vs. 4 cm) results in higher heat transfer coefficients [62]. The same setup was used for pressure drop measurements. They reported similar findings as Kim *et al.* [42] with regards to the impact of the porosity and ppi values, but further analyzed the foam properties using the inertia and form coefficient [61], and permeability. They compared their results with available correlations for the pressure drop and found no model was able to provide satisfactory agreement. A new model was thus proposed which provides good agreement (to within ±20%) with a considerable database of published data.

Salimi Jazi *et al*. [63] reported on the pressure drop and heat transfer of air flowing through two heat exchangers made with 10 and 20 ppi Ni foam. These were manufactured by spray coating an Inconel 625 layer on top of the exposed foam. Results showed that the 20 ppi foam had a higher heat transfer coefficient and pressure drop. This manufacturing process allows the heat exchangers to resist higher temperatures. In addition, a thermal barrier coating was applied to allow for even higher temperatures (up to 1000°C), and this additional thermal resistance only had an impact at higher air velocities. Dukhan and Chen [64] presented heat transfer measurements inside rectangular blocks of commercially available aluminum foam subjected to a constant heat flux on one side, cooled by air. The temperature profile decayed exponentially as the distance from the heated base increased. This showed qualitative agreement with a 2D analytical model derived for heat transport through the foam block.

T'Joen *et al.* [65] report on the heat transfer and pressure drop of a single row heat exchanger consisting of metal foam covered tubes. This idea was inspired by an earlier work

on carbon foams by Straatman *et al.* [66] who had found that air only penetrates the foam a few millimeters. In order to reduce the pressure drop, a metal foam sleeve was placed around the tube using epoxy as bonding. Different foam types were studied and the foam height and tube spacing were varied. Results showed that for metal foam covered tubes with a small tube spacing, small foam heights (2-4 mm) with a high specific surface area (i.e. thin struts) potentially offer stronger benefits (based on a volume goodness approach) as compared to helically finned tubes at higher air velocities (> 4 m/s). Boger and Heibel [67] experimentally studied the heat transfer between nitrogen gas (250-400 °C) flowing in a square-celled LCA (linear cellular alloy) and surrounding cooling water (see Fig. 9). They reported very high heat transfer coefficients up to 1000 W/m²K. The samples which were intended for use as catalytic supports had a size of 25 – 30 mm outer diameter with square channels having a hydraulic diameter between 0.9 mm and 1.6 mm..

Gas-to-gas heat exchangers

Zhao *et al.* [68] analyzed the heat transfer performance of metal-foam-filled tube-in-tube heat exchangers. Fig.10 shows examples of a single metal-foam-filled tube. The heat exchangers were made of copper, and air was used as the working fluid on both sides. Results showed that the use of metal foam can significantly improve the heat transfer performance, due to the increased surface area and excellent mixing of the fluid within the metal foam. For the same area density, the heat transfer capacity per unit length of the foam-filled annular tube was approximately three times higher than that of a longitudinally finned tube. Using spiral fins instead of longitudinal fins improved the performance of the

conventional heat exchanger but the heat transfer rate was still much lower than that achieved with the metal-foam filled annular channel. Zhao *et al.* [68] also showed that the heat transfer capacity increases with decreasing porosity or increasing pore density.

Heat sinks

Over the past decades, the evolution of micro-chips has been driven towards further miniaturization, increased computational speed and more complex dedicated architectures, e.g. graphics processing units. This has resulted in an increase of the power density of microchips and associated with this increase, a rise in the power dissipation. So there is a clear need for more effective thermal management systems in order to maintain these electronic systems within allowable temperature ranges. In many cases, heat rejection is a limiting factor for increasing the computational speed and the reliability of components. Today, heat sinks are used to reject the heat generated by the electronic components. Although for some systems passive heat sinks based on natural cooling are still used, most heat sinks today are 'active' and have fans attached to them in order to increase the heat transfer rate. In some compact systems (e.g. laptops), thermal management is even more critical. In such compact environments, the required heat sinks can be too large to be attached to the components directly so loop heat pipes are needed to transport the heat from the chip to the heat sink. For such applications, using small and light heat sinks can provide significant benefits.

Recently, metal-foam heat sinks have received considerable attention (Antohe *et al.* [16]; Camidi and Mahajan [37]; Hsieh *et al.* [69]; Kim *et al.* [70]; Lee *et al.* [71]) due to their interesting material properties. As stated earlier, metal foams not only possess desirable

properties of the bulk metal such as corrosion resistance, acceptance of coatings, and high electrical and thermal conductivity, but also qualities such as a low density, high strength-to-weight ratio, high porosity, and extremely large surface-area-to-volume ratios. Hsieh *et al.* [69] experimentally determined heat transfer correlations for six types of Al foam heat sinks (pore density: 10 - 40 ppi, porosity: 0.87 - 0.96) and found that increasing the porosity and pore density results in a higher Nusselt number. The studied configuration is shown in Fig. 11 and is similar to a processor cooling heat sink with a fan mounted on top blowing air through the sink. Shih *et al.* [72] further studied the impact of the height of the heat sink and found that an optimal height exist related to the foam porosity. By reducing the height of the heat sink, more air was allowed to reach the base surface resulting in a larger heat transfer rate; however, below a certain height, further reduction of the height removes exterior surface area and thus reduces the performance.

Kim *et al.* [70] investigated the thermal performance of aluminum-foam heat sinks for forced air-cooling of electronics. Test specimens of the aluminum-foam heat sink were made by brazing the aluminum foam block (porosity: 0.92, pore density: 10, 20, 40) to a base plate as illustrated in Fig. 12 (a). A thin base plate was adopted to reduce the influence of the conduction thermal resistance through the base plate on the overall thermal resistance. As a reference, a conventional heat sink with parallel plate fins (Fig. 12 (b)) was manufactured to have a base plate of the same thickness and height (i.e. half of the wind tunnel height). The heat sink was mounted in a wind tunnel allowing for flow bypass. The results showed that compared to the plate fin heat sinks, the aluminum foam heat sinks were able to reduce the thermal resistance by up to 28%. The pore density has a strong impact on the results as the

heat sink with 10 ppi foam obtained *Nu* values that were 16-27% higher than those of the heat sink with 40 ppi foam. This is of course was due to the reduced flow resistance of the more open flow which reduced the bypass. It should also be noted that the weight of the Al foam heat sinks was only 25% of that of the plate fin heat sink, again stressing the advantage of these materials.

Lee *et al.* [71] investigated metal foams as high performance air-cooled heat sinks in electronic packaging. In their experimental work, they demonstrated that aluminum foams could reject heat fluxes up to 100 W/cm². Ozmat *et al.* [2] presented heat transfer and pressure drop data for a heat sink made of compressed copper foam as well as the overall thermal resistance for different heat sinks (rejecting 500-800 W) with varying foam-fluid (air, water) combinations. The results again showed the low thermal resistance that can be obtained using metallic foams. Mahdi *et al.* [73] studied Al foam heat sinks for CPU cooling using natural convection. They found that the thermal resistance was reduced by more than 70% compared to finned heat sinks and reported that the thermal resistance was inversely proportional to the pore density.

Dempsey *et al.* [74] experimentally compared the heat transfer performance of a stochastic cellular metal heat sink to a square-celled LCA heat sink (similar to the one shown in Fig. 9). The external dimensions of the heat sinks were 20 mm in height, 25 mm in length, and 25 mm in width. The inlet air velocity was 4 m/s. The results showed that the LCA provided comparable heat removal at half the pressure drop of the stochastic cellular metal heat sink. The ability of the square cell LCA heat sink to provide relatively high steady-state heat transfer rates at relatively low pressure drops via laminar flow is attractive in electronic

package cooling applications. Because they are extruded with closed exterior faces, LCA heat sinks can be designed with an internal bypass (selectively larger interior cells), offer low noise characteristics, and be operated with other higher conductivity working fluids to achieve enhanced heat transfer. It would be interesting to compare the relative performance of LCA heat sinks operated at higher air flow rates in the turbulent flow regime with that of metal foam heat sinks.

Bhattacharya and Mahajan [75, 76] developed a new heat sink design, a finned metal foam heat exchanger. It consisted of a number of parallel plate fins with metal foam joined between as shown in Fig. 13. When used in natural convection mode, Bhattacharya and Mahajan [76] found that the finned metal foam heat sink provided an increase in heat transfer compared to an optimized plate fin heat sink. The 5 ppi foam resulted in an increase of the heat transfer coefficient ranging from 65% to 24% depending on the temperature difference between the base and the inlet air (10°C and 50°C, respectively). In forced convection [75], the finned metal foam heat sinks also outperformed the parallel plate heat sinks by a factor of 1.5 to 2. Denser foams provided less benefit due to increased flow resistance in both natural and forced convection. The results also indicated that there exists an optimal number of fins depending on the application. It should be pointed out that these designs were not optimized, so further performance improvement could be expected, and more importantly, the metal foams were joined to the plate fin surface using epoxy glue and were not brazed. As shown by other researchers (e.g. Bastawros and Evans [11] and T'Joen et al. [65]), this bonding method can result in poor heat transfer of the foam configuration.

Garrity *et al.* [77] compared aluminum and carbon foam heat sinks to a conventional

louvered fin design. To reduce the pressure drop of the carbon foam to the same level as that of the aluminum foam (due to the lower porosity) holes were drilled into the sample, parallel to the air stream. Three different criteria were considered: coefficient of performance (COP: ratio of heat removed to the fan power consumption), compactness (ratio of the removed heat to the total volume), and power density (ratio of the removed heat to the total mass). The results showed that the carbon foams provide a higher compactness, followed closely by the aluminum foams, but that the louvered fin is clearly dominant when COP and power density are considered, which is due to the large pressure drop of the foam compared to the fins, and the very light weight fin structure used. The high pressure drop is due to the long flow length through the foam (15.24 mm), reducing this could affect the results significantly.

Manufacturing feasibility and implementation assessment of metal foams and MMCs for heat exchangers

Manufacturing processes to produce and machine simple metals and metal alloys are well established and are widely used to construct conventional metallic heat exchangers. Therefore, our attention is focused on the methods specifically relevant to the novel forms of metals within the scope of this review. In the following paragraphs, a review of manufacturing feasibility is presented for periodic cellular structures, stochastic foams, and metal matrix composites.

