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Pressure drop modeling on SOLID foam: State-of-the art correlation

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ABSTRACT

The use of porous structures with high external surface area represents an important breakthrough in industrial applications. Foam structures receive more and more scientific and industrial interest as catalyst support. Knowledge of pressure drop induced by these foam matrices is essential for successful design and operation of high performance industrial systems. In this context, the aim of this paper is to critically review the relation between permeability and structural parameters of the different foam structures. This work is willing to examine the effect of a large number of structural parameters (struts diameter, porosity, size of pores, specific surface area . . .) in the prediction of bed permeability based on principals of experimental and theoretical works on the single-phase flow model found in the literature. The state-of-the-art of modeling pressure drop in foams is summarized in Table 1. The goal was to assess and to critically evaluate all available design tools, whether empirical or theoretical.

1. Introduction

The use of porous structures with high external surface area represents an important breakthrough in industrial applications, especially in catalytic systems. The main advantage of using these porous structures is the high contact surface (specific surface) between the fluid and solid phase and also the low pressure drop along the catalyst bed. One eminent example is a packed bed, which is frequently utilized in catalytic converters and thermal energy storage device [1]. However, due to the low porosity (in the range of 0.3–0.6), packed bed induces an important pressure drop at high flow which is detrimental for the operating system, especially when high space velocity is required for maintaining acceptable selectivity. In addition, the conduction through the packed bed is less perfect as the particles in a packed bed were not well connected from each other but by local contact points; therefore, the effective thermal conductivity of such system is generally low and some heterogeneous temperature zones could be formed inside the catalyst bed [2]. It is then of interest to find new support materials which could remediate these drawbacks.

The idea of moving from the traditional packed bed, e.g. spheres, pellets, to the structured bed, i.e. monolith, wire or foam either made of stainless steel or ceramic, is becoming more and more popular during the last decade. Foam matrices have been recently introduced to overcome some of the above shortcomings dealing with the use of the packed bed. On the one hand, this new medium has a highly permeable porous structure with high porosity (0.60–0.95), which enables a considerable reduction of the pressure drop along the catalyst bed even at high gaseous space velocity and on the other hand, the solid ligaments (or struts) in foam material allows the continuous connection of the different catalyst domains which increase the effective thermal conductivity on the entire system without thermal breaking points as encountered with the packed bed.

The foam can be manufactured with different geometries and shapes, allowing for example the adjustment of axial or radial flow patterns in the reactor. The pore structure of a typical commercial product of foam, shown in Fig. 1, evidences a high degree of interconnectivity through the entire matrix of the foam. The small thickness of the struts or wall constituting the foam or monolith can allow the significant reduction of the diffusional phenomena reducing secondary reactions and by-products. Most characteristic parameters are the size of the windows (or pore diameter (a)), which is measured by several techniques and correlates with the pore density (the number of pores per linear inch, ppi) and the struts diameter (d_s).

Today, ceramic-based (Al_2O_3, cordierite, SiC . . .) and metals-based (aluminum, copper, etc.) cellular foams are widely used in a large range of applications, especially in the field of thermal applications (Lu et al. [3]). These peculiar structures are commonly applied for packaging of food, disposable hot-drinks cup (Gibson et al. [4]), packed cryogenic microsphere insulations, solar energy utilization, transpiration cooling, cavity wall insulation (Beavers et al. [5]). Solid foam structures also receive more and more scientific

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Nomenclature

a	pore diameter (μm)
a_c	external specific surface (m^{-1})
d_s	strut diameter (μm)
d_p	particle diameter or equivalent diameter (μm)
$E_{1,2}$	Ergun constants
k_1	permeability coefficient (m^2)
k_2	inertial coefficient (m^{-1})
L	length of foam (m)
Re	Reynolds number
u	fluid velocity ($m\,s^{-1}$)

Greek letters

χ	tortuosity
ε	porosity
ρ_g	apparent density ($g\,l^{-1}$)
ρ_s	strut bulk density ($g\,l^{-1}$)
ΔP	pressure drop (Pa)

