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Analysis of permeability and effective viscosity by CFD on isotropic and anisotropic metallic foams

P. Magnico

Laboratoire de Génie des Procédés Catalytiques, CNRS-ESCPE Lyon, 43 bd du 11 novembre 1918, B.P. 2077, 69616 Villeurbanne Cedex, France

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ABSTRACT

Hydrodynamic properties of open-cell metallic foams are analyzed at the pore scale on a microtomographied sample from creeping flow to unsteady inertial flow. The influence of the anisotropy, obtained by shearing the initial sample, is also analyzed. The simulations show that the Darcy–Forchheimer law is valid at $Re_{dI} > 1$ and that the inertial coefficient tensor can be asymmetric as proved by Whitaker [1996. The Forchheimer equation: a theoretical development. Transp. Porous Media 25, 27–61] and checked by the lattice Boltzmann method. Despite this property, the eigen vectors are nearly orthogonal to each other and their orientation follows the shear angle. To evaluate the accuracy of the results, the analysis of the REV leads to a REV size lower than $2.5d_p$ for the velocity and is lower than $4.5d_p$ for the inertial flow permeability tensor. It is shown also that the CFD approach, validated by MRI investigation [Graf von den Schulenburg et al., 2007. Flow through an evolving porous media-compressed foam. J. Mater. Sci. 42 6541–6548], matches the 3D-Brinkman–Forchheimer model if the effective viscosity is close to two.

1. Introduction

Among other attractive properties, high porosity, low relative density, low pressure drop, high thermal conductivity of the ligaments make the metallic open-cell foams particularly efficient in heat and mass transfer, so that they are used in a wide area of applications such as catalytic reactors and heat exchangers. The mixing efficiency is increased in highly inertial flow regime and in turbulent one. These regimes can be reached easily owing to the high permeability. But despite this property, the pressure drop becomes significant.

In order to predict the pressure drop with the foam characteristic parameters, numerical and theoretical studies are performed at the pore scale by means of a cell modelling approach. The foam morphology is approximated to a periodic array of ligaments as cubic cell or 14-sided tetrakaidecahedron cell. The theoretical approaches (Du Plessis et al., 1994; Lacroix et al., 2007; Fourie and Du Plessis, 2002; Bhattacharya et al., 2002) lead to analytical or semi analytical expressions of the permeability, which show a good agreement with cited experimental data. More recently Boomsma et al. (2003) used the surface minimization program Surface Evolver (Weaire and Phelan, 1996) in order to mimic the DUOCEL production process. The periodic foam is composed of eight equal volume cells: six 14-sided polyhedra having 12 pentagonal and two hexagonal faces, and two pentagonal dodecahedra. The authors determined the creeping flow permeability (CFP) by computing the velocity field by computational fluid dynamics (CFD). A good agreement with experimental data within 25% was found.

In order to be more realistic, 3D tomographied image can be used. This time, the microscopic model is composed of several tenth pores. Petrasch et al. (2008) analyzed the CFP and the inertial coefficient of a 10-ppi reticulated porous ceramic from the Stokes flow regime to the unsteady flow regime. Assuming that the sample is homogeneous and isotropic, the authors used the 2-point correlation method of Berryman and Blair (1986) and a mathematical morphology operation to evaluate the specific surface and the pore diameter. Performing CFD computations with the commercial code CFX, the simulations predict the correlation of Kozeny Carman and the Ergun one within 15% and 12%, respectively.

In all the literature based on the cell modelling approach, the foam is assumed to be isotropic. But Laschet et al. (2008) studied the CFP tensor of an iron-based SlipReaction foam sample by the homogenization method. Assuming that the CFP tensor is symmetric, the authors computed the principal diagonal and one non-diagonal element only. Three unit cell models located at different places were used in their study. But the scatter of the permeability value shows that the sample size of 2.5 times the pore diameter is too small.

E-mail address: pmo@lobivia.cpe.fr

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The present work deals with the influence of the foam anisotropy on the inertial flow permeability (IFP) tensor. The term IFP is the extension of the permeability concept, defined in Stokes flow regime, to inertial flow. The IFP is used to establish a relationship between mean velocity and macroscopic pressure gradient whatever the Reynolds number.

Two phenomenological laws in a 3D extended formulation are studied and validated: the Darcy–Forchheimer (DF) law and the Brinkman–Forchheimer (BF) one. In this aim, the velocity field is computed in a NiCr (17–23) Recemat sample by solving the unsteady Navier–Stokes equation from the creeping flow regime to the unsteady inertial one. The reconstructed morphology has been obtained from 3D X-ray tomography. The foam being isotropic, the non-diagonal elements of the IFP tensor are not significant. An anisotropy is introduced by shearing the cell model. This foam has been characterised in detail by the Tadrist research group (Topin et al., 2006; Vicente et al., 2006) (morphology and permeability). Therefore, the 3D tomographied image is used here in order to perform CFD simulations on a realistic medium. The influence of the morphology of this foam on the hydrodynamic is not studied here.

In a first step, the simulations performed with periodic boundary conditions are analysed by means of the 3D-DF equations. The inverse IFP tensor of the two samples is assumed to be a combination of the inverse CFP tensor and the inertial coefficient one. The evolution of the eigen vectors and the eigen values vs. the Reynolds number (based on the ligament diameter) is also studied. In order to check the independence of the IFP tensor on the domain size, the evaluation of the size of the representative element volume is carried out.

