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Thermohydraulics of a metal foam-filled annulus

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ABSTRACT

This paper offers numerical and experimental analysis of forced convection through an annulus filled with aluminium foam. Effects of flow rate and foam pore density on the performance of the heat exchanger were investigated. Specifically, 5 and 20 pore per inch (PPI) aluminium metal foams were tested at three different airflow rates; 20, 85 and 150 standard litre per minute. In parallel, the problem has been simulated numerically. Once validated against experimental data, numerical simulations were conducted to add to the level of details obtained from experiments. The thermal study was done by analysing the temperature field throughout the porous volume and determining the thermal entrance length. This parameter, the thermal entrance length, establishes a reliable design criteria for metal foam-filled heat exchangers, since it marks the length beyond which heat transfer does not significantly increase while the pressure drop keeps growing.

1. Introduction

Open-cell metal foams have been investigated extensively for heat exchanger applications due to their promising properties such as lightweight, high surface area, high thermal conductivity, tortuous flow paths and good mechanical strength and stiffness [1–4]. Many studies have proved that the metal foams can augment the heat transfer compared to an identical heat exchanger with no foams or even different surface extension techniques [1]. Accordingly, a great deal of information is available in the literature addressing metal-foam filled tubes [5,6], metal-foam wrapped tubes [7–10], fully-filled channels [11–18], partially filled channels [19,20] and other constructions [21,22] in order to match different applications. Due to significant improvement in heat transfer at the expense of higher pressure drop, many studies [9,10,21] have investigated the trade-off between the heat transfer and pressure drop increase. Odabaee et al. [9] numerically investigated a metal foam-wrapped tube with different foam thickness by varying the ratio of porous medium radius and surface radius from 1.025 to 2. Their results showed that the pressure drop and the heat transfer rate were increasing with the foam thickness. Odabaee and Hooman [23] extended their investigation on the same samples through an optimization study based on the first and second law of thermodynamics and concluded that the metal foam heat exchangers would have 2–6 times higher performance factor than finned-tubes in the air-cooled condenser application. Chumpia and Hooman [10] experimentally studied the thermo-hydraulic of five foam wrapped heat exchangers with different thickness (5–20 mm). They showed that an optimum thickness of metal foam that provide a similar level of pressure drop to a finned tube will have better heat transfer performances. Mao et al. [24] also proved that the foam thickness of metal foam-wrapped tube has significant effects on the pressure drop and heat transfer performances. The study also claimed that only porosity has significant influence on the form coefficient, neither the pore size nor the pore shape. However, Hu et al. [3] demonstrated that a metal foam heat exchanger exhibited higher pressure drop and heat transfer rate as compared to a fin-and-tube heat exchanger when increasing the pore density and the relative humidity of the inlet air. Jin and Leong [25] also reported that the pressure drop was increasing with the pore density based on their study on steady and oscillating flows within 10, 20 and 40 PPI foams. Huisseune et al. [21] numerically designed two tube rows in a staggered tube layout inside a metal foam block which was a comparable design to a louvered finned heat exchanger. The study showed that the high pore density metal foam (>40 PPI) would have better performance than the finned heat exchanger and six times higher heat transfer compared to the bare tube.

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Nomenclature

A	area (m^2)
cd	cell density (equiv. to PPI, pores per inch) (1/m)
C_p	specific heat capacity (J/kg K)
d	diameter (m)
e	error (%)
E	total energy (J)
f	inertia coefficient (–)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
h_i	enthalpy of species i (J/kg)
Ji	diffusion flux of species i (kg/m^2 s)
k	thermal conductivity (W/m K)
k_1	Darcian permeability (m^2)
L	length (m)
LMTD	logarithmic mean temperature difference (K)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
ΔP	pressure drop (Pa)
Q	heat transfer rate (W)
S_f^h	fluid enthalpy source term (W/m^3)
S_s^h	solid enthalpy source term (W/m^3)
SLPM	standard litre per minute
ΔT	temperature difference (K)
t	thickness (m)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
z	axial direction (m)
$\frac{\partial \eta}{\partial z}$	efficiency gradient (m^{-1})

Subscripts

a	air
ai	air inlet
EA	external air
eff	effective
EW	external wall
f	fluid
F	foam
fs	fluid/solid interface
fx	fixed
i	inlet
IW	internal wall
l	ligament (struts in the foam)
m	mean
o	outlet
p	pore
r	random
s	solid
T	total
TA	air temperature
te	thermal entrance
∞	ambient
w	water
wi	water inlet

Greek symbols

β	Forchheimer coefficient (inertial resistance) (1/m)
β	$= f/\sqrt{k_1})$
ε	porosity
δ	uncertainty
ϕ	non-dimensional temperature
η	efficiency
ρ	density (kg/m^3)
θ	angle (degrees)
μ	viscosity (kg/s m)

In addition to the effects of foam thickness and its microstructural properties, there are also studies of heat transfer due to oscillating flow [26], as well as the thermal development in the flow directions [27,28]. Iasiello et al. [27] investigated the developing thermal airflow through an open-cell metal foam based on the Kelvin's tetrakaidecahedron foam model. They stated that the presented correlation agreed with the existing results, within 20% and 30%, for interfacial and volumetric heat transfer coefficients, respectively. They also identified three regions in the foam along the flow direction; an impingement region, a thermally developing region and a thermally developed region, where the impingement effects were dominants at the inlet section.

Dukhan et al. [28] stated that the thermal entrance regions must be considered based on their findings on the heat transfer of water run inside a metal foam-filled tube. They identified two thermal behaviours based on the local Nusselt number, which then classified as thermally-developing and fully-developed conditions. In a similar metal foam construction, Bagci et al. [26] studied the heat transfer of oscillating water flow, as its thermal dispersion could not be neglected, unlike gas in the porous media. Details studies on the thermal dispersion have been conducted in different constructions e.g. a porous-saturated pipe [29] and parallel plate porous channel [30]. In another interesting study, Dukhan et al. [31] proved that their experimental results on the fluid temperatures inside a heated aluminium foam-filled tube showed unexplainable behaviour when compared to the existing analytical solution. They proposed analytical solution which has been under-predicting fluid temperatures to achieve a comparable result to the experimental data. Meanwhile, some other experimental studies have addressed the difficulties in measuring the temperature within foam microstructures [12,31].

It is important to note that the fluid temperature measurement within the foam microstructure unveils some uncertainties. When measuring with thermocouples at high temperature, errors may arise from the transient states and the high thermal gradients between the temperature of the solid and the temperature of the fluid [32]. To consider the temperature effects at pore level, Dukhan and Chen [12] measured the temperatures within three metal foam samples with different porosities by inserting thermocouples directly into the drilled holes. They presented the results as a function of the position and predicted an uncertainty in the temperature of about 11.7%, and in the non-dimensional temperature of about 13.9%. Meanwhile, Dukhan et al. [31] designed and fabricated a system to measure the internal temperature by using common thermocouples, but isolating their tips with small perforated aluminium tubes.

In this study, the ambient air is sucked into the porous structure of metal foam fills an annular section. The local temperatures were measured by positioning a thermocouple using a singular and in-house manufactured clamp. The internal temperature measurements have covered almost the entire foam structure to identify the air temperature distribution. Possible errors in the temperature measurements are counteracted with the increase in the number of measuring points, especially at the entrance region where higher temperature gradients are expected. This study also investigated the effects of the cell density (5 and 20 PPI) and the airflow rates