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Morphology and transport properties of fibrous porous media

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ABSTRACT

The exploration of flow permeability of fibrous media is of great important significance in many industrial applications. Flow permeability strongly depends on the pore-scale structures. In order to explore the morphology of fibrous porous media and furthermore evaluate the transport properties, high-resolution X-ray tomography was employed to study the porous media in this paper. Morphology statistics data of porosity, specific surface area, tortuosity, and pore diameter were obtained. The size of representative volume element (RVE) determined according to geometry statistical deviation was consistent with that estimated with Brickman screening length criterion. The lattice Boltzmann simulation was then performed based on RVE to explore macroscopic transport properties. The transverse flow permeability obtained with Darcy's law at the steady state was consistent with the results in analytical models of layered fiber arrangement. Moreover, the impacts of the size and spatial resolution of simulation domain on the numerical results were discussed. Finally, the linear relationship between permeability and square pore diameter was quantitatively evaluated.

1. Introduction

Porous metal fiber sintered sheet (PMFSS), as a new porous media, has been extensively studied. PMFSS exhibits remarkable properties, such as high porosity, high specific surface area, and excellent mechanical strength. Its relevant transport properties are determined by the architecture of the solid and pore phases, which can be controlled and optimized by altering manufacture parameters. Therefore, it is important to study the microstructure and transport properties of porous media for improving their performances in industrial applications including filtration process, separation treatment, and fuel cells [1–3]. Especially, the flow laws through such media draw wide attention. In the exploration of creeping flow in microstructure at pore-scale level, the most common exploration method is numerical simulation. The most common simulation methods for flow property include finite volume method (FVM) [4–6] and lattice Boltzmann method (LBM) [7,8]. The latter is accurate and efficient in solving the flow in the materials with complex geometries [9], such as porous media.

Flow passing through porous media at very low flow rate is governed by Darcy's law:

$$-\frac{dP}{dz}=\frac{\mu}{k}u, \qquad (1)$$

where k is the permeability; dP/dz is the pressure gradient along the main flow direction; u is superficial velocity, which means the fluid velocity averaged over the cross-section area; and μ is the flow viscosity. Permeability largely depends on the material's geometry. With lattice Boltzmann method, Clague et al. [10] explored the Darcy permeability of fibrous media with ordered and disordered fiber arrangements both in 2D and 3D and discussed the effect of simulation domain size of bounded fibrous media on the calculated permeability. Nabovati et al. [11] reconstructed fibrous media with straight cylinders of random arrangement and calculated the permeability of virtual media with the porosities ranging from 0.08 to 0.99. The impacts of the curvature and aspect ratio of fibers on the permeability were discussed as well. These studies revealed the coupling between microstructures and macroscopic transportation properties to some extent. However, such results were derived from artificial models without verification through the structures of actual materials.

X-ray tomography has been widely applied in material science, especially in non-destructive characterization of porous materials, including granular materials [12], metal foams [13], and fiber materials [14]. X-ray tomography can provide 3D images with the submicron spatial resolution. Combined with lattice Boltzmann method, X-ray tomography can be used to study the transport property. Koivu et al. [15] studied the permeability of plastic felt and hand-sheet paper, compared simulation results (by lattice Boltzmann method and finite difference method) with experimental results, and discussed the impact of grid density on the simulation results. Degrutyer et al. [16,17] investigated the permeability of different pumices with the 3D images with high spatial

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resolution obtained through X-ray microtomography and discussed the simulation results in view of geometrical and topological characteristics of the pore space, such as porosity, tortuosity, and specific surface area. Rama et al. [18] described the combination of full morphological reconstruction of fuel cell structures with X-ray computed tomography and lattice Boltzmann modeling in the simulation of fluid flow at the pore-scale. Moreover, Soltani et al. [19] and Pradhan et al. [20] discussed the effect of 3D fiber orientation on the permeability of fibrous porous media.

Most of the reported results highlighted the microstructural characteristics of solid phase (fiber part), and especially fiber orientation. However, the quantitative evaluation of the void phase, which affected the flow through porous media more directly, was seldom reported. Moreover, most studies focused on single specific aspect, such as modeling size, resolution, microstructural characteristics, and its impact on transport property. There lacks a systematic investigation involving all these matters. In this paper, we combined X-ray tomography with lattice Boltzmann method to study the morphology and transport properties of PMFSS. 3D tomographic images of PMFSS with different porosities were obtained. Then, based on the obtained images, morphological explorations of solid and pore phases were performed. The size of representative volume element determined through geometry criterion was also discussed. The values of transverse permeability obtained through LBM were compared with analytical results. Moreover, the impacts of the size and spatial resolution of simulation domain on the numerical results were discussed. Finally, the permeability results were analyzed and the geometrical characteristics of the pore space were preliminarily quantified.

