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Experimental study of fluid flow behaviour and pressure drop in channels partially filled with metal foams

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ABSTRACT

This study experimentally investigates the effects of pore density, inlet velocity and blockage ratio on fluid flow behaviour and pressure drop in channels partially filled with a metal foam block. The fluid velocities in the free stream region, which is a clear (from foam) region on the top of foam block, are measured using Laser Doppler Anemometry (LDA) and hot-wire anemometry. The metal foam data are compared to those of solid blocks with the same size. For low blockage ratios, i.e. thin foam layers, the pressure drop caused by a solid block is higher than that of the foam when tested under identical conditions. Interestingly, nonetheless, beyond a threshold blockage ratio value, the pressure drop induced by the metal foam block exceeds that of the solid block of the same height tested at the same air flow rate. This behaviour is best described as the interplay between resistance caused by blockage versus that of the wake forms downstream and over the objects and additional frictional effects within the porous region and on the interface. Furthermore, a correlation, with ± 16% deviation, is developed to predict the flow resistance caused by the solid and foam blocks across the partially filled channel.

1. Introduction

Metal foam heat exchanger has been considered in numerous applications due to its superior thermal capabilities [1–3]. The foam can be used to fill a channel and increase the heat transfer from the wall (compared to no foam case). However, the metal foam microstructures induce massive pressure drop, which becomes one of the major concerns in design of metal foam heat exchangers. Alternatively, a partially filled configuration is preferred to minimise the excess pressure drop yet at reasonably higher heat transfer rate; compared to no-foam case [4]. Despite that, a proper selection of microstructural properties, e.g., pore density (PPI) is essential to ensure optimum fluid goes into a porous region instead of the non-porous region. Ideally, most of the incoming flows will naturally evade the high pore-ligament restrictions and choose the non-porous region or unobstructed pathway. In that case, the benefits of the complicated foam structures [5] could not be fully utilized. Past studies have investigated the thermo-hydraulic properties of the partially filled configuration analytically [6–9] and numerically [10,11]. In all of these studies one needs to make assumptions to model the interface between a porous medium and the non-porous region. Even though there are established theories of porous medium/fluid interfaces [12,13] that can be used for porous metal foams, the interface condition remains controversy due to the discrepancies in findings and lack of experimental studies.

It is worth to note that many experimental studies have investigated the flow pattern around foamed cylinders e.g. separation flow, wakes or vortex shedding to identify the effects of metal foam structure [14–16]. However, to the best of authors' knowledge, only Sauret et al. [17] investigated the velocity profiles in a channel partially filled with a metal foam block. The study considered inlet velocity and foam block height as the variable parameters to measure the velocity profiles at the interface using hot-wire anemometry. The experimental results were in agreement with their numerical model, but they found significant discrepancies when comparing their data with an existing theoretical model. Nevertheless, the difficulty in modelling the exact condition outside (interface) of the porous medium/metal foam has been addressed in [4]. A boundary layer will form on a non-porous solid-fluid interface but for a porous-clear fluid interface this boundary layer can be continuously disrupted if the momentum exchange at the interface go both ways. This is likely due to tortuous flow with a continuous disruption of the pore level boundary layers [18]. Alternatively, experimental velocity profiles in a free stream region of a partially filled configuration could represent the direct effects of complex foam microstructure, boundary layer and slip velocity (if present).

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Nomenclature

A_f	frontal area (m^2)
Da	Darcy number, K/H^2
d_p	pore diameter (m)
d_l	ligament diameter (m)
Dh	hydraulic diameter (m)
e	error
exp	experiment
f	friction factor
FOV	field of view
h	metal foam height (m)
H	channel or test section height (m)
Hf	free stream region height (m)
h/H	blockage ratio
K	permeability (m^2)
L	pressure taps distance (m)
L_C	channel length (m)
Lf	foam length (m)
m	mass (kg)
N	number of sample size
ΔP	pressure drop (Pa)
P	pressure (Pa)
PPI	pore per linear inch
Q	volume flow rate (m^3/s)
Re	Reynolds number
$\overline{u}$	average velocity of partially filled channel (m/s)
u_f	free stream region velocity (m/s)
u_o	inlet velocity (m/s)
u_p	average pore velocity (m/s)
V	volume (m^3)
W	channel width (m)
wf	foam width (m)
WT-1	test facility with $Dh = 0.088\,m$
WT-2	test facility with $Dh = 0.320\,m$

Subscripts

corr	correlated or predicted
Dh	channel hydraulic diameter
ds	downstream
exp	experimental data
f	free stream region
fx	fixed
h	foam height
H	channel height
pf	partially filled
r	random
T	total
us	upstream
p	pore (porous region)

Greek symbols

ε	porosity
δ	uncertainty
ρ	density (kg/m$^{3)}$
μ	viscosity (kg/(m·s))
λ	laser wavelength (nm)

There exists a few number of experimental studies on the partially filled configuration with porous metal foam in the literature. Sener et al. [19] experimentally investigated 10 and 20 PPI aluminium foams inside a channel with four different configurations; convex, concave and triangular and completely filled channel. Their result showed that the effect of Reynolds number (Re) on the pressure drop decreases for a surface curvature parameter larger than zero, regardless of the pore density. Those authors derived empirical correlations for the pressure gradient of laminar and turbulent channel flows, with ± 25% deviations from the experimental data. Liu et al. [20] experimentally investigated the thermo-hydraulic properties of a tube partially filled with metal foam to note that by increasing the PPI, the pressure drop would increase first and then decrease. The authors claimed that the fluctuations of the pressure drop in the high PPI foams are due to (1) the high number of ligaments that increase the flow resistances and (2) the reduction of mass flow rate in the low permeability foam, resulting in the smaller flow resistances. Lu et al. [21] described the pressure drop performances of metal foam by employing porous media characteristics such as Brinkman-extended Darcy model. Their analytical results showed that the pressure drop is increasing with PPI, but the substantial increments only occurred with low PPI foams (less than 15 PPI). Besides, the high PPI foam with more restrictions were found to force the flow into the free stream region, which lessen the effects of porous structure on the overall resistance. Additionally, their study also showed a higher pressure drop could be attained by increasing the foam height and flow velocity, but the former effect is found to be more dominant. Through their numerical study, Forooghi et al. [22] also stated that the pressure drop effects were remarkable once the porous medium has filled more than half of the channel. The study stated that a smaller Darcy number, $Da = 10^{-5}$ would only cause a higher pressure drop, than $Da = 10^{-4}$, when the blockage ratio exceeds 0.4 Similarly, Sung et al. [23] numerically investigated the effects of Darcy number on the flow characteristics of a channel partially filled with a porous block. A larger recirculation zone appeared behind the porous block with a higher Reynolds number, $Re = 500$, as compared to $Re = 100$, at a constant Darcy number, $Da = 10^{-5}$. However, no recirculation zone appears with a higher Darcy number, $Da = 10^{-2}$. The study also found that the pressure drop increases with the porous height but a fully filled channel caused 400 times higher pressure drop compared to a clear channel. Shuja and Yilbas [24] numerically investigated the effects of porosity of a porous block in a vertical channel with different aspect ratios.

A channel partially filled with a solid block could be considered as forward-backward facing step flow, where three recirculation zones appears in the upstream, above the step (solid block), and immediate vicinity of the downstream regions [25]. However, if one replaces the solid block with a permeable one of the same size, the local velocity profiles and, thereby, the pressure drops would be different. Interestingly, Kouidri and Madani [26] qualitatively analysed the roughness of foam surfaces to note that a smooth foam when compared with a highly rough surface has difference effects on the pressure drop and the surface roughness enhances the process of flow regime transition.

The aforementioned experimental studies have considered only the total pressure drop, but no further explanation on the local pressure losses involving the upstream, core (porous region) and downstream regions were offered. This could be because of the presumption that the major part of the flow resistance can be attributed to the core. Thus, this study experimentally investigates the effects of various foam samples, channel blockage ratios and inlet velocities on the velocity profiles of partially filled channels. The total pressure drops are also measured and the results are compared to equivalent solid blocks. This study introduced an appropriate range of PPIs and blockage ratios for optimum flow at the expense of low-pressure drop effects. The presented results are the direct effects of a real and complicated structure of the metal foam, instead of relying on the assumptions and idealized foam in those above-mentioned numerical and mathematical studies.

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