Hayes *et al.* [78] studied the mechanical properties of linear cellular alloys (LCAs) to be used as heat exchanger materials. They pointed out that LCAs hold promise because of the high thermal conductivity of the walls, high surface-area-to-volume ratio, and the ability to

tailor cell size and shape to optimize the performance (e.g. changing the cell size of a honeycomb structure can have a strong impact on the resulting performance, as shown numerically by Lu [79]). LCAs are produced in a two-step process: extrusion of metal oxide powders followed by a chemical reaction/sintering process to form near fully dense walls. Hayes *et al.* [78] argued that, for practical applications, the optimal topography of the cell structure (i.e. cross-sectional geometry) is non-uniform, because of the conflicting functional requirements, a trade-off exists between high structural rigidity and high thermal-hydraulic performance. Based on their suggestion, an ideal configuration for LCA should have graded cell structures that accommodate both stiffness and heat transfer depending on the relative importance of either functional requirement. For example, triangular cells can be used at the locations where structural integrity is critical, and hexagonal cells can be used where hydraulic performance is important. An example of combining both of these requirements was presented by Queheillalt *et al.* [55]. Currently, LCAs are used in a range of applications primarily for their good mechanical properties. Considering that in many of those applications heat transfer and/or thermal management are also important, the authors believe that integrating the two functionalities into one component will provide large benefits for applications such as cooled aircraft skins, high temperature engines, heat pipes, vapor chambers, etc.. However, further research is needed before the potential benefits of this concept are fully quantified and understood.

It appears that, although mechanical contact may be "sufficient" in some applications, further improvement of thermal contact may be necessary, especially for porous metal foams. Howard and Korinko [80] examined various vacuum furnace brazing methods to bond a

reticulated open-cell copper form to a stainless-steel tube. They found that a high-temperature brazing (i.e. 980°C) with Au-Cu braze alloy resulted in excessive creep damage to the copper foam. Using a copper-tin braze alloy caused excessive braze erosion, and it was difficult to control the brazing process. Silver solid state diffusion bonding did not provide sufficient strength. The best result was obtained by using an Au-In braze alloy at moderate temperatures (i.e. 500-650°C). Here, thermal creep or expansion damage was minimized, a good wetting of the braze alloy on both copper and stainless steel was achieved, and no excessive braze erosion was observed. Salimi Jazi *et al.* [63] used a wire-arc spray coating process to deposit a layer of Inconel 625 on 10 and 20 ppi Ni foam. This resulted in a thin metal covering on top of the foam with maximum contact between the foam and the layer as it was formed in situ by the coalescence of molten metal particles on top of the barrier layer. Batawros and Evans [11] showed that using an epoxy bonding to connect metal foam to the carrier, even one with a high thermal conductivity results in decreased performance as compared to brazing the foam. Similar findings were reported by Sekulic *et al.* [81] who compared brazed and unbrazed metal foam heat exchanger samples and T'Joen *et al.* [65] who reported that at higher air velocities up to half of the total thermal resistance of the heat exchanger was due to the epoxy layer used to bond the foam to the tubes. Boger and Heibel [67] also reported that the contact resistance between the square-celled LCA and the surrounding tube had a strong impact on the overall performance. Boomsma *et al.* [17] stated that imperfect brazing can affect the flow and heat transfer behavior due to added flow resistance near the wall. Thus, it is clear that in order to fully exploit the benefits of these materials, more research is required into bonding-brazing technology and methods to assess the brazing performance.

Some researchers have described specific manufacturing processes to create cellular metal structures. Tian *et al.* [28] described a detailed procedure to produce a textile heat sink as shown in Fig. 14. The heat sinks consisted of laminated textile cores of plain woven copper wires which were fabricated using transient liquid phase bonding and brazing. Wadley [30] described a variety of manufacturing techniques for multifunctional cellular periodic metals such as honeycombs (through strip bonding or stacking of corrugated plates), lattice truss structures (through investment casting, folding of perforated sheets or by weaving-braiding of metallic wires) on a mass production scale. Using hollow tubes instead of solid wires for lattice truss structures has advantages of very low core density and increased buckling strength from a higher moment of inertia of the tubes. However, a more sophisticated fabrication technique is required, such as a precision drilling method used to fabricate hollow pyramidal lattices. Banhart [82] summarized the manufacturing processes for stochastic cellular metals and metal foams into four categories: producing the porous structure from (1) liquid metal, (2) solid metal in powdered form, (3) metal vapor or gaseous metallic compounds, and (4) metal ion solutions. Depending on the processes, the porous metal foam attains an open-cell or a closed-cell structure. For example, metal foams produced by a direct foaming method by gas or a blowing agent usually result in a closed-cell structure. Also, the solid-gas eutectic solidification method (known as "gasars") produces a unique, heterogeneous, directional, closed-cell porous structure as shown in Fig. 15. Manufacturing methods that produce open-cell porous structures include investment casting and the electro-deposition technique. Angel *et al.* [83] described a new and promising method, Slip Reaction Foam Sintering (SRFS), which has proven to be advantageous in producing

open-cell metallic foams. It allows prescription of the density of the foam and the pore form through several process parameters, and foams based on various metals and alloys are producible. Moreover, these parameters lead to different structural and functional properties, and foam production at room temperature can be easily controlled. Thus, it is clear that for most cellular metals well established techniques are available even for mass production. Nevertheless, more research is required into the further improvement of existing techniques (reducing waste and energy consumption), and into the manufacturing of new types of LCAs (by varying the cellular element shape locally) and foams (particularly in combination with brazing techniques for heat sinks).

Degischer [84] classified metal matrix composites into two types: (1) discontinuously reinforced and (2) continuous fiber reinforced metal matrices. Discontinuously reinforced MMCs are produced by embedding particulates, platelets, or short fibers of high aspect ratios within metal alloys, and conventional shaping methods like casting, forging, and extrusion can be applied. For continuous fiber reinforced MMCs, individual filament (i.e. mono-filaments) or bundled filaments (i.e. multi-filaments) are embedded within the matrix. These composites should be manufactured by a net shape technique to preserve the continuous fibers. Such methods must properly address two processing problems: (1) wetting of the fiber reinforcements by molten metal, and (2) preventing property degradation by chemical reactions between the matrix and the reinforcing phase. Ibrahim *et al.* [85] conducted a review of particulate reinforced metal matrix composites and identified three processing methods for MMCs: liquid phase, solid state, and two phase (solid-liquid) processes. In a liquid phase process, ceramic particulates can be mixed into the molten metal

and cast into MMCs. This method can present difficulties in particle dispersion, agglomeration, settling, and segregation. Alternatively, a melt infiltration method can be used in which a molten alloy is forced into a porous ceramic pre-form. This method can yield an undesirable structural non-uniformity and is limited to coarse grain sizes. In melt oxidation processes, a ceramic preform (which is formed into the final product shape by pressing, injection molding, or slip casting), is continuously infiltrated by a molten alloy. During this process, the metal alloy is oxidized by the surrounding air, and metal oxides appear at the ceramic-metal interfaces of the final product. In solid phase processes, solidified metal powders are rapidly mixed with the particulate reinforcements. The mixture is then pressed and degassed. The final consolidated product can be obtained by extrusion, forging, rolling, or other hot working methods. Two-phase processes for MMCs include the Osprey process and rheocasting. In the Osprey process, the reinforcement particulates are mixed with the molten alloy which is subsequently atomized by jets of inert gas. The sprayed mixture is then collected on a substrate in the form of a reinforced metal matrix billet. In rheocasting, ceramic particulates are added into a metallic alloy matrix at a temperature within the solid-liquid range of the alloy, followed by a vigorous agitation to form a low-viscosity slurry. This method prevents particulate agglomeration and settling, and thus helps produce a homogeneous composite. Although these composites are well established, further improvements can be achieved by modifying production processes or by altering the composition focused on modifying specific material properties. Recent advances in polymer composites (Jordan *et al.* [86], T'Joen *et al.* [87]) have shown the benefits of nano-scale composites (using clays or carbon nanotubes) which could also have a strong impact on MMC

technology.

A potential issue that could arise for heat exchangers and heat sinks formed using metal foams or cellular metals is, of course, fouling. As these materials rely on tortuous flow paths and small pore sizes to provide the large specific surface area, one can assume that fouling with particulates can create blockages and subsequently result in decreased performance. Unfortunately, no information is available on the impact of fouling on these types of materials due to the lack of finalized heat exchanger designs. However, Haghighi-Khoshkhoo and McCluskey [88] reported some interesting results on the impact of particulate fouling on compact louvered fin heat exchangers. They studied the impact of the particulate size and distribution and reported that particles approaching a compact heat exchanger either pass through without hindrance, are blocked over a shallow depth at the front, rest on the outer surface while the air speed is non-zero, or rebound from the surface and drop to the wind tunnel floor. Those that penetrate into the sub-surface region are the most detrimental to exchanger performance. They found that a critical particle size exists, for which this penetration is maximal. This was found to be 0.6 times the diameter of the largest sphere that can be inscribed in the fin spacing. The penetration depth was found to be small—only about 3 or 4 mm. Interestingly, fouling did not affect the thermal performance in the considered circumstances. It can be assumed that similar findings would also hold for cellular metals.

The presented overview of the available thermo-hydraulic data for the metal foam and metal matrix composites has highlighted some key issues. First, using these materials often creates a delicate balancing exercise. The metal foams have a very high specific surface area,

but also generate very high pressure drop. Thus, even if they result in a very compact heat exchanger, the fan power requirements for the heat transfer will be very high. Therefore, designs must seek ways to exploit the material benefits without incurring these high pressure drops, or more advanced material tailoring is required, whereby the foam structure itself is designed to result in a higher effectiveness (e.g. through pore size variation). Different strategies have already been presented to minimize the pressure drop: using finned structures or gaps within the foam matrix (see Leong *et al.* [89], Gallego and Klett [90] and Jamin and Mohamad [91], all using carbon foam), or using a thin layer of foam parallel to the flow (see Straatman *et al.* [66] for carbon foam, and T'Joen *et al.* [65] for metal foam covered tubes). This latter idea, provided that good bonding can be realized, seems to hold a lot of promise, as it would permit a significant increase in the heat transfer rate of flat hot surfaces without the need of complex heat exchangers.

Second, despite considerable research in analytical and numerical modeling and experimental measurements of thermo-physical properties and thermal hydraulic performance of foam, considerable ambiguity exists in published performance of foam materials. This is in part due to the uncertainty of the measured specific surface area. Some authors combine a simplified model of the geometric structure (e.g. tetrakaidecahedron) with scan data of pore and strut diameter to estimate the specific surface area. This resulted in a number of different models (some are listed by Mahjoob and Vafai [92]). In a recent paper, Schmierer and Razani [93] used tomography to study a series of aluminum foam samples. They reported a large standard deviation (i.e. 28%) of the mean value for the strut diameter, which is due ligament thinning. Care should thus be taken when determining an 'average' value for the strut diameter based

on data from small samples via optical microscopy. To process the foam images taken by microscopy, various types of image processing software and algorithms are used which filter the grey scale images and define the object perimeter based on a 'cut-off' value. This can introduce significant uncertainty. When comparing their results with data published in the literature, Schmierer and Razani [93] found a considerable difference for the specific surface area, up to 40%. Based on a thorough error analysis, Schmierer and Razani [93] reported an uncertainty of 18% on their specific surface area values. Using these measured values for A_{ext} would result in Nusselt numbers with a large uncertainty which have little value for comparison. Moffat *et al.* [94] also noted this and proposed to ''simply keep the parameters (h_{ext} and A_{ext}, exterior heat transfer coefficient and surface area, respectively) as one entity" to prevent misinterpretation when comparing data from different sources. This, if practiced consistently in future studies, can allow for a more useful comparison.

Numerical modeling of flow and heat transfer in metal foams

Over the past decades, extensive efforts have been put into the modeling of flow and heat transfer in porous media. Reviews have been presented by a number of researchers (e.g. Ashby *et al.* [10], Kaviany [12], Hsu [95] and Mahjoob and Vafai [92]). This section aims to briefly summarize some of the key findings, without providing an exhaustive review as has already been covered in the cited papers. As stated earlier, determining the geometric characteristics of metal foam (i.e. specific surface area, tortuosity, mean pore diameter, etc.) is a challenging task. Some authors therefore have developed correlations based on a simplified model of the foam geometry with these geometric parameters expressed as a function of e.g.

the porosity of the foam. Different models have been considered: cubic unit cell with slender cylinders, dodecahedron or a tetrakaidecahedron, interconnected hexagonal cells. Using such basic representations of the unit cell, a large number of studies have been published predicting the pressure drop (e.g. [2], [38], [96]), effective thermal conductivity (e.g. [2], [12], [14], [34]) , heat transfer rate (e.g. [32], [97]]) or mechanical properties (e.g. [98]) of the metal foam. These results are determined through purely analytical modeling with our without additional empirical information (e.g. modeling the extra metal mass at the interconnection of the struts [38]) or finite element solutions of the conservation equations. To determine the heat transfer rate, existing correlations are used to describe the heat transfer between the tubes (representing the struts) and the fluid. These models are able to predict trends (i.e. dependence on foam relative density, duct geometries, fluid velocity, etc.) which agree well with experimental findings. When applying these models, it is important to verify that the assumptions on which they are based such as local thermal equilibrium, negligible thermal dispersion are valid. Dispersion is a hydrodynamic phenomenon which becomes prominent at high Reynolds numbers, especially if the conductivity is small in magnitude. In essence, thermal dispersion distributes energy within the porous continuum such that higher temperature differences and thus higher interstitial exchange occurs. This was studied in detail by Calmidi and Mahajan [37] using the Zukauskas [99] correlation with a model for the effective thermal conductivity. They showed that if the thermal conductivity of the fluid is much smaller than that of the foam (e.g. aluminum foam-air), then the effect of dispersion is negligible; while if it is comparable (e.g. aluminum foam-water), the effect can be very pronounced and account for the bulk of the thermal transport. Their model for thermal

dispersion has been successfully applied to carbon foam as well (Straatman *et al.* [66]). Recently, Yang and Nakayama [100] provided a more in-depth study of the thermal dispersion phenomena in porous media.

In extending these modeling attempts, CFD software has also recently been applied to study the flow and heat transfer through metal foam structures. Boomsma *et al.* [101] considered a representative volume consisting of eight cells (six tetrakaidekahedra and two dodecahedra), scaled to correspond to a pore density of 40 ppi with periodic boundary flow conditions. Their results indicated that the pressure drop was under-predicted by 25% as compared to experimentally measured values. Kopanidis *et al.* [102] performed a CFD study on flow and heat transfer through a 40 ppi foam with a larger domain than Boomsma *et al.* [101]. Comparison with experimental data showed good agreement for pressure drop and heat transfer. The influence of entrance effects was investigated and found to be significant. For applications where the foam depth in the flow direction is small due to pressure drop restrictions, nominal pressure drop values calculated from measurements using larger scale samples may therefore have to be adjusted. When heat transfer is considered, entrance effects, near wall effects and heat conduction through the solid ligaments lead to significant deviations from the usual assumption of constant ligament temperature.

Although the simplified models have proven to be effective for trend analysis, it is clear that detailed modeling of the flow and heat transfer behavior within a realistic foam or LCA structure should lead to further improvement of both the heat transfer performance and the optimization of the geometry.

Conclusions

The thermo-physical properties of cellular metals (i.e. foams and LCAs) and MMCs can offer advantages over conventional metals for heat exchanger construction. In particular, the thermal conductivity, coefficient of thermal expansion, surface-area-to-volume ratio, weight, convective heat transfer performance and structural integrity may be superior. There have been some successful applications of these materials as heat exchangers, showing promise in liquid-to-gas, gas-to-gas, liquid-to-liquid, and heat-sink applications. Some tested designs of heat exchangers with novel metallic materials have been demonstrated to exceed the performance of the current state of the art. Metallic foams seem to have a particularly bright future in heat sink applications due to their low thermal resistance and lightweight properties. A particular promise is the integration of different functions into a single component (for example, using LCAs not only for their improved structural support but also for improved thermal management). Metal foams could also be used as a catalyst carrier in a reactor while at the same time facilitating more effective heat transfer.

However, several issues related to metal foams, LCAs, and MMCs remain which need to be resolved. Currently, there is no mass production available for metal foams. This makes the material currently very expensive to use in these applications, and thus only suited for high-end niche markets (e.g. racing cars). Reliable large scale production capacity is required to lower the prices of these materials. There is also insufficient information available in the open technical literatures to facilitate the careful design and optimization of heat exchangers made from these materials. Further work to characterize the thermal-hydraulic behavior of these materials and full-scale testing of new designs and integrated systems is still needed,

bearing in mind the recommendations made by Moffat *et al.* [94] with regards to the data analysis. Manufacturing methods have evolved for the production of the needed materials, but more attention is needed to resolve the issues related to joining and construction. Experimental studies have shown that metallic contact (i.e. brazing) will be required to fully exploit the material properties, but no cost effective brazing process is currently known. Some bonding processes have been identified such as spray coating or brazing with expensive materials such as an Au-In alloy. This clearly is one of the key issues to be resolved to allow for further development of this technology. Another interesting manufacturing option would be to further tailor these materials towards their applications such as foams that have a varying porosity moving away from the wall to minimize the pressure drop.

Acknowledgements

This work was sponsored by the Air-Conditioning and Refrigeration Technology Institute (ARTI).

Nomenclature

A_{ext}	=	exterior heat transfer surface area (m^2)
CTE	=	coefficients of thermal expansion
LCA	=	linear cellular alloy
MMCs	=	metal matrix composites
R	=	the foam relative density
h_{ext}	=	exterior heat transfer coefficient ($w/m^2 \cdot K$)
k_s	=	the base metal thermal conductivity (W/m K)
k_{eff}	=	the effective foam thermal conductivity(W/m K)
ppi	=	pores per inch
$E\beta$	=	friction power
$\eta_s h\beta$	=	the air-side performance of the porous fin for a unit volume

References

[1]. Zweben, C., Thermal Materials Solve Power Electronics Challenges, *Power Electronics Technology*, vol. 32, pp. 40-47, 2006.

[2]. Ozmat, B., Leyda, B., Benson, B., Thermal Applications of Open-cell Metal Foams, *Materials and Manufacturing Processes,* vol. 19, pp. 839-862, 2004.

[3]. Chung, D.D.L., Materials for Thermal Conduction, *Applied Thermal Engineering*, vol. 21, pp. 1593-1605, 2001.

[4]. Koch, R.A., Watts, R., Benson-Tolle, T., and Strong, K., Challenges and opportunities for thermal management materials, *International SAMPE Symposium and Exhibition* (*Proceedings*), vol.48 I , pp. 84-89, 2003.

[5]. http://www.matweb.com

[6]. Incropera, F.P. and DeWit, D.P., Fundamentals of heat and mass transfer, 6th edition, John Wiley & Sons, Inc., 2007.

[7]. Liu, P.S., Liang, K.M., Functional Materials of Porous Metals Made by P/M, Electroplating and Some Other Techniques, *Journal of Materials Science,* vol. 36, pp. 5059-5072, 2001.

[8]. Tang, H., Liao, J., Zhu, J., Porous Metals of Northwest Institute for Non-ferrous Metal Research, *Materials Science Forum,* vol. 534-536, pp. 1281-1284, 2007.

[9]. Tuchinskiy, L., Novel Fabrication Technology for Metal Foam, *Journal of Advanced Materials,* vol. 37, pp. 60-65, 2005.

[10]. Ashby, M.F., Evans, A., Fleck, N.A., Gibson, L.J., Hutchinson, J.W., Wadley, H.N.G., *Metal foams: a design guide*, Butterworth-Heinemann, Boston, 2000.

[11]. Bastawros, A.F., Evans, A.G., Characterization of Open Cell Aluminum Alloy Foams as Heat Sinks for High Power Electronic Devices, *Proceedings of the ASME Conference on CAE/CAD and Thermal Management Issues in Electronic Systems*, EEP-23/HTD-356, Dallas, 1997.

[12]. Kaviany, M., *Principles of Heat Transfer in Porous Media*, Springer, New York, 1995.

[13]. Ruiz, E.C., Modelling of heat transfer in open cell metal foams. MS thesis, University of Puerto Rico, 2004.

[14]. Boomsma, K., Poulikakos, D., On the Effective Thermal Conductivity of a Three Dimensionally Structured Fluid Saturated Metal Foam, *International Journal of Heat and Mass Transfer,* vol. 44, pp. 827-836, 2001.

[15]. Zhao, C.Y., Kim, T., Lu, T.J., Hodson, H.P., Thermal Transport in High Porosity Cellular Metal Foams, *Journal of Thermophysics and Heat Transfer*, vol. 18, pp. 358-363, 2004.

[16]. Anthohe, B.V., Lage, J.L., Price, D.C. Weber, R.M., Numerical Characterization of Micro Heat Exchangers using Experimentally Tested Porous Aluminum Layers, *International Journal of Heat and Fluid Flow*, vol. 17, pp. 594–603, 1996.

