Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 75 (2014) 273–286

Acta MATERIALIA

www.elsevier.com/locate/actamat

The geometric and thermohydraulic characterization of ceramic foams: An analytical approach

Prashant Kumar [*], Frederic Topin

IUSTI, CNRS UMR 7343, Aix-Marseille University, Marseille, France

Received 17 November 2013; received in revised form 20 April 2014; accepted 27 April 2014
Available online 6 June 2014

Abstract

Knowledge of the thermohydraulic properties of industrial components is often necessary for planning and designing chemical engineering processes. The thermohydraulic behavior of open-cell foams depends on their microscopic structure. Based on the tetrakaidecahedron geometry and different strut morphologies of the ceramic foams, we have derived a generalized analytical model that encompasses all geometrical parameters precisely. A special treatment is developed to take the hollow nature of ceramic foam struts into account. Various relationships between different geometrical parameters and porosities are presented. As strut geometries substantially affect flow characteristics, correlations have been developed to determine the hydraulic diameter for ceramic foams using geometric parameters from measured pressure drop data. Two analytical models are derived in order to predict intrinsic solid phase conductivity, λ_s, and effective thermal conductivity, λ_{eff}, simultaneously. A modified correlation term, F, is introduced in the analytical resistor model to take into account the thermal conductivities of constituent phases and a modified Lemlich model is derived. The analytical results are compared with the experimental data reported in the literature and an excellent agreement is observed.

Keywords: Strut morphology; Flow characteristics; Resistor model; Limelich model; Effective thermal conductivity

1. Introduction

Open-cell foam (ceramic or metallic) is a cellular material defined by solid material surrounded by a three-dimensional network of voids. As a lightweight porous material, open-cell foam possesses a high strength and stiffness relative to its weight, making it an attractive option for a variety of applications. In comparison with packed beds of spheres, open-cell foams have higher specific surface area, leading to higher external mass transfer rates. They are also highly porous, which results in low pressure drop. Their specific shape enhances the mixing and improves heat transfer [1–5].

For the application of foam structures as catalyst supports in chemical engineering, reticulated ceramic foams have many attractive features [6,7]. For the planning and designing of numerous chemical engineering processes, precise knowledge of geometrical characteristics, specific surface area and pressure-drop properties is extremely important [7–16]. The relationship between geometrical parameters and thermal properties such as the effective thermal conductivity is critical for conductive heat transfer in foams of highly porous cellular materials, mainly metal foams [17–21]. The continuous strut network enables good heat conductivity, and the void structure allows for pronounced heat transfer through radiation at elevated temperatures.

There are various methodologies for manufacturing ceramic foams. One method involves direct foaming (gel casting) [22], giving solid struts without internal voids.

---

[*] Corresponding author. Tel.: +33 (0) 04 91 10 68 36.
E-mail address: prashant.kumar@etu.univ-amu.fr (P. Kumar).

http://dx.doi.org/10.1016/j.actamat.2014.04.061

Nomenclature

Latin symbols	
a_c	Specific surface area, m^{-1}
$A]_D$	Ergun parameter, dimensionless [15], Eq.3
$B]_D$	Ergun parameter, dimensionless [15], Eq.3
$A]_E$	Ergun parameter, dimensionless, Eq. 1
$B]_E$	Ergun parameter, dimensionless, Eq. 1
C	Correction factor, dimensionless
d_{cell}	Cell diameter, m
d_h	hydraulic diameter, m
$d_h]_D$	hydraulic diameter, m [15], Eq.3
d_p	Pore diameter, m
D_p	Particle diameter, m
d_s	Strut diameter, m
d_w	Window diameter, m
F	Constant, dimensionless
K_1	Permeability coefficient of viscous term, m^2
K_2	Permeability coefficient of inertial term, m
L	Node length, m
L_s	Strut length, m
ΔL	Length of the foam, m
n	Constant, dimensionless
N	Void length, m
ΔP	Pressure drop, Pa
R	Strut Radius, m
Re	Reynolds number, dimensionless
S	Constant, dimensionless
V_s	Solid volume of foam, m^3
V_T	Total volume of cubic cell, m^3
Greek symbols	
ε_n	Nominal porosity, dimensionless
ε_t	Total porosity, dimensionless
ε_0	Open porosity, dimensionless
ε_s	Strut porosity, dimensionless
Ω	Constant, dimensionless
α	Constant, dimensionless
β	Constant, dimensionless
χ	Constant, dimensionless
Λ	Constant, dimensionless
μ	Dynamic viscosity, kg/m/s
ρ	Density of fluid, kg/m^3
λ_s	Intrinsic solid phase conductivity, W/mK
λ_f	Fluid phase conductivity, W/mK
λ_{eff}	Effective thermal conductivity, W/mK
$\lambda_{parallel}$	Parallel thermal conductivity, W/mK
λ_{series}	Series thermal conductivity, W/mK
ζ	Numerical value, Dimensionless
Π	Numerical value, Dimensionless
ψ	Constant, dimensionless
Abbreviations	
CT	Computed tomography
MRI	Magnetic resonance imaging
PPI	Pores per inch

The other commonly employed method is a replication technique that results in foams featuring hollow struts (internal voids in the struts) which are not normally accessible to fluid flow [23]. The foam matrices can be described by their morphological parameters, namely cell and window diameter, strut thickness and porosity [8,12].

Due to the unavailability of resources to measure the specific surface area of ceramic foams, Richardson et al. [8] used the relationships of Gibson and Ashby [24] to derive the specific surface area (a_c) for the pentagonal dodecahedron geometrical model. Similarly, Buciuman et al. [25] developed the expression for calculating the specific surface area of ceramic foams using the approach of Gibson and Ashby [24]. Lacroix et al. [11] used the cubic cell model (considering solid struts) to develop the correlation for the specific surface area, using the open porosity (ε_o) of the foam structure and the strut thickness (d_s). The expressions derived by these authors [8,11,25] induce many discrepancies in determining specific surface area precisely. Moreover, these expressions are based on only two geometrical parameters and do not attain the same results because of low-accuracy measurements or ill-defined geometrical quantities.

Recently, with the advancement in measurement techniques and the evolution of new methodologies, a few authors [13,26] have used magnetic resonance imaging (MRI) to measure the specific surface area of ceramic foams. These authors investigated ceramic alumina foams using MRI. X-ray computed tomography (CT) has been applied by different authors to characterize the morphological parameters of foam structures [27].

Incera Garrido et al. [13] have reported that the cubic model proposed by Lacroix et al. [11] results in a stronger overprediction of the surface area than the tetrakaidecahedron model. Grosse et al. [26] used the Weaire–Phelan structure to model their foams. They derived the correlation using nominal porosity (ε_n) and later used an empirical fitting procedure to redefine the coefficient using open porosity and obtained the semi-empirical correlation which gave close agreement with their experimental data. Inayat et al. [16] have proposed empirical correlations (for different strut shapes, namely triangular, circular and concave triangular) using the geometrical relationships of Richardson et al. [8] with open porosity, window and strut diameter. Their correlation is in good agreement with experimental specific surface area. Inayat et al. [16] argued that the tetrakaidecahedra unit cell should be used, because this is the most consistent with the observed properties and derived geometric relationships for the unit cell (see also Gibson and Ashby [24]). Importantly, the regular