Quantitative analysis on fluid permeation and pore structure in tortuous fibrous layer using particle model

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Abstract Fluid permeation in fibrous layer plays an important role in various engineering processes. In this study, we examined the influence of pore structure in fibrous layer on fluid permeability. We suggest a particle model in which a fiber is expressed by a line of particles and the random arrangement of multiple lines indicates the fibrous layer. In order to obtain the tortuous fibers, the particle line was bent at arbitrary angle. Under low-Reynolds-number condition, the permeability for various fiber bend angles was calculated by Stokesian dynamics approach. The results indicate that the permeability of the sharply-bend fibers was significantly lower than the slowly-bend fibers. We employed the Voronoi tessellation for the pore structure analysis. The effective flow path in the fibrous layer was modeled by the assembly of the frustums which are obtained from Voronoi vertices and edges. Then, the hydraulic radius was estimated from the effective flow path. The fluid permeability in the complicated tortuous fibrous layer would be evaluated by the hydraulic radius calculated from the effective flow path.

Keywords: Fluid permeability, Stokes flow, Pore structure, Voronoi tessellation

1 Introduction

Fibrous layer has a great advantage in efficiency of heat, mass transfer and chemical reaction, and it is used for various engineering processes such as heat exchange, filtration and catalysis. The wide use of fibrous layer is attributed to large surface area and high permeability which are resulted from the complicated fiber structure with high porosity. Therefore, the effect of fiber shapes on the fluid permeability in the layer has attracted an extensive attention for a long time. In previous researches, experimental and theoretical approaches have been established to observe the fiber structure on micro- and nano-scales and to obtain the permeability of fibrous media [1]. However, the fundamental understanding of the relation between the tortuous fiber shape and the permeability remains required. In the present study, the particle model is suggested to represent tortuous fibers. The theoretical calculation of fluid permeability and the analysis of pore structure has been performed. The effect of pore size and network formed in the fibrous layer on the fluid permeability is investigated.

2 Methods

We defined a particle model to represent tortuous fibrous layers. A fiber is expressed by a line of particles [2]. The fiber length is decided by the number of particles. A fibrous layer consists of random and uniform arrangement of the multiple particle lines. The orientation of each fiber is also given randomly. Various tortuous fibers are modeled by bending the particle lines. The angle and interval of the bend represent the characteristics of fiber tortuosity. In the present paper, the number of particles which compose a fiber is 12. For tortuous fibrous layers, the particle line bends at intervals of three particles. The bend angle is set from 0° to 90°. The volume fraction of the fibrous layer is set to be 0.10.

According to the Darcy’s law, fluid permeability in a laminar flow through particulate bed depends on the fluid velocity and the pressure gradient which is attributed to the force exerted by particles on fluid. In order to obtain the relation between the velocity and the force, the Stokesian dynamics approach [3] was employed on the assumption of low Reynolds number. The relative motion of particles and fluid is derived theoretically so that the hydrodynamic interaction among many particles in a viscous fluid is considered. By application of the multipole expansion to the solution of the Stokes equation and the equation of continuity, the velocity and the force are related by the mobility matrix that is determined from positional relationship among all particles. The three-dimensional periodic boundary condition was adopted to the mobility matrix.

For quantitative analysis of pore structure, the Voronoi tessellation [4] was applied to the particle model. We set the centers of fiber particles as “seeds” and calculated the Voronoi vertices and edges that mark the boundary equidistant from neighboring seeds. This boundary can be considered the flow path and therefore
the Voronoi vertices and edges represent pore nodes and links, respectively.

3 Results and Discussion

For the fibrous layers with various bend angle at the same volume fraction, the results suggest that the permeability is smaller as the fiber bends more largely. Particularly, the permeability is more affected by the bend angle in the case of slightly-bending fibers (small bend angle), while there does not seem to be significant difference in permeability in the case of bend angles close to 90°. It is found that the fiber bend decreases the permeability by up to 53 percent. The same tendency is observed regardless of the fiber positions and orientations which are decided randomly, and also observed under the different volume fractions.

The geometrical characteristics of the pore networks were evaluated by application of the Voronoi tessellation to the fiber layer. We obtained the position of the pore nodes and their links throughout the computational domain. Firstly, we investigated the orientation of the obtained pore networks by calculating the orientation tensors of pore links. The results indicate that the orientation of the pore networks is roughly isotropic as the fiber arrangement is originally set to be isotropic. There is no significant difference depending on the fiber shape. Secondly, we calculated the pore size at each pore node. It was found that the layer composed of linear fibers tends to have more pores of larger size. It is inferred that fiber bend divides the pore space and reduces the number of the large pores. This could be one of the reasons that the permeability decreases with fiber tortuosity.

The Voronoi tessellation was also employed for quantitative evaluation of the pore-network. The flow path was modeled by the assembly of frustums which are composed of two bases (pore cross-sections at two neighboring nodes) and a height (length of their link). Considering Stokes flow, we assume that the assembly of the frustums could be an effective flow path since the fluid is hard to flow in narrow spaces close to the fiber particles. We estimated the hydraulic radius of the fiber layers from the volume and the area of side face of all frustums which correspond to effective pore volume and wetted perimeter area. The results indicate the slight dependence of the hydraulic radius on fiber shape. The hydraulic radius appears to be similar values in the fiber layers with small bend angle (0° and 27°). On the other hand, the layer in which fibers are bent at a 90° shows a tendency for the hydraulic radius smaller than that of the linear layers. From these results, the permeability and the hydraulic radius have a roughly positive correlation. Consequently, the fluid permeability and the pore structure in complicated tortuous fibrous layer could be described by the hydraulic radius calculated on the basis of the assembly of the frustums.

4 Conclusion

We have performed the theoretical calculation of the fluid permeability and the geometrical analysis of the pore structure in tortuous fibrous layer based on a particle model. The fluid permeability is associated with the pore structure determined by the fiber tortuosity. The frequency of larger pore appearance is dependent on the fiber shape. The results suggested that the tortuous fibrous layer hampers the flow more, and therefore it reduces the fluid permeability. We adopted Voronoi tessellation for the pore structure analysis, and obtained effective flow path as the assembly of the frustums. It was found that the fluid permeability in the complicated tortuous fibrous layer would be evaluated by the hydraulic radius calculated from the effective flow path.

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References