[17]. Boomsma, K., Poulikakos, D., Zwick, F., Metal Foams as Compact High Performance Heat Exchangers, *Mechanics of Materials,* vol. 35, pp. 1161–1176, 2003.

[18]. Banhart, J., Baumeister, J., Weber, M., Metal Foams Near Commercialization, *Metal Powder Report (UK)*, vol. 52, pp. 38-41, 1997.

[19]. Koltsakis, G.C., Samaras, Z., Naumann, D., Saberi, S., Boehm, A., Markomanolakis, I, Development of Metal Foam Based Aftertreatment on a Diesel Passenger Car. SAE paper 2008-01-0619, 2008.

[20]. Ismagilov, Z.R., Pushkarev, V.V., Podyacheva, O.Y., Koryabkina, N.A., Veringa, H., A Catalytic Heat Exchanging Tubular Reactor for Combining of High Temperature Exothermic and Endothermic Reactions, *Chemical Engineering Journal,* vol. 82, pp. 355-360, 2001.

[21]. Wilkinson, D.S., Paserin, V., Processing and Properties of Nickel Foams for Battery Electrodes, *Proceedings of the 2nd Symposium on Advanced Materials for Energy Conversion*, 2004.

[22]. Kim, A., Hasan, M.A., Nahm, S.H., Cho, S.S., Evaluation of the Compressive Mechanical Properties of Al-foams using Electrical Conductivity, *Composite Structures,* vol. 71, pp. 191-198, 2005.

[23]. Kang, B., Kim, K., Lee, B., Noh, J., Heat Transfer and Acoustic Properties of Open Cell Aluminum Foams, *Journal of Material Science and Technology*, vol. 24, pp. 1-6, 2008.

[24]. Losito, O., An Analytical Characterization of Metal Foams for Shielding Applications, *Proceedings of the Progress in Electromagnetics Research Symposium*, Cambridge USA, pp. 247-252, 2008.

[25]. Spoerke, E.D., Murray, N.G., Li, H., Brinson, L.C., Dunand, D.C., Stupp, S., A Bioactive Titanium Foam Scaffold for Bone Repair, *Acta Biomaterialia,* vol. 1, pp. 523-533, 2005.

[26]. Azzi, W., Roberts, W.L., Rabiei, A., A Study on Pressure Drop and Heat Transfer in Open Cell Metal Foams for Jet Engine Applications, *Materials and Design,* vol. 28, pp. 569-574, 2007.

[27]. Liu, P., Yu B., Hu, A., Liang, K.M., Gu, S.R., Development in Applications of Porous Metals, *Trans. Nonferrous Met. Soc. China*, vol. 11, pp. 630-638, 2001.

[28]. Tian, J., Kim, T., Lu, T.J., Hodson, H.P., Queheillalt, D.T., Sypeck, D.J., Wadley, H.N.G., The Effects of Topology upon Fluid-flow and Heat-transfer within Cellular Copper Structures, *International Journal of Heat and Mass Transfer,* vol. 47, pp. 3171–3186, 2004.

[29]. Wadley, H.N.G., Cellular Metals Manufacturing, *Advanced Engineering Materials*, vol. 4, pp. 726–733, 2002.

[30]. Wadley, H.N.G., Multifunctional Periodic Cellular Metals, *Philosophical Transactions of the Royal Society A,* vol. 364, pp. 31–68, 2006.

[31]. Evans, A.G., Hutchinson, J.W., Fleck, N.A., Ashby, M.F., Wadley, H.N.G., The Topological Design of Multifunctional Cellular Metals, *Progress In Materials Science*, vol. 46, pp. 309–327, 2001.

[32]. Lu, T.J., Stone, H.A., Ashby, M.F., Heat Transfer in Metal Foams, *Acta Materialia*, vol. 46, pp. 3619-3635, 1998.

[33]. Haack, D.P., Butcher, K.R., Kim, T., Lu, T.J., Novel Lightweight Metal Foam Heat Exchanger, *Proceedings of 2001 ASME International Mechanical Engineering Congress and Exposition*, November 11-16, New York, NY PID-vol.6, 2001.

[34]. Dai, Z., Nawaz, K., Park, Y.G.., Bock, J., Jacobi, A.,M., Correcting and Extending the Boomsma-Poulikakos Effective Thermal Conductivity Model for Three-dimensional, Fluid-saturated Metal Foams, *International Communications in Heat and Mass Transfer*, vol. 37, no. 6, pp. 575-580, 2010.

[35]. Alazmi, B., Vafai, K., Analysis of Variants within the Porous Media Transport Models, *Journal of Heat Transfer,* vol. 122, pp. 303-326, 2000.

[36]. Hsu, C.T., Cheng, P., Wong, K.W., A Lumped Parameter Model for Stagnant Thermal Conductivity of Spatially Periodic Porous Media, *Journal of Heat Transfer*, vol. 117, pp. 264-269, 1995.

[37]. Calmidi, V.V., Mahajan, R.L., Forced Convection in High Porosity Metal Foams. *Journal of Heat Transfer*, vol. 122, pp. 557–565, 2000.

[38]. Bhattacharya, A., Calmidi, V.V., Mahajan, R.L., Thermophysical Properties of High Porosity Metal Foams, *International Journal of Heat and Mass Transfer,* vol. 45, pp. 1017-1031, 2002.

[39]. Singh, R., Kasana, H.S., Computational Aspects of Effective Thermal Conductivity of Highly Porous Metal Foams, *Applied Thermal Engineering*, vol. 24, pp. 1841-1849, 2004.

[40]. Hunt, M.L., Tien, C.L., Effect of Thermal Dispersion on Forced Convection in Fibrous Media, *International Journal of Heat and Mass Transfer,* vol. 31, pp. 301-309, 1988.

[41]. Leong, K.C., Jin, L.W., Effect of oscillatory frequency on heat transfer in metal foam heat sinks of various pore densities. *International Journal of Heat and Mass Transf*er, vol.,49, pp 671-681, 2006..

[42]. Kim, S.Y., Paek, J.W., Kang, B.H., Flow and Heat Transfer Correlations for Porous Fin in a Plate-fin Heat Exchanger, *Journal of Heat transfer*, vol. 122, pp. 573-578, 2000.

[43]. Zweben, C., Emerging High-volume Applications for Advanced Thermally Conductive Materials, *Proceedings of the International SAMPE Symposium and Exhibition 49 - Materials and Processing Technology - 60 Years of SAMPE Progress*, pp. 4046-4057, 2004.

[44]. Zweben, C., Overview of Composite Materials for Opto-mechanical, Data Storage and Thermal Management Systems, *Proceedings of SPIE – The International Society for Optical Engineering*, vol. 3786, pp. 148-161, 1999.

[45]. Zweben, C., High-performance Thermal Management Materials, *Advanced Packaging,* vol. 15, pp. 20-22, 2006.

[46]. Zweben, C., New Material Options for High-power Diode Laser Packaging, *Proceedings of the SPIE – The International Society for Optical Engineering*, vol. 5336, pp. 166-175, 2004.

[47]. Smeding, S.F., Bakker, N., de Boer, R., Design, S*imulation and Experiments o*n a New Flat Plate Sandwich Heat Exchanger, *HEX-13. Proceedings of the 13th International Heat Transfer Conference*, Sydney, Australia, 2006.

[48]. Haije, W.G., *Veldhuis, J., Smeding, S.F., Grisel, R., Solid/vapour Sorption Heat* Transformer: Design and Performance, *Applied Thermal Engineering,* vol. 27, pp. 1371-1376, 2007.

[49]. Tadrist, L., Miscevic, M., Rahli, O., Topin, F., About the Use of Fibrous Materials in Compact Heat Exchangers, *Experimental Thermal and Fluid Science,* vol. 28, pp. 193–199, 2004.

[50]. Wheatley, J.C., Vilches, O.E., Abel, W.R., Principles and Methods of Dilution Refrigeration, *Physics,* vol. 4, pp. 1-64, 1968.

[51]. Severijns, A.D., Heat Exchanger and Method of Manufacturing the Same, US Patent 3794110, 1974.

[52]. Ferrouillat, S., Tochon, P., Peerhossaini, H., Micromixing Enhancement by Turbulence: Application to Multifunctional Heat Exchangers, *Chemical Engineering and Processing,* vol. 35, pp. 633-640, 2006.

[53]. Klein, J., Whiteside, J., Application of Foam Metal Technology to Aircraft Systems-direction and Status, Northrop Grumman Corp Melbourne FL Integrated Systems Sector, Report A628004, 2001.

[54]. Metafoam: http://www.metafoam.com

[55]. Queheillalt, D.T., Carbajal, G., Peterson, G.P., Wadley, H., A Multifunctional Heat Pipe Sandwich Panel Structure, *International Journal of Heat and Mass Transfer,* vol. 51, pp. 312-326, 2008.

[56]. Li, F.H., van der Meer, T.H., Heat Transfer Enhancement by Metallic Foams, HTE-11. *Proceedings of the 13th International Heat Transfer Conference*, Sydney, Australia. 2006.

[57]. Ejlali, A., Ejlali, A., Hooman, K., Gurgenci, H., Application of High Porosity Metal Foams as Air-cooled Heat Exchangers to High Heat Load Removal Systems, *International Communications in Heat and Mass Transfer*, vol. 36, pp. 674–679, 2009.

[58]. Giani, L., Groppi, G., Troconi, E., Heat Transfer Characteristics of Metallic Foams, *Industrial & Engineering Chemistry Research*, vol. 44, pp. 9078-9085, 2005.

[59]. Giani, L., Groppi, G., Troconi, E., Heat Transfer Characteristics of Metallic Foams, *Industrial & Engineering Chemistry Research,* vol. 44, pp. 4993-5002, 2005.

[60]. Groppi, G., Giani, L., Troconi, E., Generalized Correlation for Gas/solid Mass-transfer Coefficients in Metallic and Ceramic Foams, *Industrial & Engineering Chemistry Research,* vol. 46, pp. 3955-3958, 2007.

[61]. Mancin, S., Zilio, C., Cavallini, A., Rossetto, A., Pressure Drop During Air Flows in Aluminum Foams, *International Journal of Heat and Mass Transfer*, vol. 53, pp. 3121-3130, 2010.

[62]. Mancin, S., Zilio, C., Cavallini, A., Rossetto, A., Heat Transfer During Air Flow in Aluminum Foams, *International Journal of Heat and Mass Transfer,* vol. 53, pp. 4976-4984, 2010.