The relevance of 3D-BF equations is checked in the case of a cylinder filled with a foam. This phenomenological law is all the more important that heat transfer between the container wall and the core of the foam is controlled by the hydrodynamic boundary layer located along the wall. In this model, an effective viscosity must replace the fluid one (Brinkman, 1947; Lungren, 1972). The main problem is to predict accurately the effective viscosity on which the width of the hydrodynamic boundary layer depends. Until now, experimental investigations lead to an effective viscosity depending on the Reynolds number (Givler and Altobelli, 1994; Bey and Eigenberger, 1997; Giese et al., 1998).

In this last part, the simulations are first validated with MRI investigation performed by Graf von den Schulenburg et al. (2007) in the case of the isotropic foam. Then the effective viscosity is estimated in order to match the 3D-BF model with the simulations performed with the isotropic and with the anisotropic foam.

2. Microscopic approach

2.1. Open cell metallic foam characteristics

The Recemat metallic foam studied here is the reinforced Nickel–Chrome NCX-1723 (17–23 ppi). The foam is first synthesized from an open-cell polyurethane foam. The foam is then metallized and finally is pyrolysed in order to remove the polyurethane. Tadrist research group has studied several Recemat foams. Vicente et al. (2006) analyzed first their morphology from microtomographied image. In the case of the NCX-1723, the porosity (ε) is 87.3%, and the specific surface, computed by the marching cube method, is 1658 m^{-1}. Using a 3D segmentation method, the cells were individualized and their shape was analysed. Owing to the foam manufacturing process, gravity makes the pores ellipsoidal. But, the analysis does not reveal a preferential pore orientation so that the foam remains isotropic. The sphere volume equivalent diameter (d_p) is 1841 μm. The extraction of the solid skeleton by means of a centreline extraction gives a ligament length (l_l) of 725 μm and

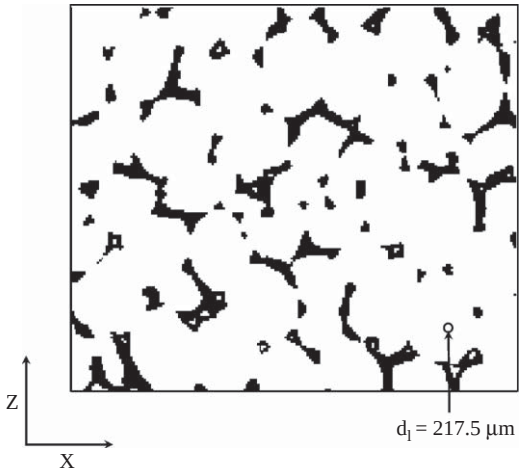

Fig. 1. 2D cut of the reinforced Nickel–Chrome NCX-1723 Recemat foam. Voxel size: 58.9 μm. The circle shows the ligament diameter (217.5 μm).

an equivalent diameter (d_l) of 217.5 μm. d_p is computed with the number of voxels included in the pore considered as a sphere. l_l is defined as the mean distance between the two intersections, ending a ligament, with other ligaments. Assuming that the ligaments are cylinders, d_l is determined from the total length of ligament and the porosity. Topin et al. (2006), measured the permeability of Recemat foams in the case of water, air and biphasic flow. The experimental investigations on Ni, NiCr and Cu foams over more than one order of magnitude of flow rate show that the pressure drop follows the 1D-DF phenomenological flow model:

$$-\frac{dP}{dz} = \frac{\eta}{A}U = \frac{\eta}{K}U + \beta\rho U^2 \tag{1}$$

where, P is the pressure, η is the dynamic viscosity, A is the IFP, K is the apparent-CFP, U is the mean superficial velocity, ρ is the density and β is the inertial coefficient. K is not the true-CFP $K(0)$ determined in creeping flow regime because K^{-1} is the intercept to the abscissa U of the inverse IFP. We will see below that in the intermediate flow regime, the phenomenological flow model (1) is not valid. The water apparent-CFP (K_{water}) of NCX-1723 is 2.32×10^{-8} m^2 and the water inertial coefficient β_{water} is 631 m^{-1}. However, the air flow data give a noticeable difference ($K_{air} = 2.81\times10^{-8}$ m^2 and $\beta_{air} = 490$ m^{-1}). This difference of flow properties is observed over all the analyzed samples.

2.2. Numerical method

The hydrodynamic properties of the NCX foam are studied by Direct Numerical Simulation at the pore scale. The dimensions of the tomographied sample are 1.008 cm, 1.167 and 1.167 cm in the Z, X and Y directions, respectively. The voxel dimension (δ) being 58.94 μm, the computational domain contains 171×198×198 (6 703 884) numerical ones. Therefore, the pore space resolution d_p/δ is 31. The sample contains about 220 pores ($(N_xN_yN_z) \times (\delta/d_p)^3 \sim 6^3$). Fig. 1 shows a 2D cut of the digitalized sample. The shape of the ligament is very different from the shape of a cylinder (represented by a circle). Therefore the foam cannot be compared to a bundle of disordered fibrous media. In the present work, d_l is a characteristic length which is used only by convention. Owing to the digitalization process the specific surface of the computational domain is higher by a factor of 1.53 than the one computed by Vicente et al. (2006).

In order to introduce an anisotropy, the sample is deformed by a shear in the X direction. This simple process allows to give a specified pore orientation controlled by the shear rate. Each layer normal to