Acta Materialia 126 (2017) 280–293

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Fluid flow through replicated microcellular materials in the Darcy-Forchheimer regime

L. Weber [a, *], D. Ingram [a, c], S. Guardia [b], A. Athanasiou-Ioannou [a], A. Mortensen [a]

[a] Laboratory for Mechanical Metallurgy, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[b] Technical University of Catalonia, Barcelona, Spain
[c] ETEL SA, Môtiers, Switzerland

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form
23 December 2016
Accepted 28 December 2016
Available online 29 December 2016

Keywords:
Microcellular material
Permeability
Forchheimer-regime
Replication

ABSTRACT

We extend here a "bottleneck" flow model derived earlier for incompressible fluids flowing under creeping flow conditions [Despois, J. and Mortensen, A: Acta Materialia 53 (2005) 1381] to flow regimes where inertial losses are no longer negligible, causing the governing flow law to deviate from Darcy's law and become the Darcy-Forchheimer law. The proposed law is compared with measurements of the Darcian permeability K_D and of the Forchheimer coefficient C in forced-flow of air through microcellular aluminium made by the replication process. The geometrical features of the cellular medium are varied in terms of volume fraction of porosity (in the range of 0.66–0.86) and the average cell diameter from (108–425 μm). As found previously in measurements with water, the Darcy permeability of the foams for airflow is also reasonably well captured by the model. In the Forchheimer-regime the model gives good quantitative agreement with data if one assumes that the amount of air kinetic energy that is dissipated when passing across each bottleneck linking one pore to its neighbour along the fluid flow path corresponds to the difference, in a stream of constant cross-sectional area, between a uniform fluid velocity profile and the non-uniform profile that is created by the no-slip condition along the window boundary.

1. Introduction

Knowledge of the pressure drop required to drive forced flow of a given fluid through an open-porous structure, be it a packed bed of granular material or an open-porous cellular material, is of considerable interest to chemical process engineering, to studies of drainage in soils, or to forced fluid flow through microcellular materials as used, e.g., for improved heat extraction in electronic devices. The subject has been covered in several textbooks [1–4] and recent reviews [5–7]. Even when limiting oneself to the subclass of cellular materials, i.e. leaving out the extensive body of literature on granular porous media, a considerable amount of experimental data is available and the various proposed modelling approaches [8,9] have been frequently assessed [5,6,10] against those experimental data.

In a nutshell, the pressure gradient across a sample, ∇P, is linked to the flow rate, expressed by the seepage or Darcian velocity, v_D (defined as the volumetric flow rate, Q, divided by the cross-section crossed by the flow, A), by an equation containing a linear and a square term in Darcian velocity. This is generally known as the Darcy-Forchheimer (or Dupuit-Darcy, or Hazen-Dupuit-Darcy) equation [4,11]:

$$-\nabla P = \frac{\mu}{K_D} v_D + \rho C v_D^2 \quad (1)$$

The linear term in Eq. (1) is linked to viscous losses while the second order term is variably associated with inertial losses (at the pore scale) or form drag, *cf.*, *e.g.*, Lage for an extensive discussion [11]. The prefactor of the linear term in v_D is the ratio of the viscosity of the fluid, μ, to the fluid permeability, K_D, of the structure, while the coefficient of the square term in v_D is the fluid density ρ times a *form factor* C. Alternative ways of writing the prefactor of the square term in Eq. (1) comprise replacing C by $C'/\sqrt{K_D}$; this is motivated by a desire to apply the same characteristic length-scale to the inertia/form drag term as to the permeability term. Hooman and Dukhan [9] found that, by doing so with data gathered on cellular metal samples, C' became a constant for different samples, albeit only for a fairly limited range

* Corresponding author. LMM-IMX-STI-EPFL, Station 12, CH-1015 Lausanne, Switzerland.
E-mail address: ludger.weber@epfl.ch (L. Weber).

http://dx.doi.org/10.1016/j.actamat.2016.12.067
1359-6454/

of pore volume fraction, while C' increased as the volume fraction of pores decreased [9].

Both the linear and the square contributions have been estimated by various authors e.g. Refs. [12–19] but mostly for low volume fraction cellular metal, produced by various processes: coating of polyurethane precursors [12–14,20–22], investment casting (e.g. the ERG process) [23–25], or additive manufacturing [26]. Topologically, these cellular materials have been viewed as packings of irregular polyhedra or regular cubes [27–34], regular dodekahedra [22], or tetrakaidekahedra [12,13,20], whose edges are solid struts. Both, the Lord Kelvin [35] and the Weaire-Phelan [36] tetrakaidekahedra have been considered [37]. The analysis is usually based on known expressions for the flow resistance of an individual strut or a limited number of struts viewed as the building blocks of the cellular material. Varying the cross-section of the struts leads to different flow resistance for a given volume fraction [14]. The characteristic length scale and the volume fraction of solid are implicitly given by the typical length of a strut and the length-to-thickness ratio of the struts, respectively. While these models are appropriate for low volume fraction solid cellular materials, the equations can formally be extrapolated to high volume fraction solids, while maintaining the topology and hence the open-celled nature, and gradually reducing the opening of the pore windows as the solid fraction increases.