Subscripts

g	gas
l	liquid

and industrial interest as catalyst support for high space velocity reactions during the last decade. However, foam structures have a relatively low surface interaction and specific surface area for performing good anchorage and dispersion of the active phase and usually, a wash-coat layer of alumina is required for fulfilling such tasks. Recently, β-SiC foam with a medium specific surface area and a natural wash-coat layer, i.e. SiO_2 and SiO_xC_y topmost passivation layer (2–4 nm) formed by air oxidation of the ceramic at room temperature, has been synthesized and widely employed in several catalytic reactions (Ledoux et al. [6]). The passivation layer allows the good anchorage of the deposited active phase which enhance the number of active sites per linear surface while its low thickness allows the conservation of the intrinsic thermal conductivity of the underlying support (Winé et al. [7]). The main reason why reticulated foams are so attractive in the catalysis field is its high effectiveness in the heat and mass transfer properties along with the low-pressure drop (Richardson et al. [8], Groppi et al. [9]). The three-dimensional cellular structure of foam materials provided a turbulent mode of fluid flow, which significantly increased the extent of active surface utilization and catalyst efficiency. Permeability is also an important parameter for the characterization of foams employed in industrial applications. Knowledge of pressure drop induced by these foam matrices is essential for successful design and operation of high performance industrial systems. During the last decade, numerous experimental and theoretical models on single-phase flow in foams have been led. However, a strong discrepancy within the literature results appears today, which severely limits the development and validation of model of flow properties as a function of geometrical parameters of the used foam. Most of these studies, dealing with foam transport properties, were based on periodic structures which represent a low accuracy with respect to the real structure of the foam. The morphology of such open-celled matrices was characterized using struts diameter and/or pore size presented in Fig. 2 and the relative foam density.

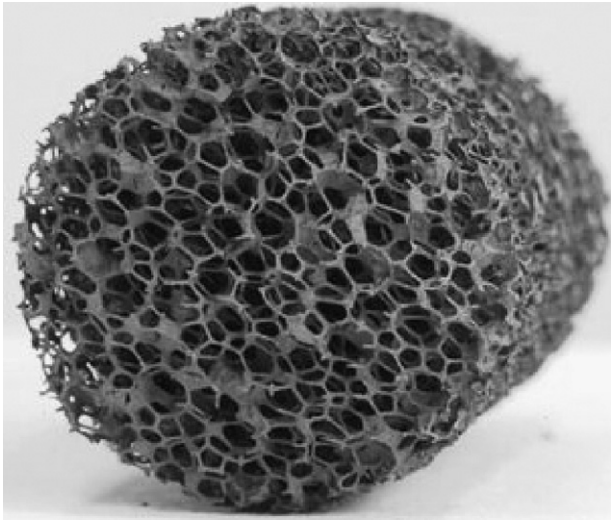

Fig. 1. SiC foam prepared by shape memory synthesis showing the well interconnection within the overall matrix.

In this context, the aim of this paper is to critically review the relation between permeability and structural parameters of the different foam structures. This work is willing to examine the effect of a large number of structural parameters (struts diameter, porosity, size of pores, specific surface area ...) in the prediction of bed permeability based on principals of experimental and theoretical works on the single-phase flow model found in the literature. The state-of-the-art of modeling pressure drop in foams is summarized in Table 1. The goal was to assess and to critically evaluate all available design tools, whether empirical or theoretical.

2. Characteristics of the foams and structural relationship

2.1. Morphological parameters

Several researchers have conduced experimental studies to correlate permeability with structural parameters of foam. However, due to the complexity of the geometric shape of these porous medium, there is no general consensus to define the main structural characteristics. Thus, the major problem in the permeability evaluation of foam is to define structural properties playing a role in pressure drop modeling. Today, in the literature survey [3,8–12], the permeability of the foams to gas flow can be related to macroscopic properties such as the number of pores per unit length, the apparent density, or the void fraction. The foams described in the literature, consist of a network of struts of materials (ceramic, metals, SiC, carbon ...). In Fig. 2, we can see that these struts are connected in vertices and surround the cells. These cells can be modeled for example by a dodecahedron [11,14], a polyhedra [13], tetrakaidecahedron [8,15], etc. This peculiar geometry is a consequence of the forming process of foams (replica technique [8,11,13,16,17]).

Macroscopic properties of these structures were accessible in routine measurements and as indicated in Fig. 2, generally three morphological parameters, namely respectively d_s (struts diameter), a (pores diameter) and ε (foam porosity) are used to describe the foams matrices.

The main morphological characteristics of foams were examined with an optical microscope and the diameters of the windows (or pores diameter, a) and the thickness of the struts (d_s) was measured by means of the sizing technique (see, for instance [8,11,13]).

The third important parameter of these structures is the foam porosity (ε) which is the volume available for the fluids flow through the open-cell structure. Generally in the literature, ε can be calculated on the basis of mass and volume measurements using the expression $\varepsilon = 1 - \rho_g/\rho_s$, where ρ_g is the foam apparent density and ρ_s is the materials density of the struts, which can be porous