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Numerical simulation of heat transfer in the near-wall region of tubular reactors packed with metal open-cell foams

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HIGHLIGHTS

- Conjugated heat transfer simulations for air or water flow through aluminium open-cell foams.
- The role of reactor wall-foam support thermal coupling is investigated in detail.
- A novel correlation for the wall heat transfer of metal open-cell foam reactors is presented.

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ABSTRACT

A numerical investigation of the thermal transport processes in the near-wall region of a reactor packed with metal open-cell foams is presented in view of the development of externally-cooled tubular reactors packed with catalytically active foams. Two different aluminium open-cell foams were scanned by X-ray micro-computed tomography in order to generate the 3D models used in this study. The conjugated solid–fluid heat transfer problem is solved by finite volume analysis (FVA) for different flow rates and fluid properties (Peclet number range from 1 to 10^5). Predictive correlations for the wall heat transfer coefficient are derived according to different thermal coupling scenarios between the open-cell foam bed and the reactor wall. Such kind of systematic study and the proposed correlations that account for the gap size represent a novelty in the field of published literature on open-cell foams.

1. Introduction

In non-adiabatic fixed bed reactors the use of structured catalyst supports offers superior control on the bed transport characteristics with the possibility to adjust the support properties in an optimal manner. In this regard, open-cell metallic foams (sometimes referred to as sponges) are characterized by particularly promising features. Their light structure, with a porosity generally higher than 80%, is less prone to excessive pressure drop [1–3] even in applications with high spatial velocities. At the same time, the relatively high value of the surface area density [4–6] allows for realizing reasonably high catalyst loads in the reactor [7,8]. Moreover, the continuity of the solid support provides an additional path for the heat flux, particularly in the case of foams made of highly conductive metals, without the problem of preventing radial mixing as encountered in monolithic honeycomb structures.

It is worth noticing that, despite a general similarity between the physical processes, a main difference exists in the relative importance of heat transfer mechanisms in open-cell foams on the one side and conventional packed beds on the other side. For example, in a particle random packing the near wall region is generally characterized by different hydrodynamic conditions, because the void fraction is not constant but much higher close to the reactor wall [9]. Moreover, the role of inter-particle conduction is extremely weak as a result of the finite number of confined point contacts. The conduction inside the interconnected solid matrix of consolidated porous media such as open-cell foams, in contrast, is quite significant and may even represent the main contribution to heat transfer for systems operating with low conductive fluids and/or low flow rates [6,10].

For these reasons, the correlations for the effective heat transfer coefficients that are available in literature [11] from extensive analysis of unconsolidated packed beds are not directly applicable to open-cell foam beds [12]. Instead, new data must be collected and evaluated for the specific application. Open-cell foams made

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Nomenclature

List of symbols

A [m^2] area of the heated surface
Bi [–] Biot number
c [J kg^{-1} K^{-1}] specific heat capacity
D_h [m] hydraulic channel diameter
d_h [m] hydraulic pore diameter, $\frac{4\varepsilon}{S_v}$
d_p [m] average pore inner diameter
d_c [m] average cell inner diameter
e [J kg^{-1}] specific internal energy
F [–] Forchheimer inertial coefficient
H [m] height of the 3D foam model
Hg [–] Hagen number, $\frac{\Delta p}{\Delta L}\frac{\rho u d_h^3}{\mu^2}$;
h_i [W m^{-2} K^{-1}] interphase heat transfer coefficient
h_U [W m^{-2} K^{-1}] heat transfer coefficient between the fluid and the unfinned wall
h_W [W m^{-2} K^{-1}] wall heat transfer coefficient
k [W m^{-1} K^{-1}] thermal conductivity
k_f [W m^{-1} K^{-1}] fluid thermal conductivity
k_s [W m^{-1} K^{-1}] solid thermal conductivity
k_e [W m^{-1} K^{-1}] effective conductivity of the foam bed
K [m^2] permeability
L [m] length of the 3D foam model
m [m^{-1}] equivalent Biot number for a single strut;
M [m^{-1}] corrected m coefficient for open-cell foam structure;
Nu [–] Nusselt number at the wall, $\frac{h_W d_p}{k_f}$
p [Pa] pressure
Pe [–] Peclet number based on interstitial velocity, $\frac{\rho u c_f d_p}{\varepsilon k_f}$
Pr [–] Prandtl number, $\frac{\mu c_f}{k_f}$
q [W m^{-2}] heat flux for unit area
R [m K W^{-1}] thermal resistance
Re [–] Reynolds number based on pore diameter and interstitial velocity, $\frac{\rho u d_p}{\varepsilon\mu}$
S [m^2] interphase open-cell foam area
S_v [m^{-1}] geometric interfacial area density, or volumetric surface, of foam
t_s [m] average middle strut section
T [K] temperature
u [m s^{-1}] velocity
U [W m^{-2} K^{-1}] overall heat transfer coefficient
W [m] width of the 3D foam model
X, Y, Z [m] Cartesian coordinates