[63]. Salimi Jazi, H.R., Mostaghimi, J., Chandra, S., Pershin, L., Coyle, L., Spray Formed, Metal-foam Heat Exchangers for High Temperature Applications, *Journal of Thermal Science and Engineering Applications,* vol. 1, pp. 031008-031014, 2009.

[64]. Dukhan, N., Chen, K.C., Heat Transfer Measurements in Metal Foam Subjected to Constant Heat Flux, *Experimental Thermal and Fluid Science*, vol. 32, pp. 624-631, 2007.

[65]. T'Joen C., De Jaeger, P., Huisseune, H., Van Heerzele, S., Vorst, N., De Paepe, M., Thermohydraulic Study of a Single Row Heat Exchanger, Consisting of Metal Foam Covered Round Tubes*, International Journal of Heat and Mass Transfer,* vol 53, pp. 3262-3274, 2010.

[66]. Straatman, A.G., Gallego, N.C., Thompson, B.E., Hangan, H., Thermal Characterization of Porous Carbon Foam – Convection in Parallel Flow, *International Journal of Heat and Mass Transfer,* vol. 49, pp. 1991-1998, 2006.

[67]. Boger, T., Heibel, A.K., Heat Transfer in Conductive Monolith Structures, *Chemical Engineering Science,* vol. 60, pp. 1823-1835, 2005.

[68]. Zhao, C.Y., Lu, W., Tassou, S.A., Thermal Analysis on Metal-foam Filled Heat Exchangers, Part II: Tube Heat Exchangers, *International Journal of Heat and Mass Transfer,* vol. 49, pp. 2762-2770, 2006.

[69]. Hsieh, W.H., Wu, J.Y., Shih, W.H., Chiu, W.C., Experimental Investigation of Heat-transfer Characteristics of Aluminum Foam Heat Sinks, *International Journal of Heat and Mass Transfer,* vol. 47, pp. 5149–5157, 2004.

[70]. Kim, Y., Paek, J.W., Kang, B.H., Thermal Performance of Aluminum-foam Heat Sinks by Forced Air Cooling, *IEEE Transactions on Components and Packaging Technologies,* vol. 26, pp. 262–267, 2003.

[71]. Lee, Y.C., Zhang, W., Xie, H., Mahajan, R.L., Cooling of an FCHIP Package with 100 W 1 cm² Chip, *Proceedings of the 1993 ASME International Electronic Package Conference*, Vol. 1, pp. 419-424, 1993.

[72]. Shih, W.H., Chiu, W.C., Hsieh, W.H., Height Effect on Heat Transfer Characteristics of Aluminum Foam Heat Sinks*, Journal of Heat Transfer,* vol. 128, pp. 530-537, 2006.

[73]. Mahdi, H., Lopez, P. Jr, Fuentes, A., Jones, R., Thermal Performance of Aluminum-foam CPU Heat Exchangers, *International Journal of Energy Research*, vol. 30, pp. 851–860, 2006.

[74]. Dempsey, B.M., Eisele, S., McDowell, D.L., Heat Sink Applications of Extruded Metal Honeycombs, *International Journal of Heat and Mass Transfer*, vol. 48, pp. 527–535, 2005.

[75]. Bhattacharya, A., Mahajan, R.L., Finned Metal Foam Heat Sinks for Electronics Cooling in Forced Convection, *Journal of Electronics Packaging*, vol. 124, pp. 155-163, 2002.

[76]. Bhattacharya, A., Mahajan, R.L., Metal Foam and Finned Metal Foam Heat Sinks for Electronics Cooling in Buoyancy-induced Convection, *Journal of Electronics Packaging,* vol. 128, pp. 259-266, 2006.

[77]. Garrity, P., Klausner, J.F., Mei, R., Performance of Aluminum and Carbon Foams for Air Side Heat Transfer Augmentation, *Journal of Heat Transfer,* vol. 132, pp. 121901-121909, 2010.

[78]. Hayes, A.M., Wang, A.-J., Dempsey, B.M., McDowell, D.L., Mechanics of Linear Cellular Alloys, *Mechanics of Materials*, vol. 36, pp. 691–671, 2004.

[79]. Lu, T.J., Heat Transfer Efficiency of Metal Honeycombs, *International Journal of Heat and Mass Transfer*, vol. 42, pp. 2031-2040, 1999.

[80]. Howard, S.R., Korinko, P.S., Vacuum Furnace Brazing Open Cell Reticulated Foam to Stainless Steel Tubing, WSRC-MS-2002-00424. *Proceedings of the 2nd International Brazing and Soldering Conference*, San Diego, California, 2003.

[81]. Sekulic, D.P., Dakhoul, Y.M., Zhao, H., Liu, W., Aluminum Foam Compact Heat Exchangers: Brazing Technology Development vs. Thermal Performance, *Proceedings of the Cellmet Conference 2008*, Dresden Germany, 2008.

[82]. Banhart, J., Manufacture, Characterization and Application of Cellular Metals and Metal Foams, *Progress in Materials Science*, vol. 46, pp. 559–632, 2001.

[83]. Angel, S., Bleck, W., Harksen, S., Scholz, P., Functional and Structural Characteristics of Metallic Foams produced by the Slip Reaction Foam Sintering (SRFS)-Process. *Materials Science Forum* vol. 492-493, pp. 39-46, 2005.

[84]. Degischer, H.P., Innovative Light Metals: Metal Matrix Composites and Foamed Aluminum, *Materials & Design*, vol. 18, pp. 221-226, 1997.

[85]. Ibrahim, I.A., Mohamed, F.A., Lavernia, E.J., Particulate Reinforced Metal Matrix Composites - A Review, *Journal of Materials Science*, vol. 26, pp. 1137-1156, 1991.

[86]. Jordan, J., Jacob, K., Tannenbaum, R., Sharaf, M., Jasiuk, I., Experimental Trends in Nanocomposites – A Review, *Material Science and Engineering A*, vol. 393, pp. 1-11, 2005.

[87]. T'Joen, C., Park, Y., Wang, Q., Sommers, A., Han, X., Jacobi, A., A Review on Polymer Heat Exchangers for HVAC&R Applications, *International Journal of Refrigeration*, vol. 32, pp. 763-779, 2009.

[88]. Haghighi-Khoshkhoo, R., McCluskey, F.M., Air Side Fouling of Compact Heat Exchangers for Discrete Particle Size Ranges, *Heat Transfer Engineering*, vol. 28, pp. 58-64, 2007.

[89]. Leong, K.C., Li, H.Y., Jin, L.W., Chai, J.C., Numerical and Experimental Study of Forced Convection in Graphite Foams of Different Configurations, *Applied Thermal Engineering*, vol. 30, pp. 520-532, 2010.

[90]. Gallego, N.C., Klett, J.W., Carbon Foams for Thermal Management, *Carbon,* vol. 41, pp. 1461-1466, 2003.

[91]. Jamin, Y.L., Mohamad, A.A., Enhanced Heat Transfer Using Porous Carbon Foam in Cross Flow – Part 1: Forced Convection, *Journal of Heat Transfer*, vol. 129, pp. 735-742, 2007.

[92]. Mahjoob, S., Vafai, K., A Synthesis of Fluid and Thermal Transport Models for Metal Foam Heat Exchangers, *International Journal of Heat and Mass Transfer*, vol. 51, pp. 3701-3711, 2008.

[93]. Schmierer, E.N., Razani, A., Self Consistent Open-celled Metal Foam Model for Thermal Applications, *Journal of Heat Transfer*, vol. 128, pp. 1194-1203, 2006.

[94]. Moffat, R.J., Eaton, J.K., Onstad, A., A Method for Determining the Heat Transfer Properties of Foam Fins, *Journal of Heat Transfer*, vol. 131, 011603, 2009.

[95]. Hsu, C.T., in *Handbook of porous media*, ed. K. Vafai , pp. 171-200, Marcel Dekker, Inc., New York, 2000.

[96]. Du Plessis, P., Montillet, A., Comiti, J., Legrand, J., Pressure Drop Prediction for Flow Through High Porosity Metallic Foams, *Chemical Engineering Science*, vol. 57, pp. 3545-3553, 1994.

[97]. Ghosh, I., Heat Transfer Correlation for High-porosity Open Cell Foam, *International Journal of Heat and Mass Transfer,* vol. 52, pp. 1488-1494, 2009.

[98]. Kwon, Y.W., Cooke, R.E., Park, C., Representative Unit Cell Models for Open Cell Metal Foams with or without Elastic Filler, *Material Science and Engineering A*, vol. 343, pp. 63-70, 2002.

[99]. Zukauskas, A. A., *Convective Heat Transfer in Cross-Flow, Hand-book of Single-Phase Heat Transfer*, Kakac, S., et al., eds. Wiley, New York, 1987.

[100]. Yang, C., Nakayama, A., A Synthesis of Tortuosity and Dispersion in Effective Thermal Conductivity of Porous Media, *International Journal of Heat and Mass Transfer*, vol. 53, pp. 3222-3230, 2010.

[101]. Boomsma, K., Poulikakos, D., Ventikos, Y., Simulations of Flow Through Open Cell Metal Foams using an Idealized Periodic Cell Structure, *International Journal of Heat and Fluid Flow,* vol. 24, pp. 825-834, 2003.

[102]. Kopanidis, A., Theodorakakos, A., Gavaises, E., Bouris, D., 3D Numerical Simulation of Flow and Conjugate Heat Transfer Through a Pore Scale Model of High Porosity Open Cell Metal Foam, *International Journal of Heat and Mass Transfer*, vol. 53, pp. 2539-2550, 2010.

