Experimental Thermal and Fluid Science 99 (2018) 13–25

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Air flow through confined metal foam passage: Experimental investigation and mathematical modelling

Mohammad Sajid Hossain*, Bahman Shabani

School of Engineering, RMIT University, Australia

ARTICLE INFO

Keywords:
Fluid flow
Confined flow passage
Metal foam
Experimental study
Theoretical modeling

ABSTRACT

This paper deals with flow behaviour through a confined passage filled with metal foams (MFs). Two sets (four samples) of aluminium foams of 20 and 40 ppi pore densities with 9–11% and 12–16% relative densities (RD) individually (as per supplier's specification) were used for the study. Former RD belonged to uncompressed metal foams whereas the later was achieved by unidirectional compression of metal foam of 6–8% RD. Measured porosities of the uncompressed 20 and 40 ppi MF samples were equal, which was 0.88. However, measured porosities were 0.83 and 0.86 for compressed 20 and 40 ppi MF samples. Flow characteristics of both compressed and uncompressed samples were experimentally measured. Fourie-Plessis's representative unit cell (RUC) model was used as an analytical tool for estimating pressure drop gradient through MFs because of its simplistic approach and independency from flow characteristics. Possible encasing wall effect on pressure drop was theoretically conducted. Due to a significant difference in estimated and experimentally obtained pressure drop gradient, authors have proposed a modification in the RUC model. The modified version of the RUC model was able to estimate pressure drop gradient of the uncompressed samples with a considerably higher accuracy.

1. Introduction

Metal foams (MFs) are new kind of engineered porous metal structure that is very light in comparison with solid materials of the same volume. There are two types of MFs with open pores and close pores (Fig. 1). Open-pore MFs are fluid conducting. This article deals with open-pore MFs and from this point forward the term MF/MFs refers to only open-pore MFs unless it is mentioned otherwise. MFs have a high surface to volume ratio that makes them an appropriate candidate for compact heat exchangers [1–4], various applications in different industries [4], and most recently as flow field in fuel cells [4–15]. MFs, directly or indirectly, act as flow medium in all the above-mentioned application areas.

Flow of gas through MFs is a complex phenomenon, where the hydrodynamic boundary layers face continuous obstructions that result in recirculation and eddies [1]. Complex geometry [16] of MFs boosts nonlinear effect of the gas and the turbulence to promote heat transfer rate from solid to the gas [4,17], which can possibly increase with an increase in porosity but at the cost of increased pressure drop in MFs [18–20]. Size of MF flow passage has a significant effect on flow characteristics (e.g. pressure drop gradient, permeability, drag coefficients, etc.) as well [7,19]. Therefore, it is important to consider encasing effect (transverse wall effect) in the case of confined MF flow passages.

Different types of gas flow models for determining flow characteristics through porous media have been found in literature, such as the models based on Navier-Stokes equations, semi-empirical relations (e.g. Darcy, Forchheimer, Ergun, etc., relations), and empirical relations. There are different types and sources of MFs with varieties of physical characteristics, which are reported in experimental research works reported in the literature to date. Estimated flow parameters such as permeability, form and friction drag coefficients and as a consequence pressure drop, do not match very well to all the available experimental data [21] because of dependency of the existing models on specific experimental reports and lack of wide range of experimental data. Furthermore, selection of characteristic dimensions (e.g. characteristic length used for calculating the Reynolds number) has been different in different studies.

Different approaches by various researchers have been reported to overcome discrepancies between estimated and experimental data. Piątek, Gancarczyk, Iwaniszyn, Jodłowski, Łojewska and Kołodziej [22] have recently proposed a total drag coefficient based model for pressure drop estimation through MFs, where they have compared their own experimental results for two MF samples at low Reynolds numbers. A wide range of experimental data for MFs was reported by Kumar and Topin [23] in their very recent article, where they have proposed

---

* Corresponding author.
E-mail addresses: mohammad.sajidhossain@rmit.edu.au (M. Sajid Hossain), bahman.shabani@rmit.edu.au (B. Shabani).

https://doi.org/10.1016/j.expthermflusci.2018.07.018
Received 11 January 2018; Received in revised form 2 July 2018; Accepted 17 July 2018

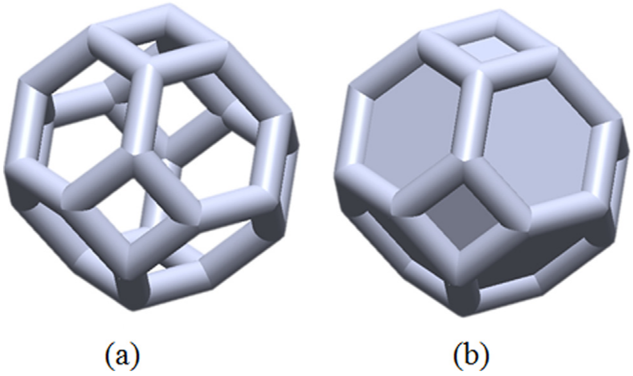

Fig. 1. Unit cells of metal foam; (a) open cell, (b) closed cell.

models that are based on morphological characteristics to estimate flow parameters through MFs. These very recent works along with others (e.g. [18,24–30]) demonstrate the importance as well as the necessity for further investigation in this field. Edouard, Lacroix, Huu and Luck [21] analysed state of the art correlations for MFs' flow characterisation and they have concluded that Fourie-Du Plessis [31] and Lacroix [32] models give better estimations compared to others at that time. Kumar and Topin [23] have provided an up-to-date overview of flow through MFs in their recent work. They have proposed some correlations based on ligament cross-section to determine flow characteristics (permeability and drag coefficients). It should be noted that all the models/correlations were developed for large samples of porous media/MFs.