Another class of models comprises the "equivalent-bed-of-spheres" models [6,10,38–40]. These make use of Ergun's equation [41] initially developed for packed particles by approximating a cellular material as an equivalent bed of spheres, the size of which is chosen such that they have the same solid fraction and the same specific surface area as the cellular material to be modelled. Topological features, such as the connectivity of the pore space, are not accounted for in such models.

High solid fraction cellular materials (of pore volume fraction roughly in the range 0.6–0.9) can be produced by compressing low volume fraction solid material; however, these can also be produced directly, using various processes. Replication is one of the most widely used of such processes. It comes in two variants, one based on powder metallurgy, the other on liquid metal infiltration [7]. Both routes produce cellular materials that contain pores, the geometry of which is that of the assembly of close-packed partially sintered spaceholder particles that are removed by dissolution when producing the foam. Adjacent pores are hence connected by windows, the opening of which depends on the degree of spaceholder particle densification [42], and also on the ratio of spaceholder-to-matrix material in the powder metallurgical variant of the process, or on the infiltration pressure in the infiltration-based variant of the process [43].

It has been reasoned for cellular materials made by replication that the windows connecting the cells are bottlenecks that control their permeability in the creeping flow regime. This has led to the formulation of analytical predictions of their Darcian permeability, K_D, which have been shown to agree well with experimental data [42] [43]. In the present contribution we extend the model by Despois and Mortensen [42] to flow rates beyond the creeping flow regime. We then confront the predictions of the model to experiments conducted on microcellular aluminium made by replication, exploring pore volume fractions from 0.66 to 0.86 and nominal pore sizes from 108 to 425 μm.

2. Theory

The model presented by Despois and Mortensen [42] addressed creeping viscous incompressible fluid flow through replicated microcellular materials. It is extended here to account for i) inertial losses, and ii) compressibility of the flowing fluid. The microcellular material considered here was made by replication, *i.e.*, it contains pores corresponding to the spherical spaceholders that formed the packed preform whose open pore space was filled with another material (by infiltration or using powder processing). The pores are connected with their nearest neighbours at windows whose radius, r_w, depends on the spaceholder particle radius, r_p, and the spaceholder volume fraction before and after preform densification, Δ_0 and Δ, respectively (we use the notation of the earlier paper by Despois and Mortensen [42], itself based on the notation of Ashby [44]). Following Helle [45] the window size is linked to the spaceholder size by

$$\frac{r_w}{r_p} = \frac{1}{\sqrt{3}}\left(\frac{\Delta - \Delta_0}{1 - \Delta_0}\right)^{1/2}. \quad (2)$$

For the tapping density of the spaceholders, if the particles are spherical, one usually takes $\Delta_0 \approx 0.64$, i.e. the random dense packing density of equisized spheres [46]. If the particles are not spherical, their initial tapping density Δ_0 will vary somewhat with particle size and particle shape. Hence, Δ_0 is left as a parameter in the derivation; note that it is nevertheless not a free parameter, since it can be measured for the relevant spaceholder particle preforms.

As in Ref. [42] we assume that for every cell the flowing fluid enters each pore through one window and exits it through another opposite window, the line linking the two windows being roughly aligned with the direction of the applied pressure gradient. Consider now a slice of the microcellular material, one pore radius (r_p) thick and a square meter in cross section, oriented normal to the fluid flow direction: there will be one window per pore limiting flow of the fluid, *cf.* Fig. 1. The number of pores, n, and hence of windows per meter squared, is given by

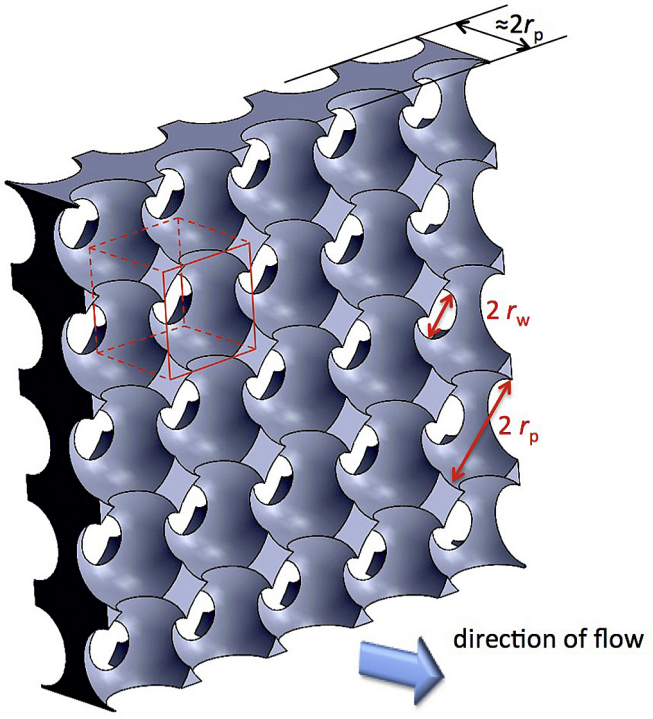

Fig. 1. Schematic drawing of the pore space considered in this work, indicating the window diameter, $2r_w$, and the pore diameter, $2r_p$.