Table 1. Thermo-physical properties of representative monolithic metals

Material	Density g/cm^3	Thermal Conductivity W/m-K	CTE μm/m/K	Specific Thermal Conductivity W/m-K	Source
Aluminum	2.7	247	23	91.5	[3]
Beryllium	2.1	210	13.9	10	[4]
Copper	8.9	398	17	44.7	[3]
Cu/I/Cu	8.4	164	8.4	19.5	[1]
Cu/Mo/Cu	9.9	182	6.0	18	[1]
Cu/Mo-Cu/Cu	9.4	245-280	6.0-10.0	26-30	[1]
Gold	19.32	315	14	16.3	[3]
Invar	8.05	10	1.6	1.2	[3]
Kovar	8.36	17	5.1	2.0	[3]
Lead	11	30	39	2.7	[3]
Molybdenum	10.22	142	4.9	13.9	[3]
Silver	10.49	429	18.9	40.9	[5]
Stainless steel	8.1	15.1	17.3	1.9	[6]
Titanium	4.4	7.2	9.5	1.6	[1]
Tungsten	19.3	155	4.5	8.0	[3]

Table 2. Thermo-physical properties of some Al foam samples

Sample	Bulk density (g/mL)	Relative Density (%)	Porosity	Effective conductivity (W/m-K)	Specific surface (m^2/m^3)	Source
10 ppi	0.217	8.1	0.9085	6.71	899	[2]
20 ppi	0.165	6.1	0.92	5.97	1266	[2]
30 ppi	0.145	5.4			1477	[2]
10 ppi			0.91	4.1	820	[41]
20 ppi			0.9	5.1	1700	[41]
30 ppi			0.9	5.9	2800	[41]
10 ppi			0.92	5.33	790	[42]
20 ppi			0.92	5.56	1720	[42]
40 ppi			0.92	6.01	2740	[42]
20 ppi			0.89	6.77	2020	[42]
20 ppi			0.94	4.27	1510	[42]
20 ppi			0.96	2.82	1240	[42]

Table 3 Thermo-physical properties of MMCs

Reinforcement Filler	Matrix	Density g/cm	Thermal Conductivity W/mK		CTE 10^{-6}m/m/℃	Specific Thermal Conductivity W/m·K		Source
			In-Plane	Thro-Plane	In-Plane	In-Plane	Thro-Plane	
Copper	Tungsten	15-17	157-190	157-190	5.7-8.3	9-13	9-13	[1]
Copper	Molybdenum	9.9-10.0	184-197	184-197	7.0-7.1	18-20	18-20	[1]
Discontinuous Carbon Fibers	Copper	6.8	300	200	6.5-9.5	44	29	[1]
SiC Particles	Copper	6.6	320	320	7.0-10.9	48	48	[1]
Carbon Foam	Copper	5.7	350	350	7.4	61	61	[1]
Continuous Carbon Fibers	Copper	5.3-8.2	400-420	200	0.5-16.0	49-79	25-38	[1]
Diamond Particles	Copper	5.9	600-1200	600-1200	5.8	102-203	102-203	[1]
Diamond Particles	Cobalt	4.12	>600	>600	3.0	>145	>145	[1]
Diamond Particles	Silver	5.8	400-600	400-600	5.8	69-103	69-103	[1]
Diamond Particles	Magnesium	N/A	550	550	8	N/A	N/A	[1]
Beryllia Particles	Beryllium	2.6	240	N/A	6.1	92	N/A	[46]
Invar	Silver	8.8	153	N/A	6.5	17	N/A	[46]
Beryllium	Aluminum	2.1	210	N/A	13.9	100	N/A	[46]
Silicon	Aluminum	2.5-2.6	126-160	N/A	6.5-17.0	49-63	N/A	[46]
Discontinuous Carbon Fibers	Aluminum	2.5	190-230	120-150	3.0-9.5	76-92	48-60	[46]
Continuous Carbon Fibers	Aluminum	2.5	200-290	120-150	0-16	80-116	48-60	[46]
Graphite Flake	Aluminum	2.3	400-600	80-110	4.5-5.0	174-260	35-48	[1]
Diamond Particles	Aluminum	3.1	550-600	550-600	7.0-7.5	177-194	177-194	[1]

LIST OF FIGURES

Fig. 14. Sandwich construction with textile technology [28]: (a) a transient liquid phase joins the wire-mesh screen laminated at all points of contact; (b) sheets are added to the textile core.

Fig. 15. Pore structure of a gasar, a stochastic cellular metal with closed cells [82].

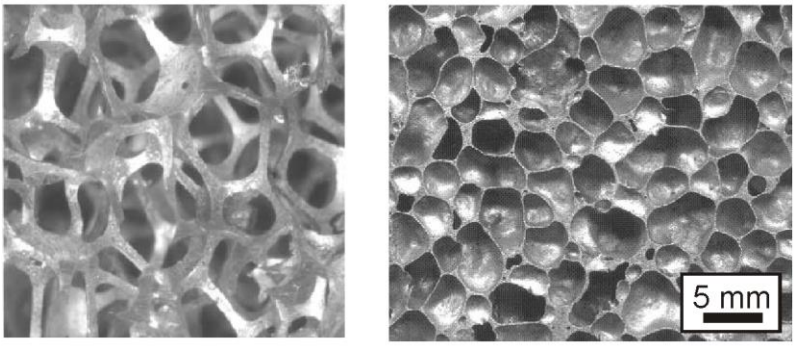


Fig. 1. Structure of cellular metal foams: open foam (left) vs. closed foam (right).

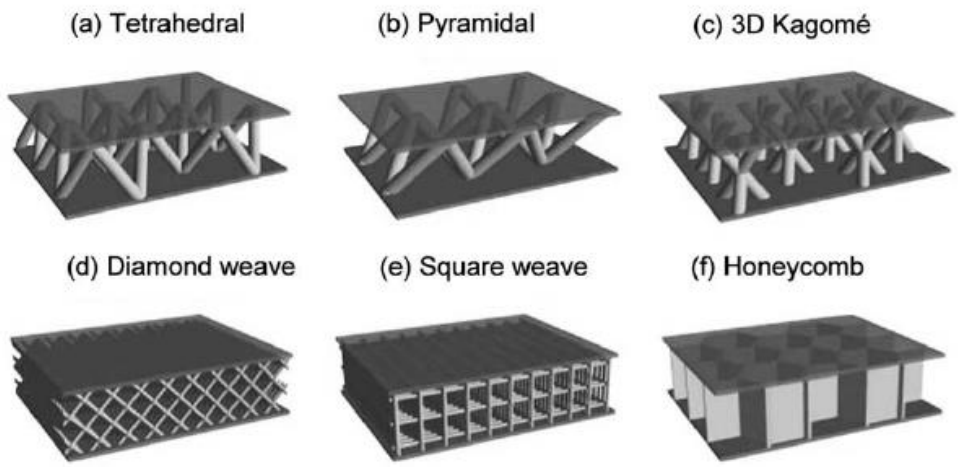
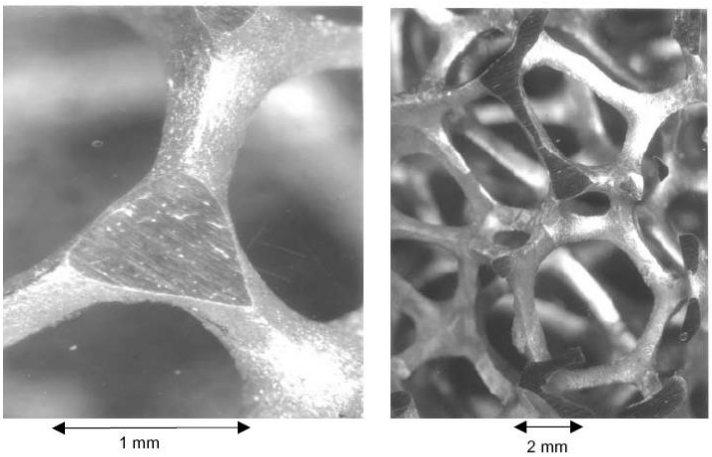
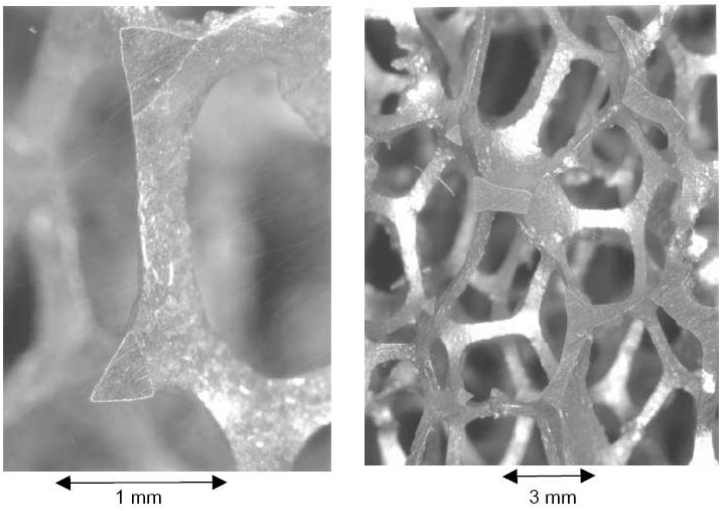


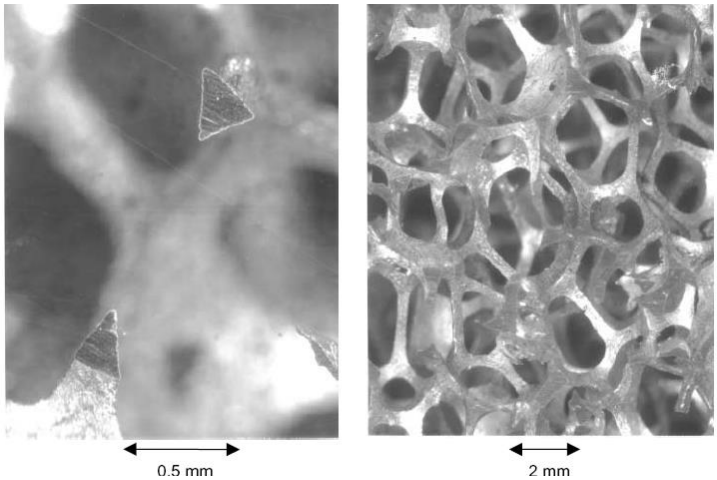
Fig. 2. Schematic representations of open- and close-celled periodic structures [28].



(a)

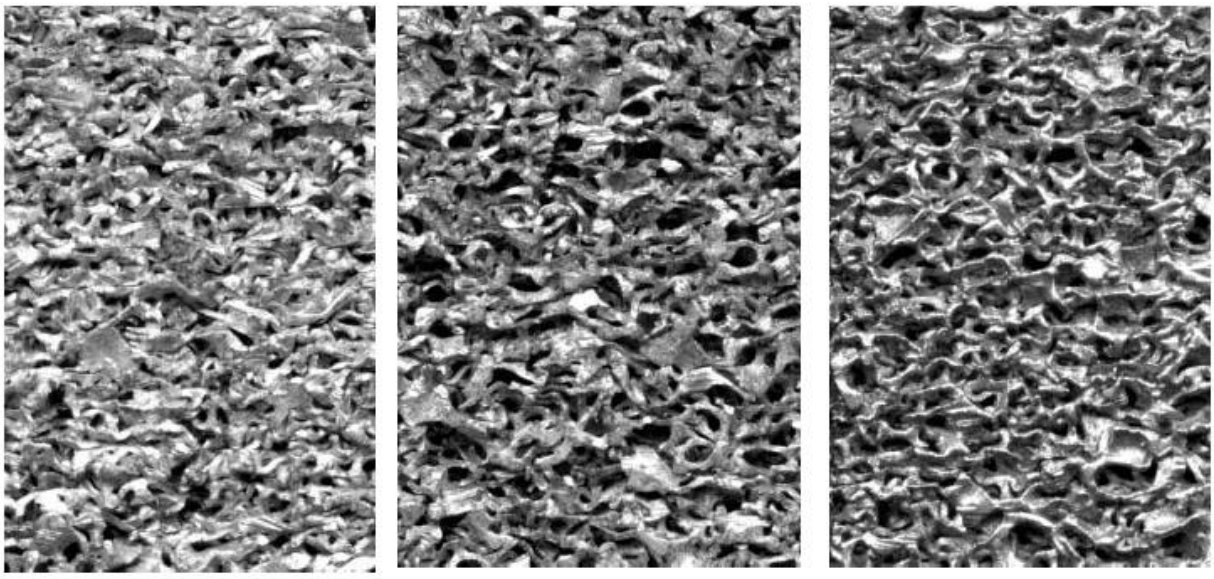


(b)



(c)

Fig. 3. Aluminum foams with a relative density of 8% [2]: (a) 10 ppi, (b) 20 ppi, (c) 30 ppi.



(a) (b) (c)

Fig. 4. Compressed metal foam [2]: 30 ppi foam uni-axially compressed to 35% density (a) in plane and (b) out of plane (middle), and (c) 30 ppi bi-axially compressed to 35% density.

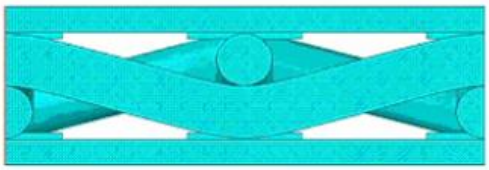


Fig. 5. Drawing of a cross section of the sandwich plate structure. The heat exchanger consists of stacks of two plates with a wire mesh brazed in between [47].

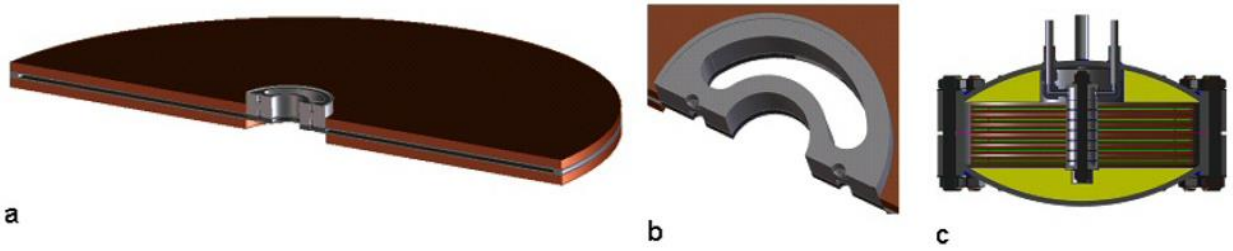
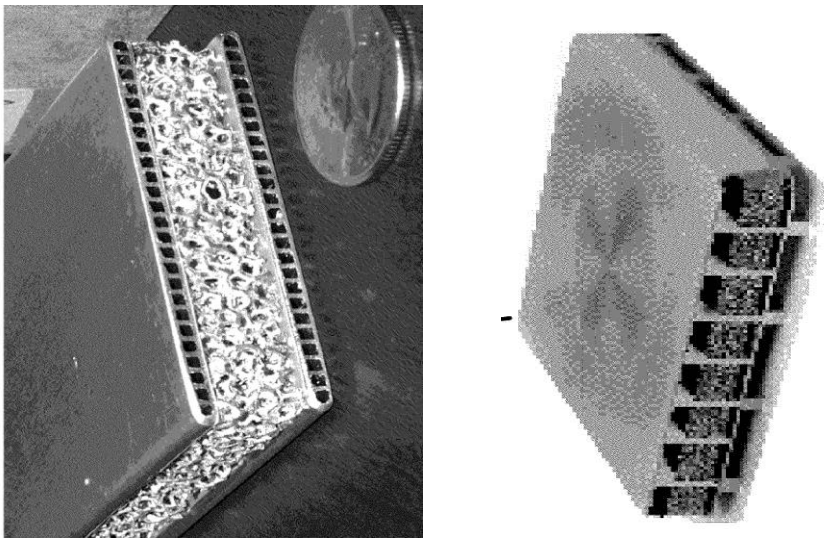


Fig. 6. (a) Plate-cross section of the sandwich plate and metal foam mesh, (b) detail of the flow manifold, and (c) brazed plates assembled [47].



(a) (b)

Fig. 7. Compressed metal foam cross flow heat exchanger Klein and Whiteside [53].

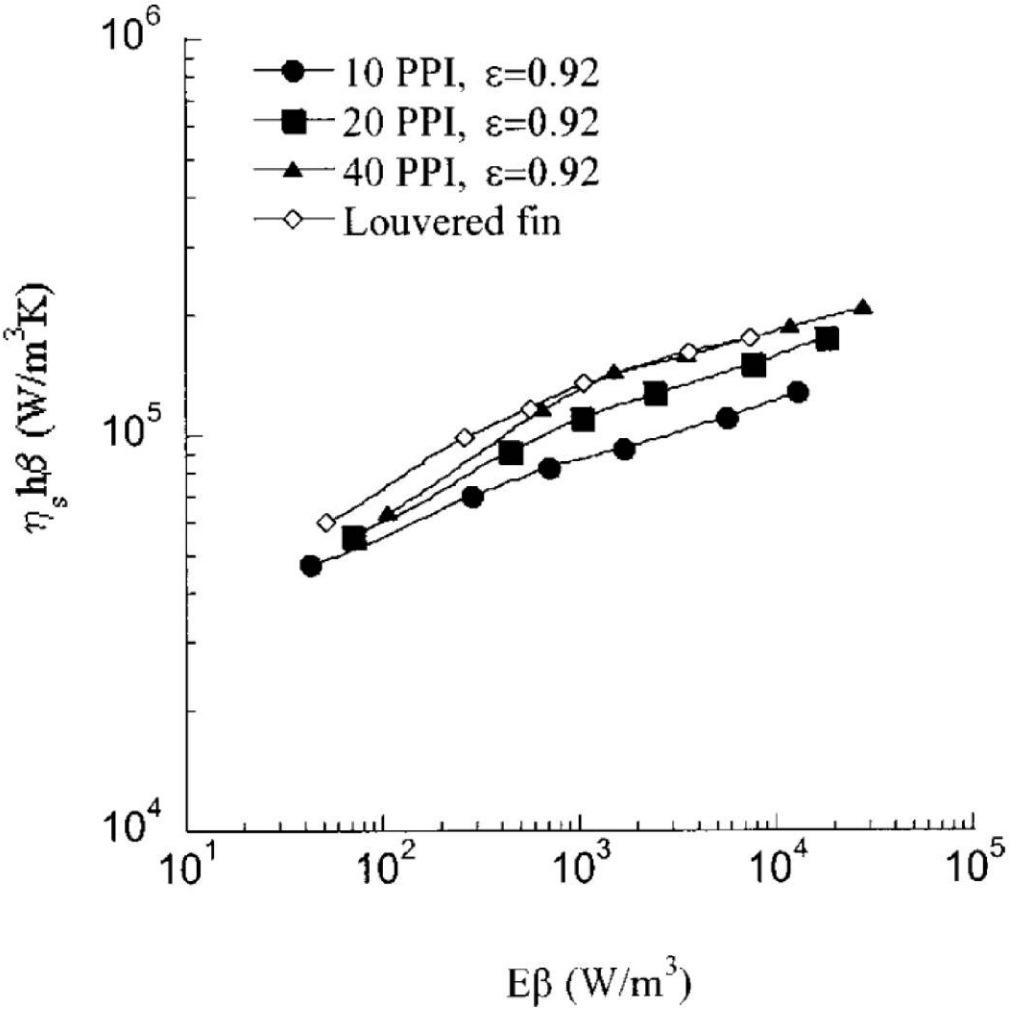


Fig. 8. Comparison of three Al metal foam fins (porosity 0.92; pore density 10, 20, 40 ppi) and a louvered fin based on the volume goodness approach [42].

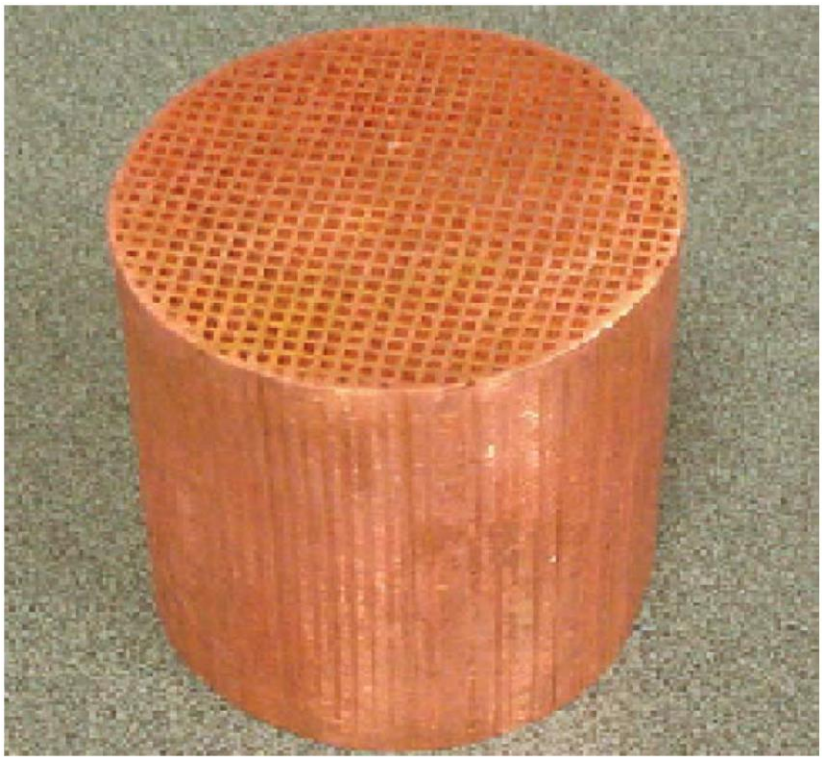


Fig. 9. Copper based monolith catalyst support: a square celled LCA, Boger and Heibel [67].