Antohe et al. [33] investigated permeability and inertia coefficients aluminium MF of 1 mm height (transverse height to flow direction) at different mechanical compression ratio of MF. They observed that flow characteristics (permeability, inertia coefficient, etc.) of MFs were sensitive to air flow velocity range. Darcy velocity range in their study was 0.05–1.5 ms^{-1}. Kouidri and Madani [27] studied flow characteristic of three different MFs of different materials but constant pore density of 20 ppi with water as flowing fluid. They observed that permeability was dependent on flow velocity range. Paek, Kang, Kim and Hyun [16] experimentally investigated permeability and thermal conductivity of aluminium MFs of 9.1 mm height. They found that the permeability was dependent on porosity as well as pore size. They measured the permeability for an air flow velocity range of 0–4 ms^{-1}. Wang and Guo [25] experimentally studied pressure drop and heat transfer characteristics through circular tube of 10 mm diameter and filled with stainless steel MFs of 10, 30, and 70 ppi pore densities and 93% porosity. They reported permeability of their MFs for an air flow velocity range of 7–26 ms^{-1}. The flow characteristics of MFs are estimated from Forchheimer model (as presented as Eq. (2) in this work) where pressure drop gradient is a quadratic function of velocity. Hence, any parameter that influences pressure drop should be influencing the flow characteristics as well. Kamath, Balaji and Venkateshan [34] observed that MF height had significant effect on pressure drop. They used aluminium and copper MFs of 10 and 20 ppi pore densities, and 95% and 87% porosities. Similar observation by Dukhan and Ali [7] from their investigation on air flow through cylindrical flow passage of multiple diameter filled with aluminium MFs of 10 and 20 ppi pore densities bound them to conclude strong boundary effect on pressure drop. On the contrary, no significant difference in pressure drop gradient was found for air flow through aluminium MFs of 20 mm and 40 mm height by Mancin, Zilio, Rossetto and Cavallini [20].

Humidity of air does play an important role in increasing pressure drop as well. Lai, Hu, Ding and Weng [35] experimentally investigated flow and heat transfer characteristics through 15 mm thick copper MF of different porosities and pore densities. They reported that pressure drop increases with an increase in humidity along with pore density. Effect of humidity was prominent for relative humidity above 50%. An increase of 62% in pressure drop through copper MF was reported for wet air of relative humidity above 50% compared to dry air [36]. Han, Kashif, Bock and Jacobi [37] studied pressure drop and heat transfer characteristics of aluminium MF of 10 ppi pore density, 94.2% porosity, and 15 mm thickness. They observed higher pressure drop for wet air ($>$ 85% relative humidity) compared to dry air. To avoid water accumulation due to dehumidification of wet air, hydrophobic coating on MF was applied in an experimental investigation on heat transfer and pressure drop by Hu et al. [38]. They reported that the hydrophobic coating enhanced heat transfer for a humidity range of 30–90%; however, overall performance was reduced due to significant increase in pressure drop at above 30% relative humidity of air compared to uncoated MF samples.

It is being tried by almost all researchers working on this topic to avoid encasing wall effect for flow characteristic measurement. A sample size of MF such as 30 cells diameter/height [7] is considered as critical to avoid transverse wall effect, and the sample of 100 cells length [19] is considered as critical to obtain meaningful and repeatable flow characteristics through MF only. Confining effect of walls is termed as "blockage" [39], which is defined as the ratio of cylinder diameter to width of the test section/wind tunnel, (d/b). Zdravkovich [39] has described blockage effects on circular cylinders by dividing blockage in several ranges for non-laminar flow such as, (i) blockage effect is small for $d/b < 0.1$, (ii) significant blockage effect for $0.1 < d/b < 0.6$, and (iii) drastic blockage effect for $d/b > 0.6$. Blockage effect is important for even very low d/b for laminar flow (low Re). Eddy/vortex shedding happens when fluid passes over obstacles [39,40]. Separation of shear layer (e.g. from cylindrical obstacles as shown in Fig. 2) generates vortex shedding, which increases drag. Presence of eddy/vortex has effects on pressure and friction drags. Turbulence effect on flow through porous material for even low Reynolds numbers has been reported in a very recent numerical study of flow through porous media by Nimvari and Jouybari [41]. Hence, both experimental and modelling works need to be conducted for confined flow passages.

Due to avoidance of encasing effects on flow through MFs in most of the literature on both experimental and modelling works, general

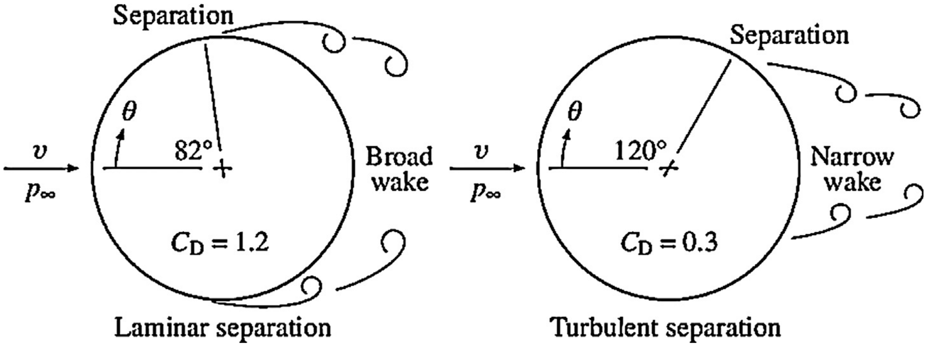

Fig. 2. Flow separations over a cylindrical body [40].