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Particle size distribution effects on preferential deposition areas in metal foam wrapped tube bundle

E. Sauret [a,*], K. Hooman [b]

[a] School of Chemistry, Physics & Mechanical Engineering, Queensland University of Technology, Brisbane, QLD 4000, Australia
[b] Queensland Geothermal Energy Centre of Excellence, The University of Queensland, St Lucia, QLD 4072, Australia

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ABSTRACT

This paper presents a numerical model for understanding particle transport and deposition in metal foam heat exchangers. Two-dimensional steady and unsteady numerical simulations of a standard single row metal foam-wrapped tube bundle are performed for different particle size distributions, i.e. uniform and normal distributions. Effects of different particle sizes and fluid inlet velocities on the overall particle transport inside and outside the foam layer are also investigated. It was noted that the simplification made in the previously-published numerical works in the literature, e.g. uniform particle deposition in the foam, is not necessarily accurate at least for the cases considered here. The results highlight the preferential particle deposition areas both along the tube walls and inside the foam using a developed particle deposition likelihood matrix. This likelihood matrix is developed based on three criteria being particle local velocity, time spent in the foam, and volume fraction. It was noted that the particles tend to deposit near both front and rear stagnation points. The former is explained by the higher momentum and direct exposure of the particles to the foam while the latter only accommodate small particles which can be entrained in the recirculation region formed behind the foam-wrapped tubes.

1. Introduction

Increasing the electricity production while reducing the carbon emissions is a priority for many countries. Australia has a high-potential to produce geothermal power thanks to hot rocks reaching 300 degrees Celsius at approximately 5 km under the surface [1]. However, these resources are mainly located in isolated arid areas. In such places, water is rare and precious and wet cooling systems are not the most appropriate solutions. Instead, air-cooled heat exchangers appear a more suitable choice [2,3]. For such geothermal power plants, the use of binary cycle with a very low thermal efficiency around 10% [4] requires high heat transfer rates. Hence, it is vital to make the technology highly efficient.

For many thermal applications such as air conditioning or refrigeration, finned-tube bundles heat exchangers have been used and studied for many years [5]. Fins are added to the tubes in order to improve the heat transfer thanks to a surface area increase. New developments further improved the efficiency of heat exchangers by replacing the fins by metal foams [6]. It has been recently suggested to replace fins by metal foams in air-cooled heat exchangers for geothermal applications [7]. Metal foams are fibrous materials which are becoming increasingly popular thanks to their attractive thermophysical properties such as high surface-to-volume ratio, low density, thermal and corrosion resistance and high mechanical strength and rigidity [8,9]. Initial preliminary numerical investigations performed by Odabaee and Hooman [10] on a four-row tube bundle in cross-flow showed that metal foam heat exchangers improve the heat transfer performance compared to conventional finned-tube heat exchangers at the expense of a slightly higher pressure drop. Heat transfer is enhanced by increasing the turbulence and mixing and dispersion induced by the ligaments of the foam as well as by high heat conductivity through the metallic ligaments. These properties lead to smaller, lighter and more efficient heat exchangers which become more attractive than conventional heat exchangers [10–12]. Finally, the reduction in production cost also makes them more and more competitive.

However, one of the challenges faced by this enhancement technique is the fouling caused by the deposition of particles inside the pores of the metal foam. As outlined by McGowan and Clark [13], Lake Eyre in Australia is the most active dust source in the Southern Hemisphere. Thus, it has a high potential of affecting the regional geothermal power plants due to dust transport that can go as far as the Philippines. The dust deposition reduces the heat transfer rate between the flow and the metallic ligaments.

* Corresponding author.
E-mail addresses: emilie.sauret@qut.edu.au (E. Sauret), k.hooman@uq.edu.au (K. Hooman).

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Nomenclature

A	tube heat transfer area [m^2]
a_{sf}	interfacial area density [m^{-1}]
c_F	form drag coefficient [-]
C_p	specific air heat capacity [J kg^{-1} K^{-1}]
d_f	mean foam fiber diameter [m]
d_p	mean pore diameter [m]
dP	mean pressure drop through the channel [Pa]
G	shape factor [-]
X_t	transversal tube pitch [mm]
k_s	aluminium thermal conductivity [W m^{-1} K^{-1}]
K	permeability [m^2]
LTMD	Logarithm Mean Temperature Difference [K]
m	wall line coordinate; see Fig. 2 [-]
$\dot{m}$	air mass flow rate [kg s^{-1}]
N	number of numerical particles [-]
P	pressure [Pa]
PPI	Pore Per Inch [m^{-1}]
$\dot{Q}$	total heat [W]
R_p	tube+foam radius [m]
R_s	tube radius [m]
R_{th}	thermal resistance [m^2 K W^{-1}]
T	temperature [K]
U	velocity [m s^{-1}]
u_x	axial component of the velocity [m s^{-1}]
x	axial direction [-]