2. Materials and methods

2.1. Manufacturing processes of PMFSS

The manufacturing processes of PMFSS [21] were mainly divided in two stages: the generation of single fibers and the fabrication of fiber sheet. Firstly, copper fibers were cut away from the bar stock with a multi-tooth tool, and came out along the parallel micro-channels continuously [22]. Then, these fibers with the average diameter of 100 μm were cut into fixed lengths ranging from 10 mm to 20 mm. To generate fiber network, fibers were randomly loaded into packing chamber of the mold pressing equipment and then sintered at 700–900 °C for 30–60 min in the box-type furnace (RXL-12-11). After the sintering process, the sample was removed from the furnace and then cooled to the room temperature. The optical photographs of PMFSS samples with different porosities and the SEM photos of the sample with the porosity of 80% are shown in Fig. 1. The porosity of PMFSS can be calculated with the previous method by Tang et al. [21]:

$$E(\%) = \left(1 - \frac{M_p}{\rho_c V_p}\right) \times 100, \tag{2}$$

where V_p is the volume of PMFSS; M_p is the mass of PMFSS; ρ_c is the density of red copper.

2.2. X-ray tomography and morphological analysis of PMFSS

2.2.1. X-ray tomography

A micro-CT device (HARRIER HP23.4JX, Metris UK Systems LTD) was employed to generate the 3D images of PMFSS. The X-ray was generated at 102 keV to form a beam current of 33 μA. To study the influence of the microstructure on transport properties, PMFSS samples with different porosities (75%, 80%, and 90%) were prepared under the same sintering conditions (800 °C, 30 min) and then scanned. At last, a set of reconstructed 3D cross section images was obtained. The pixels (voxels in 3D) of the reconstructed cross section images in *xy*-plane (material plane) stacked at the ascending height in the thickness direction (*z*-axis) make up a cubic lattice. The voxel size (9.4 μm per voxel) was recorded so that the physical size could be identified. 3D images were then cut into region of interest (ROI) and processed through anisotropic diffusion smoothing to sharpen the edges in the convolved images [23]. The 3D geometry reconstruction was then achieved with the classical "Marching cubes" algorithm [24]. Visualization of the reconstructed geometry was shown in Fig. 2(a). With the amplified virtual view, it can be clearly observed that during the sintering process, the sintering joints among fibers were easily formed due to material migration under the setting temperature. As a result, fiber's metallurgy union happened. These sintering joints divided fibers into fiber segments with various lengths and bendings, which were consequently shaped into a complex 3D fiber network with certain mechanical strength. At the same time, interconnected pores were formed in the void phase in the network. Then the 3D image was processed by binarization segmentation to divide the voxels into the void phase (pore portion) and the solid phase (fiber portion), respectively. Through gradually changing the binarization threshold, the porosity calculated according to the obtained 3D digital image might be consistent with the porosity of the actual material estimated with Eq. (2). Then, the 3D binary image was used to perform skeletonization for further morphological explorations.

2.2.2. Morphological analysis of fibrous network

Skeleton, as a kind of simple structure representation extracted from the 3D binary image, can preserve the topological characteristics of the original object and facilitate further morphological explorations. According to the tubular structure of fibers, the skeleton extraction algorithm was implemented with the thinning method based on the distance transform method and improved by introducing the scale axis transform method [23]. The skeleton was then filtered according the following loop strategy. Firstly, the skeleton network was divided according to sintered points to generate skeleton segments. Then, tiny segments with the length below certain threshold were removed. The threshold was chosen according to the rule that meaningful branches were preserved while artificial branches caused by image noise were removed. Practically, the threshold was set to be equal to the mean fiber

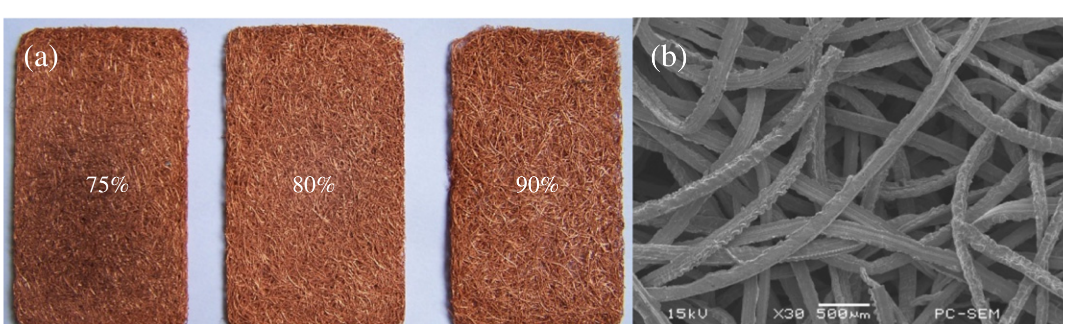

Fig. 1. (a) Optical photographs of PMFSSs with the porosities of 75%, 80%, and 90% sintered at 800 °C for 30 min, and (b) SEM picture of PMFSS with the porosity of 80%.