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Development of a heat transport model for open-cell metal foams with high cell densities

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HIGHLIGHTS

- Open-cell metal foams promising catalyst supports due to high thermal conductivity.
- Heat conduction efficiency was not far from the often-used Lemlich value of 1/3.
- Heat transfer resistance at the wall increases with increasing foam cell diameter.
- Structured tubular reactor wall heat transfer coefficient independent of flow rate.
- Shorter reactors: process intensification, smaller pressure drop: cost efficiencies.

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ABSTRACT

If made of highly conductive materials, open-cell metal foams are particularly interesting as enhanced catalyst supports for fast exo/endo-thermic reactions due to their excellent heat transfer properties. We have extended previous investigations by running heat transfer experiments on open-cell metal foams with very high porosity ($0.93 < \varepsilon < 0.98$) and cell densities (60 and 110 PPI). The foam metal (FeCrAl alloy, NiCrAl alloy, copper, and cobalt), the temperature (300 °C–500 °C), the gas flow rate, and the flowing gas (N_2 and He) were varied. Heat transfer data were collected during steady-state heating runs by measuring temperatures at 22 axial positions and 3 radial positions in the cylindrically shaped foams. A classical 2D heat transfer model was developed based on various correlations available in the literature to describe the heat transport phenomena. Altogether, 20 parameters were optimized in this model: thermal conduction efficiencies and effective wall gap sizes for each of the 8 foams, 2 effective wall heat transfer parameters in the upstream zone for the two gases used, 1 parameter in the radiative contribution, and 1 parameter in the dispersive contribution. The optimized model obtained by global regression shows a very satisfactory fit of the data for all the foams at all the test conditions. Thermal conduction through the solid connected structure was found to play a major role in the effective radial conductivity, with a heat conduction efficiency mostly quite close to the often-used Lemlich value of 1/3. Static gas conduction through an effective gap at the foam-wall interface was identified as the dominant resistance in the wall heat transfer.

1. Introduction

Open-cell foams manufactured from different metals are interesting materials for a variety of applications due to their high surface area, mechanical strength, low relative density, and complex interfacial geometry. Their structure with highly interconnected porosity makes them good candidates for applications as heat exchangers, fuel cell electrodes, high-temperature filters, electron emitters, and catalyst supports [1–7]. In open-cell metal foams the cells are interconnected, with the frame structure consisting of pores communicating through windows [8–11]. As in other structured catalysts, the high porosity and the high surface/volume ratio result in a much lower pressure drop and a greater contact surface area between catalyst and reactants in a reactor filled with catalyzed foams rather than with packed particles [6–16]. Also, open-cell metal foams as catalyst supports offer the advantage of radial mixing within their structure and enhanced mass transfer because of the tortuosity of flow in comparison to segregated laminar flow in honeycomb monoliths with no lateral mixing between channels [6–16]. The poor effective thermal conductivity of conventional packed-bed catalysts for highly exothermic and

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endothermic heterogeneous reactions may result in catalyst deactivation and a decrease in productivity and/or product selectivity [14–16]. In comparison to conventional packed-bed catalysts, thermally connected structured catalyst supports made of highly conductive metals can improve the heat transfer efficiency [14–16]. Moreover, open-cell metal foams as catalyst supports can be manufactured in different geometries allowing for the adjustment of axial or radial flow patterns in the structured reactor [11–15]. From an industrial point of view, the structured catalysts are beneficial since they have the advantages of (i) enabling manufacture of smaller reactors, (ii) providing higher yields and selectivities particularly in heat and mass transfer limited processes, and (iii) improving temperature control, heat management and safety in non adiabatic reactors [14–26].

Despite the great interest in the potential of these new materials as catalyst supports, there is still a lack of engineering models available in the open literature for the estimation of effective heat transfer coefficients in reactors loaded with metal foam catalysts at temperatures and flow rate conditions relevant for chemical processes.

For open-cell metal foams saturated with a medium, many experimental data and theoretical heat transfer models have been reported in the open literature considering explicitly the dominating stagnant (conduction) contribution and neglecting thermal radiation and convection [7,27–43]. These works can be classified as: (i) asymptotic solutions, proposing theoretical correlations originally derived for the estimation of the electric conductivity; however, by analogy these correlations can also be used for the prediction of the thermal conductivity [28–35]; (ii) unit cell approaches, suggesting theoretical models based on simplified descriptions of the foam cell considering the cell distribution homogenous/periodic in the structure, hence, e.g. the overall conductivity of the foam is represented by that of a single unit cell [27,36–42], and (iii) empirical correlations fitted to experimental data without making any assumption on the shape of the single cell; nonetheless relying on experimental data collected on a single foam sample [7,27,35,43].