Fig. 10. Metal-foam filled tubes using co-sintering technique [68].

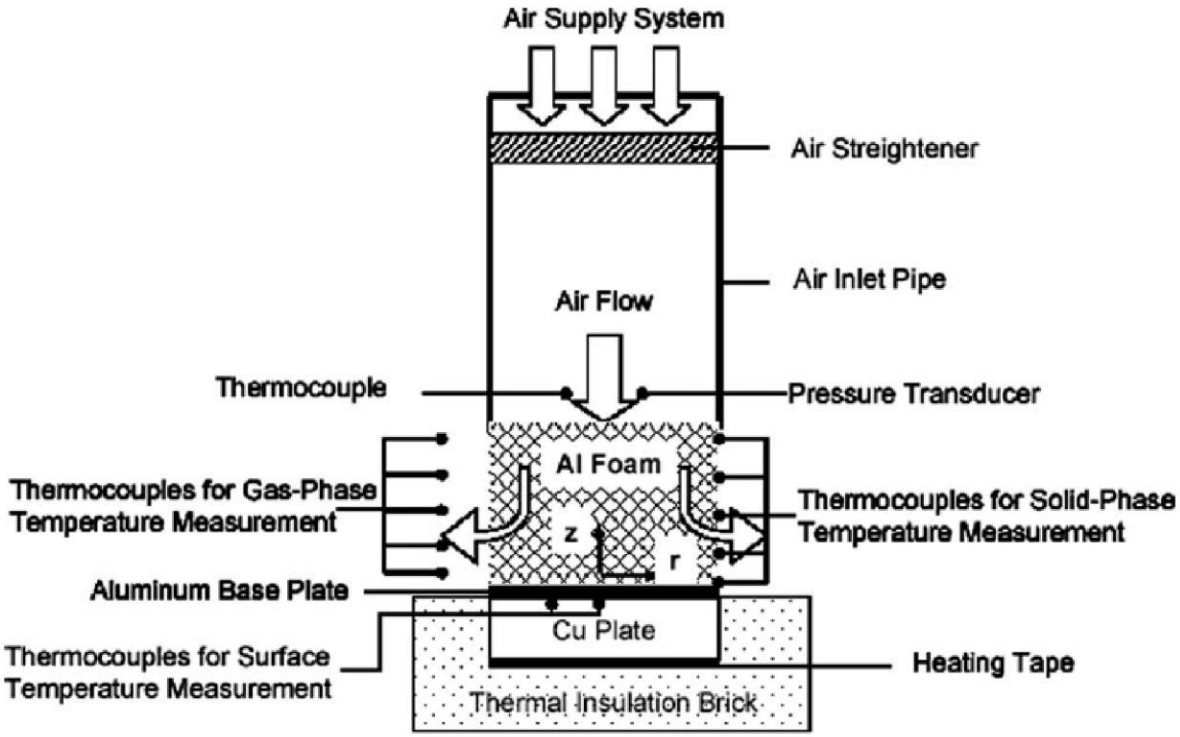
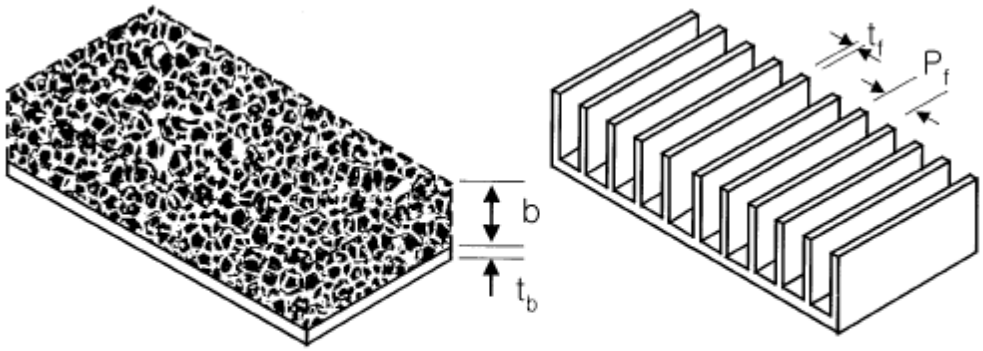


Fig. 11. Metal foam heat sink setup as used by Hsieh *et al*. [69] and Shih *et al.* [72].



(a) (b)

Fig. 12. The aluminum-foam heat sink (a) and parallel-plate heat sink (b) used as reference case [70].

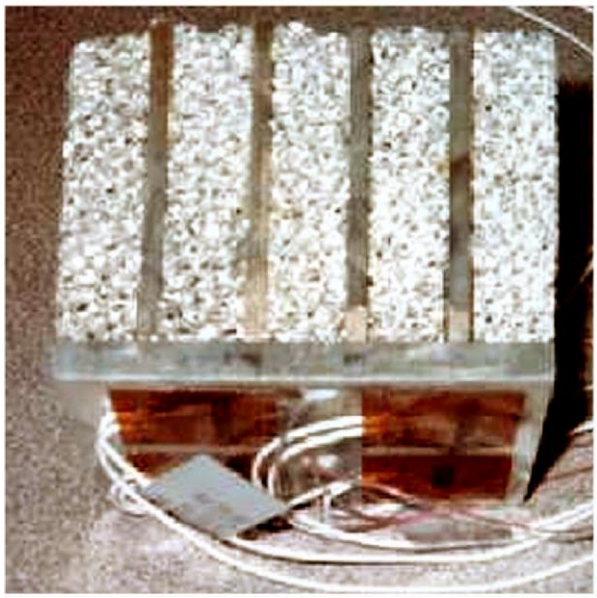
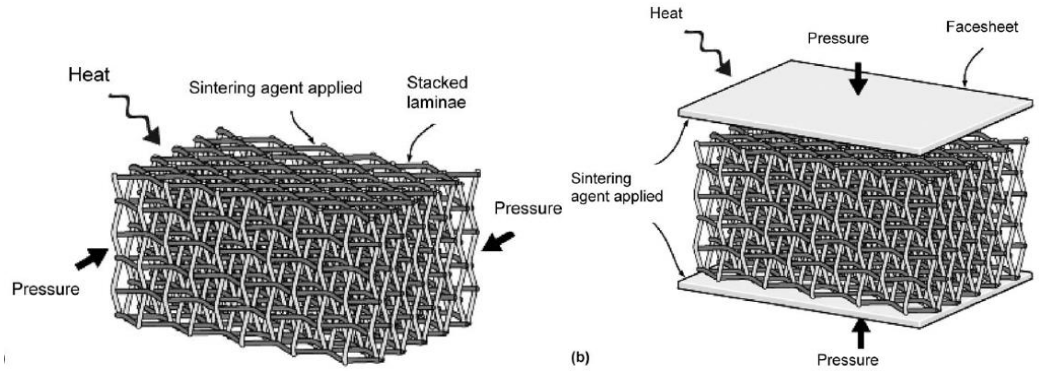


Fig. 13. Finned metal foam heat sink as developed by Bhattacharya and Mahajan [38], [76].



(a) (b)

Fig. 14. Sandwich construction with textile technology [28]: (a) a transient liquid phase joins the wire-mesh screen laminated at all points of contact; (b) sheets are added to the textile core.

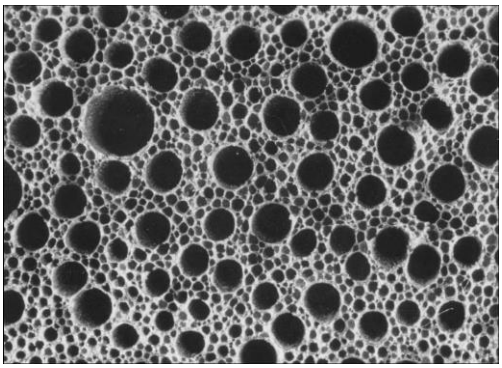


Fig. 15. Pore structure of a gasar, a stochastic cellular metal with closed cells [82].

Xiao-hong Han is an associate professor of Department of Energy Engineering at Zhejiang University, China. She receives her Ph.D. at Zhejiang University in 2005. Her research interests include auto-cascade refrigeration systems and heat pump systems, alternative refrigerant research (mainly studying the thermo-physical properties, liking vapor-liquid phase equilibrium, exploration, density, cycle performance, heat transfer characteristics of the new refrigerant, and so on), pulse heat pipe heat transfer characteristics, new low-grade heat-driven refrigeration system, and structure optimization of plate heat exchanger. She is a member of American Chemical Society. Her efforts in research and engineering education have been recognized with Most Appreciated Teacher Award (2006), The Excellent Teacher Award (2008), ·Teacher Award for the successful career and family, Zhejiang University (2008, 2010).

Qin Wang is an associate professor of Department of Energy Engineering at Zhejiang University, China. He receives his Ph.D. at Zhejiang University in 2002. He is the deputy director of the Refrigeration and Cryogenic Lab, Institute of Refrigeration and Cryogenics. His research interests include auto-cascade refrigeration systems, absorption refrigeration systems, heat pump systems, environment-friendly refrigerants, renewable energy systems, food storage machines and heat exchangers. Dr. Wang has co-authored more than 60 referenced journal and conference publications. He is currently working on development of new absorption refrigeration systems.

Young-Gil Park is an assistant professor at the University of Texas-Pan American. He received his Ph.D. degree in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 2007. He conducts research on convective heat transfer enhancement and condensate retention management in compact heat exchangers.

T'Joen Christophe is a Postdoctoral Researcher at the Department of Flow, Heat and Combustion Mechanics, Ghent University-Ugent, Belgium. He received his Master's degree in Electromechanical Engineering from the Ghent University in 2004 and his Ph.D. in 2008. Currently his main research topic is interrupted fin designs for compact heat exchangers and nuclear thermo-hydraulics. His research interests include thermo-hydraulics in complex geometries, novel materials such as metal foams and two-phase flow characterization. For his Master's dissertation he was honored with the 'Marcel Herman' price.

Andrew Sommers is an assistant professor at Miami University in Oxford, Ohio. He received his Ph.D. degree in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 2007. He has co-authored 24 papers in archival journals and conference proceedings and currently conducts research on surface wettability modification techniques for improved condensate management in heat exchangers, numerical modeling of heat exchanger performance, and issues related to enhanced air-side heat transfer.

Anthony Jacobi is the Richard W. Kritzer Distinguished Professor in the Department of Mechanical Science and Engineering at the University of Illinois, Urbana-Champaign. He is also Co-director of the ACRC, an NSF-founded industry/university cooperative research center. He conducts research in heat transfer and fluid mechanics with energy systems application.