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Experimental study on confined metal foam flow passage as compact heat exchanger surface

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ABSTRACT

This work focuses on forced convection through asymmetrically heated rectangular confined porous flow passage of aspect ratio of 50 (width/height = 150/3). Heat transfer characteristics of the porous flow passage were investigated with four different open-cell aluminium metal foams (MF) as porous media. Two sets (four samples) of aluminium foams of 20 ppi and 40 ppi pore densities with each set had two different relative densities (RD) of 9–11% and 12–16% (as per supplier's specification). One set of MFs was uncompressed (9–11% relative density) while another set was obtained by unidirectional compressing the MFs of 6–8% RD and 6 mm height flow passages. The study was systemically conducted with constant heat flux at the bottom surface of the flow passage, and on the basis of compact heat transfer surface analogy. Steady state condition was achieved before acquiring data. Temperature distribution along flow direction was investigated to study thermal development of air flow through it. It was found that thermally developed flow exists in such confined flow passages. Moreover, as a case study of a potential application, a systematic method was followed to obtain performance curves for all the flow passages as compact heat transfer surfaces for use in a Polymer Electrolyte Membrane Fuel Cell (PEMFC). The performance curves were utilised to obtain the best compact heat transfer surface for its possible use in a PEMFC.

1. Introduction

Open-cell metal foams (MFs), sometimes called metal sponges and metal matrix, have received increasing attention because of their promising physical and transport characteristics [1–6]. MFs can enhance heat transfer by its high specific surface area and further enhancement is achieved due to vortex generation in flow passages throughout their voids, resulted in a tortuous flow path [7]. A specific surface area > $700\ \mathrm{m^2/m^3}$ or a hydraulic diameter < 5 mm is arbitrary, referred to as compact heat exchanger surface [8,9]. Specific surface area of MF remains well above the defined value, which makes it one of the competitors among varieties of different heat exchanger surfaces. MFs have even exhibited substantially better heat transfer capacities than fin-and-tube heat exchangers [10], suggesting MFs as a promising option to be employed as multifunctional heat exchangers and heat sinks [4,11–14]. MFs are increasingly used in a wide range of engineering applications [7,15]. For example MFs they are becoming a strong option for use in automobile [16–18] and clinical [19,20] applications. They have also been reported to be used in fuel cell applications by several researchers as electrodes [21,22], current collectors [23], gas flow fields [14,24–33] and bipolar plates [29].

There are several researches on enhancing heat transfer performance of heat exchangers by using MFs in different ways, such as rectangular and circular passages filled with MF [34–43], tubes covered with MFs [44–46], and etc. Different enhancement levels can be found in literature from different experimental and mathematical studies, such as experimentally obtained 8–15 times higher heat transfer rates for MF filled circular and rectangular tubes [36] or analytically obtained 40 times higher heat transfer rate for MF filled circular tubes compared to their non-filled tubes [42]. Experimental investigation of Boomsma, Poulikakos and Zwick [35] on compressed MFs demonstrated heat transfer enhancement and eventually significant improvement in heat exchanger effectiveness compared to commercially available heat exchangers under identical conditions. Many mathematical models and experimental correlations for heat transfer characterisation are available in literature among which some agree with their peers while some with different outcomes reported. [47]. More details of these theoretical and experimental studies and their outcomes are provided in the following section “Overview of previous studies”.

In the case of constant heat flux boundary condition, thermally developed flow is always being assumed in both experimental and mathematical studies [44,48,49]; however, thermally developed flow

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through a flow passage of large aspect ratio was reported to be unachievable in literature [50]. Furthermore, MF is not a regular structure. Its construction can vary in different ways such as, porosity, pore density, shape, length and size of struts [37–39,51–54]; even boundary conditions are hardly matching in literature resulting in multiple opinions. Situation gets further complicated when we find different experimental outcomes in literature on the same or similar MFs (e.g. different heat transfer coefficient). In most of the cases studied to date, heat transfer coefficient was reported based on heater or hot base surface area rather than reporting it based on convection surface area. It is also not possible to use mathematical models to estimate heat transfer characteristics of compressed MFs, because the models assume MF flow passage as an isotropic structure. However, asymmetrically compressed MFs can never be an isotropic structure.

In this situation, design of any thermal system incorporating MFs as convection surface, especially with flow passage of high aspect ratio and asymmetric structure, requires direct input from specifically-designed experiments. Since MFs are considered as members of compact heat transfer surface family, the specifically-designed experimental data can be analysed on the basis of compact heat transfer surface analogy.

Effect of MFs specifications on their heat transfer characteristics has received a relatively high level attention (although with some contradictory results reported in the literature); however, these studies are less focused on metal foams with high aspect ratios (in which the boundary effect can become significant). Moreover, heat transfer characteristics of such MFs (i.e. with high aspect ratios) were less studied in an applied context. PEMFC is one of these applications, which we used in this paper as a case study. This type of application can open opportunities for future enhancement of their thermo-electrical performance while offering opportunities to make them lighter and more viable economically. Height of flow passages in both open and closed cathode PEMFCs usually kept within few millimetres at maximum. Similar measurement is maintained for air cooling flow passage as well. A nominal voltage in the range of 0.6–0.7 V represents an active area in the range of 2–4 cm^2/W [55]. Base on this information, for an average nominal voltage of 0.65 V requires $\sim 3\,\mathrm{cm}^2/\mathrm{W}$ active area. A PEM cell size is categorised as small, medium, and large for an active area below 100 cm^2, 500 cm^2, and 1700 cm^2 respectively for low risk DC voltage ($^{<}$120 V) requirement; the cell is extra-large for an active area > 1700 cm^2. Consequently, aspect ratios of the flow passages of PEMFCs (especially parallel channel) could become very high for the fuel cells of medium or higher sizes. Therefore, the context of PEMFC flow passage is a suitable choice as a case study for the porous flow passage of high aspect ratio.