In previous works, some of us reported heat transfer measurements over open-cell FeCrAl alloy and aluminum (Al–6101) foams with different cell diameters ranging from 1.55 mm to 5.09 mm [44,45]. The data pointed out the benefits of adopting foams with small cell diameters, which enhance the wall heat transfer in addition to increasing the interfacial area. In this work the investigation has been extended to eight new FeCrAl alloy, NiCrAl alloy, cobalt, and copper open-cell metal foams with cell diameters ranging from 0.58 to 1.2 mm, i.e. much smaller than those previously investigated [44,45]. The experimental results have been analyzed by global regression to develop and fit a general model of heat transfer in foams, which can be used to predict the heat transfer behavior of comparable foam materials.

2. Materials and methods

2.1. Investigated foam samples

The samples investigated in this work were open-cell metal foams made of FeCrAl alloy (foams A, B), NiCrAl alloy (foams C, D), cobalt (foams E, F), and copper (foams G, H), all supplied by Alantum Europe GmbH [46].

The thermal conductivities of the fabrication material of the foams, k_s [W m^{-1} K^{-1}], were obtained from data in the open literature. For the FeCrAl alloy material, based on the composition of the alloy (Fe:Cr:Al = 73:21:6), the solid conductivity can be expressed as a linear function of temperature [44,47]:

$$k_s = 11.103 + 0.014T;\ \ 270\text{K} < T < 1200\text{K} \tag{1}$$

For the NiCrAl alloy foam, the solid conductivity as a function of the temperature was obtained from heat transfer handbooks [48,49]. Excel software was used to find the optimal polynomial equation through these data:

$$k_s = 9.29 + 9.95 \times 10^{-3}T + 5.71 \times 10^{-6}T^2;\ \ 523\text{K} < T < 873\text{K} \tag{2}$$

For copper and cobalt foams the following expressions were used [48,49]:

$$\text{Cobalt}: k_s = 97.2 - 0.04909T;\ \ 523\text{K} < T < 823\text{K} \tag{3}$$

$$\text{Copper}: k_s = 402.3 - 0.0567T;\ \ 523\text{K} < T < 823\text{K} \tag{4}$$

The solid densities of the applied materials were taken from the open literature: 7.65 g cm^{-3} for FeCrAl alloy, 8.4 g cm^{-3} for NiCrAl alloy, 8.9 g cm^{-3} for cobalt, and 8.96 g cm^{-3} for copper.

2.2. Fluid thermal properties

For the flowing gases, nitrogen and helium, gas properties such as thermal conductivity, k_f [W m^{-1} K^{-1}], heat capacity, $C_{p,G}$ [J kg^{-1}], and gas viscosity, μ_G [kg m^{-1} s^{-1}] have been reported in Table 1 as temperature-dependent relationships and applied in stagnant and dispersive contributions to the radial effective thermal conductivity (k_{er}) [50].

2.3. Morphological characterization

2.3.1. Gravimetric analysis

The open-void fraction in a cellular solid is defined as the ratio between the void volume and the total volume [44,45]. Optical microscopy in this and in previous works [44,45] showed that the struts of some foams are hollow, not solid, see Fig. 1.

Therefore, two different porosities are defined for the open-cell metal foams: total porosity and hydrodynamic porosity. The hydrodynamic porosity, or open-void fraction, is the total porosity minus the void volume in the hollow struts [6,44,51], since this void volume is hardly accessible, neither for the reactants nor for the catalytic washcoat. The total porosity, ε_T, thus includes all void space, while the hydrodynamic porosity, ε_H, includes only the accessible void space [6,44,51]. The open-void fraction in terms of densities was determined as follows [6,44,51,52]:

$$\varepsilon_H = 1 - \frac{\rho_{foam}}{\rho_{HS}}, \tag{5}$$

$$\varepsilon_T = 1 - \frac{\rho_{foam}}{\rho_{solid}} \tag{6}$$

where, ε_T: total porosity [–]; ε_H: hydrodynamic porosity [–]; ρ_{foam}: foam mass density [kg m^{-3}]; ρ_{solid}: mass density of bulk material [kg m^{-3}]; ρ_{HS}: mass density of hollow struts [kg m^{-3}].

The foam density, ρ_{Foam}, is estimated by dividing the weight of the foam by its total measured volume, based on the cylindrical shape of the foam sample:

$$\rho_{foam} = \frac{W_{foam\ in\ air}}{V_{foam}} = \frac{W_{foam\ in\ air}}{\pi(D_{foam}/2)^2 L_{foam}} \tag{7}$$

where, $W_{foam\ in\ air}$: weight of foam in air [kg]; V_{foam}: volume of foam (in this study and previous studies [44,45] cylindrical shape) [m^3]; D_{foam}: foam diameter [m]; L_{foam}: foam length [m].

The density of the hollow struts, ρ_{HS}, is determined by using a standard pycnometry method; based on the experimental measurements of the buoyancy of the foam samples in ethanol this can be expressed as [6,44,51]: