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Development of a new pressure drop correlation for open-cell foams based completely on theoretical grounds: Taking into account strut shape and geometric tortuosity

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HIGHLIGHTS

- A generalized pressure drop correlation for open-cell foams is developed.
- A new definition/relation for geometric tortuosity of open-cell foams is proposed.
- The influence of strut shape and geometric tortuosity on pressure drop is presented.
- The proposed correlation for pressure drop prediction shows very promising results.

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ABSTRACT

Owing to their outstanding geometry and material related properties, open-cell foams as structured packing in reactors, columns or heat exchangers offer clear advantages over their traditional counterparts. For the reliable and efficient design of such systems, an accurate knowledge or prediction of the pressure drop is of fundamental importance, as it plays an important economic role in situations involving high space velocities (high Reynolds numbers). The state-of-the-art pressure drop correlations for open-cell foams are not predictive as they tend to show large deviations from measured data. These deviations are observed mainly due to empirical coefficients in the correlations that have been fitted to a particular data set, but without theoretical meaning these coefficients cannot be extrapolated to other foam structures. In addition, the incorporation of inappropriate definitions (originating from misinterpretation or negligence of important aspects) of the structural and geometrical parameters of foams can also induce a considerable error. In this paper, using the notion of geometric tortuosity and starting from the basic Hagen–Poiseuille equation, a generalized pressure drop correlation for open-cell foams is developed which is based completely on theoretical grounds. The correlation is validated for a wide range of open porosities, pore sizes and materials and its applicability for different working fluids is demonstrated. Furthermore, the definitions of structural and geometrical parameters (as mentioned, these are crucial for pressure drop correlations but are sometimes misinterpreted or neglected) of open-cell foams are reviewed. A consensus on these definitions and their incorporation into the pressure drop correlations is proposed. Consequently, with the proposed correlation, pressure drop in open-cell foams can be predicted by knowing only two structural parameters: the open porosity and the window diameter.

1. Introduction

Open-cell foams are highly porous reticulated cellular materials with a sponge-like structure (therefore sometimes also termed as sponges) that consists of an assembly of three dimensionally interconnected struts. Due to their high porosities and continuous three-dimensional cellular structure, they exhibit fascinating properties which can be beneficial in many industrial applications. In chemical engineering, the use of open-cell foams (ceramic or metal) as structured packing in reactors, columns or heat exchangers offer clear advantages over conventional randomly packed fixed beds. These advantages include high specific surface area, high mechanical strength, excellent thermal conductivity

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Nomenclature

Symbols

A	coefficient of viscous term (–)
$(A)_{d_h}$	coefficient of viscous term, w.r.t hydraulic diameter (–)
$(A)_{d_p}$	coefficient of viscous term, w.r.t particle diameter (–)
a_p	free area perpendicular to the fluid flow (m^2)
B	coefficient of inertial term (–)
$(B)_{d_h}$	coefficient of inertial term, w.r.t hydraulic diameter (–)
$(B)_{d_p}$	coefficient of inertial term, w.r.t particle diameter (–)
d_c	cell diameter (m)
d_h	hydraulic diameter of open-cell foams (m)
D_h	hydraulic diameter of empty tube (m)
D_p	characteristic pore size ($d_w + d_s$) (m)
d_s	strut diameter (m)
d_w	window diameter (m)
f	drag coefficient (–)
k_1	Darcian permeability (m^2)
k_2	non-Darcian permeability (m)
L	length (m)
M	mass (g)
P	pressure (Pa)
$S_{v\text{-}geo}$	geometric specific surface area (w.r.t. geometric volume) (m^2/m^3)
$S_{v\text{-}solid}$	solid specific surface area (w.r.t. solid volume) (m^2/m^3)
V	velocity of the fluid (m/s)

Greek symbols

α	Ergun parameter for viscous term (–)
α^*	tortuous factor for viscous term (–)
β	Ergun parameter for inertial term (–)
β^*	tortuous factor for inertial term (–)
ΔP	pressure drop (Pa)
ε_n	nominal porosity (–)
ε_o	open porosity (–)
ε_s	strut porosity (–)
ε_t	total porosity ($\varepsilon_o + \varepsilon_s$) (–)
μ	dynamic viscosity of the fluid (Pa s)
v	volume (m^3)
ϕ	constant for shape of the strut cross-section (–)
ρ	density of the fluid (kg/m^3)
ρ_g	geometric density of foam (kg/m^3)
ρ_b	strut bulk density (kg/m^3)
ρ_s	solid density of foam (kg/m^3)
τ	geometric tortuosity of open-cell foams (–)

Abbreviations

CT	computed tomography
MRI	magnetic resonance imaging
MRPE	mean relative percentage error

(e.g. metal and SiC foams), high porosity and low resulting pressure drop. These benefits can be exploited especially in situations that involve high flowrates and/or strongly exothermic or endothermic processes [1–3]. In order to take advantage of these remarkable properties of open-cell foams, however, new reactor or column designs with open-cell foams as internals are inevitable [4]. In this context, for a reliable design an accurate knowledge or prediction of the pressure drop and/or heat transfer properties is a prerequisite [5–10].

Therefore, in the past decade, considerable research has been conducted on open-cell foams which has led to a greater understanding of their structure–property relationships and to the development of important correlations. Such correlations are necessary to predict the relevant data which in turn are required for designing the chemical engineering equipment such as, e.g., reactor, column and heat exchangers with open-cell foams as internals. However, recent literature shows that the state-of-the-art correlations for predicting the heat transfer and pressure drop properties of open-cell foams lack general applicability and therefore need improvement. Hence, further research is definitely needed in this area in order to come up with correlations featuring enhanced applicability. In this regard, the focus of the present work is to address the problem of pressure drop prediction in open-cell foams, thereby achieving a higher level of accuracy and reliability.

Today, in open literature a multitude of pressure drop correlations for open-cell foams can be found [1,11–20]. A study of recent literature reveals that these correlations, when applied to wider range of porosities or pore densities, tend to show a large deviation from the experimental data [3,5,18,19]. After reviewing the literature, the present authors are convinced that one of the main sources of deviation for most correlations is the use of empirical coefficients. Since these coefficients are usually determined for a limited set of data, they are not suitable for extrapolation to a wider range of pore densities, porosities, and/or working fluids, thus causing a considerable deviation from measured pressure drop data.

Therefore, it is the aim of the present work to develop a general pressure drop correlation for open-cell foams completely based on theoretical grounds that allows for the pressure drop prediction solely based on easily measurable geometric foam properties and which thus bears an enhanced applicability and adaptability. That way, the use of any empirical coefficients or fitting of experimental pressure drop data can be avoided. For this purpose, we start with the basic Hagen–Poiseuille equation and derive a generalized pressure drop correlation for open-cell foams using the notion of geometric tortuosity. In order to determine the geometric tortuosity, we present a new correlation which is based on the geometric properties of open-cell foams and takes into account the shape of the strut cross-section.

In addition, in this paper a special emphasis is put on the structural and geometrical parameters of open-cell foams used in pressure drop correlations (which may be confused, misinterpreted or neglected) that directly or indirectly affect the pressure drop predictions and hence must be defined and determined accurately as well as applied correctly. These parameters include porosity (nominal, total or open), pore size (cell or window), shape of the strut cross-section (circular, triangular or concave triangular) and the specific surface area (based on solid volume "$S_{v\text{-}solid}$" or based on geometric volume "$S_{v\text{-}geo}$"). The incorporation of incorrect or inappropriate definitions of these parameters in pressure drop correlations can be another source of error resulting in significant deviation from experimental pressure drop data. For that reason, the definitions and the use of these parameters in literature pressure drop correlations is reviewed. A further aim is to propose a general consensus on the definitions and methods for the determination of these parameters and finally their incorporation into the pressure drop correlations in order to eliminate and/or avoid any confusion or misinterpretation for future research in this area.