Hence, objectives of this research work was to (i) investigate thermal development of air flow through a confined rectangular flow passage of high aspect ratio (i.e. 50) applicable for medium to large size PEMFCs as a possible case of application, (ii) develop a systemic method based on heat transfer surface analogy to be able to compare performances of the considered compact heat transfer surfaces of high aspect ratio.

2. Overview of previous studies

Analytical, numerical, semi-analytical, and empirical models were developed from time to time through state-of-the-art investigations to describe transport phenomena (both flow and heat) through MFs. Among very recent works, Stark, Prasad and Bergman [46] proposed analytical and semi-analytical models to predict thermal effectiveness and thermal resistance of a MF-based heat exchanger covered on a cylindrical isothermal heat source. Nie, Lin and Tong [47] developed a numerical model by using a 3D Laguerre-Voronoi foam model to investigate transport characteristics of MFs. They compared their simulation results on pressure drop with results from experimental work and empirical model by Inayat, Klumpp, Lämmermann, Freund and Schwieger [56]; upon verification of the numerical model they investigated heat transfer characteristics of their MF samples. Lu, Zhang, Yang and Wu [57] investigated flow and heat transfer characteristics through channels that are symmetrically and partially filled with MF, where MF was attached to a boundary with constant heat flux. Empirical correlations for both flow and heat transfer were proposed by Wang and Guo [58] from their experimental investigation on a MF filled in a circular tube under convective boundary condition. Although transport phenomena in porous media have received attention by a number of researchers the nature of transport behaviour in MFs is yet to be fully understood and explained. From very simple to very complex models can be found in literature that certainly describe the characteristics for certain range of porosity or certain types of ligament/strut shape or certain types of cell geometries. In fact, there are multitude of mathematical models and correlations that describe such transport phenomena very well for either specific MF properties or for a range of MF properties and samples [47]. However, correlation among different investigated parameters becomes difficult and sometimes impossible due to mismatch in conditions and assumptions [4].

Thermally developed condition is one of the mostly used assumptions in many of the heat transfer related studies reported in the literature [44,48,49]. However, according to Haji-Sheikh, Nield and Hooman [50], thermally fully-developed conditions may not be attainable in some practical applications for narrow rectangular porous passages with symmetric constant wall heat flux. According to them, for aspect ratio $b/a \geq 50$, thermally fully developed condition exists when $(x/a)/\mathrm{Re}_D\,\mathrm{Pr} \approx 1000$, which returns very high value of x. For a rectangular flow passage of 150 mm width and 3 mm height, length of the passage need to be $5.9Pe$ in meters, where characteristic lengths for Re_D and Pe are hydraulic diameter (D) of the passage and half of the height of the passage (a) [52]. Zafari, Panjepour, Davazdah Emami and Meratian [51] found thermal entry length to be dependent on not only Re number but also porosity of MF.

For constant heat flux boundary condition, Arbak, Dukhan, Bağcı and Özdemir [52] reported that thermal entry length of circular metal foam passage was independent of Re but dependent on diameter of the passage. For their specific experiment, the thermal entry length was about 2.9 pipe diameters (150 mm) for 10-ppi and 2.4 pipe diameters (122 mm) for 40-ppi foam; these were the same for Darcy and Forchheimer flow regimes and independent of flow velocity [52]. Similar claim was made by Dukhan, Bağcı and Özdemir [49] for circular metal foam passage. Dukhan, Bağcı and Özdemir [49] reported that for constant heat flux condition thermal entry length in a MF-filled circular tube was twice the diameter of the tube in Darcy flow regime, whereas it increased to 3.74 times diameter for non-Darcy flow regimes; the lengths were constant in the entire flow regime. Thermal entry length of a rectangular Al MF passage of $b/a = 2.95$ was found to have smaller thermal entry length than empty channel of the same aspect ratio [59]. They have also reported that thermal entry length increases by increasing Re_D, which is in contrast to what reported by Dukhan, Bağcı and Özdemir [49], where they found thermal entry length in a circular MF-filled duct at a constant heat flux to be independent of Re_D. Bayomy and Saghir [59] reported that Nu_{avg} increases with an increase in Re_D. They proposed empirical relation for the phenomena that satisfies $Nu_{avg} - \mathrm{Re}$ relation closely for a constant heat flux of 10.6 Wcm^{-2} and deviates $\sim \pm 18\%$ for another heat fluxes of 8.5 Wcm^{-2} and 13.8 Wcm^{-2} respectively. Further increase or decrease in heat flux will result in higher deviation since the empirical relation is independent of heat flux.

Porosity plays important role in heat transfer through a MF. Kurtbas and Celik [60] experimentally investigated heat transfer and pressure drop characteristics through a MF-filled rectangular tube. In their study outer tube surfaces were kept at constant heat flux boundary condition and surface temperature was kept at ~76 °C. They found that the Nu number increases with pore density as well as Re_H, where channel height (H) was considered as characteristic length for the Reynolds number. On the other hand, Mancin et al. [38,39] reported that local