Greek symbols

ϵ	porosity [-]
μ_{eff}	effective dynamic viscosity of the porous medium [kg m^{-1} s^{-1}]
μ_f	dynamic viscosity of the main fluid flow [kg $m^{-1}s^{-1}$]
ϕ	soot particle diameter [μm]
ϕ_{mean}	mean soot particle diameter [μm]
ρ	density [kg m^{-3}]
σ	standard deviation in normal particle-size distribution [μm]

Subscripts

∞	inlet
o	outlet
w	tube wall

The pores can be blocked causing an increase in the air-side pressure drop. In addition, in the case of metal dust, corrosion may have catastrophic consequences on the foam lifetime [14]. As noticed by Young et al. [14], the mechanisms of metal dusting is still not well understood and numerical simulations will become an increasingly useful tool to better understand this complex phenomenon. All this affects negatively the efficiency of the heat exchanger and can even damage the metal foam structure. Also, as underlined by Odabaee et al. [12], this issue has not been extensively studied in the current literature and needs further investigation especially numerical models capable of predicting the dust deposition and its effects on the heat exchanger performance.

Hooman et al. [15] theoretically investigated the impact of particle deposition on metal foam exchangers. Their findings outline the high pressure drop that can be reached due to blocked pores and the negative effect of particle deposition especially with high velocity flows. However, they assume a uniform layer distribution of dust on the foam surfaces, then noticing the importance of the challenges to accurately model such complex configurations.

In another study, Odabaee et al. [12] numerically simulated the effects of particle deposition in a single-row metal foam-wrapped tube bundle. They compared cases with different deposition distributions to the clean metal foams. However, the dust layer is assumed to be uniform with no particle modelling and the foam is considered as a simple porous medium.

In order to extend the understanding of fouling in metal foam heat exchangers, this paper looks at the particle transport in a single-row foam-wrapped tube bundle and gives insights on the preferential particle deposition areas both inside the foam and on the tube walls. The effect of the particle sizes distribution on preferential particle deposition areas is discussed under both steady and transient conditions.

2. Numerical modelling

2.1. Computational domain and boundary conditions

The computational domain is presented in Fig. 1 and the wall line coordinate is defined in Fig. 2, while the dimensions and aluminium foam properties are provided in Table 1.

The boundary conditions for the simulations are listed in Table 2. The top, bottom and side surfaces of the domain are set to symmetry. The temperature of the tube wall is fixed. At the inlet, a uniform axial velocity is specified while the static pressure at the outlet is set equal to the atmospheric pressure. The standard k-ϵ model with scalable wall function is used to model the continuous phase.

2.2. Metal foam modelling

A classical approach [10,12] is to model the foam as a homogeneous and isotropic porous medium for which the experimental permeability and porosity are set (Table 1).

Because of the complexity of the real foam geometry, the ligaments are not modeled inside the porous medium. However, the aluminum properties of the ligaments are taken into account through an interfacial area density calculated from Calmidi and Mahajan [11]:

$$a_{sf} = \frac{3\pi d_f G}{(0.59 d_p)^2}, \quad G = 1 - e^{-\frac{1-\epsilon}{0.04}} \tag{1}$$

where G is a shape factor which takes into account the variation of the ligament cross-section with the porosity. The fiber diameter d_f was related to PPI by Hooman et al. [15] while the pore diameter d_p is obtained from Battacharya et al. [16]:

$$d_f = \frac{0.431 - 0.0049\text{PPI} + \frac{2.43}{\text{PPI}^2}}{1000} \tag{2}$$

$$d_p = \frac{d_f G}{1.18}\sqrt{\frac{3\pi}{1-\epsilon}} \tag{3}$$

d_f in Eq. (2) is measured in meters and obtained by curve-fitting the experimental data with PPI measured as 1/inch. It has also been used in [15] and is found to be accurate within 9% of the experimental data.

ANSYS-CFX is used to perform the simulations using the Navier–Stokes equations as presented in Eq. (4).

$$\frac{\partial(\rho U)}{\partial t} + \nabla.(\rho U \otimes U) = -\nabla P + \nabla.\tau + S_M.F \tag{4}$$