Greek symbols

Γ [m^2] channel cross sectional area
ε [–] bed porosity
η [–] efficiency
μ [kg s^{-1} m^{-1}] dynamic viscosity of fluid
ρ [kg m^{-3}] mass density
τ [Nm^{-2}] viscous stress tensor

Subscripts

b bulk
c cell
e effective
f fluid properties
F fin
h hydraulic
i interphase
in inlet
lm logarithmic mean
n normal
out outlet
p pore
q fixed heat flux
s solid properties
T fixed temperature
U unfinned
w wall
x, y, z Cartesian coordinates

of highly conductive metals were investigated in several studies [13–16] for pure air thermal exchanger, such as compact heat sinks. However, in none of these previous studies the effect of the coupling between the foam packing and the heated surface was considered, as the metal sample was directly brazed with the exchanger walls. Owing to the high solid matrix conductivity, such a configuration leads to a relatively homogeneous temperature distribution which can be described by a 1D model for the heat transport.

In contrast, if the open-cell foam is used as catalyst support it is packed inside the reactor and thus a gap will always exist between the foam and the externally cooled or heated reactor wall. For this case, a two dimensional description of the temperature profile with a 2 parameter model is more appropriate [17]. In previous experimental studies an annulus of small, but finite size was always present between the support and the reactor wall. In some cases it was attempted to minimize the gap influence by the use of layers of carbon foil to wrap the foam samples in order to avoid bypassing in the experimental set-up [18]. In any case it becomes obvious that the size of this gap and its influence on the flow and transport properties must be considered. However, only few data are available in literature to estimate the heat transfer coefficients in the near wall region of an open-cell foam bed.

Previous publications mainly report on experimental studies of heat transfer with air in the laminar flow regime, where, e.g., a correlation for the heat wall coefficient was derived for an individual Al_2O_3 foam [17]. In another study, the average value of this parameter was estimated for different β-SiC or polyurethane foams [19]. A few estimates of the wall heat transfer coefficient for an aluminium foam and two-phase flow are also available [20]. However, in neither of these studies the effect of the gap size is considered at all. In a recent study [21], based on metal foam samples with different gas flow rates, it was pointed out that the thermal continuity was not assured despite the tight fit between the samples and the reactor wall. Nevertheless, despite the gap existence was postulated, the effect of the gap itself was not focus in these previous investigations, mainly due to the difficulty and high uncertainty in measuring this parameter in the experimental set-up.

To overcome the limitations of experimental set-ups, in this work a numerical study is therefore proposed. In fact, computational fluid dynamics (CFD) represents an appropriate method to perform a detailed analysis and characterization of thermal and fluid phenomena within catalytic fixed bed reactors [22–24]. In addition, the use of such simulations as numerical experiments allows to fully control the operative condition and the gap size at the wall. Based on these simulations, the purpose of this study is