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学位授与の日付　　2022 年 3 月 31 日

論　　文　　名

「Development and Application of a Numerical Method for Two-Way Fluid-Structure Interactions of Flow-Induced Deformable Fibrous Porous Media」

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論文要旨

Chapter 1 summaries the background, the literature survey, the research aims and the outline of this thesis. Owing to the filtration efficiency, easy handling and relatively lower production costs, nonwoven fabrics have been widely utilized in filtration processes of numerous industrial applications such as car exhaust systems and face masks. During the nonwoven fabric filtration process, each fiber is subjected to fluid forces and deforms with fiber-fiber collision/contact behaviors. This results in changing the nonwoven fabric geometry and the overall permeability, which are significantly important to the filtration performance. Hence, to design filtration products and to improve the filtration efficiency, understanding the flow-induced deformation effects under actual filtration environments on the critical parameters of the filtration, i.e. porosity, permeability and compression ratios, have been one of the essential research topics. Although various computational methods have been developed to handle such strong interactions between the deformations of numerous flexible fibers and the fluid flow profiles, their applications are still limited to a simplified problem such as configurations for handling only a small number of fibers, 2D configurations and no fiber-fiber collision/contact conditions. Therefore, the main research aims of the present work are developing a stable and efficient direct numerical scheme capable of calculating the flow-induced deformation of fibrous porous media and understanding the physics of the filtration performance of nonwoven fabrics.

Chapter 2 introduces the numerical method of the fluid solver. In this work, the lattice Boltzmann method (LBM) is employed to calculate the fluid flows through fibrous porous media. Compared with conventional continuum-based computational fluid dynamics (CFD) approaches, the LBM has the following advantages: simple fluid/structure representation of

lattice nodes by binarized on/off treatments, accurate representation of the complex geometries and easy acceleration using graphics processing units (GPU) due to its discrete nature and locality of the computational algorithm. These features allow the LBM to be employed in simulations of the two-way fluid-structure interaction (twFSI) problems containing a complex geometry such as densely distributed flexible fibers and collision/contact behaviors of multiple fibers.

Chapter 3 introduces the numerical method of the structure solver. In this work, the Cosserat rod model (CRM) is employed to calculate the motions of flexible fibers. Other structure solvers such as the discrete element method (DEM) and the finite element method (FEM) require enormous computational costs to accurately calculate large and complex deformations of a long and slender structure, due to the need of finer meshes to sufficiently resolve the diameter of the fiber. This results in the major problem especially when simulating a large number of fiber structures simultaneously. The CRM introduces model reduction techniques to approximate three-dimensional (3D) physical motions of the slender structures by one-dimensional (1D) mathematical models without losing physical accuracy. Moreover, the CRM can capture all four principal deformation modes of the fiber motion, i.e. bending, twisting, shearing and stretching, under a wide range of boundary conditions. These features of high accuracy and low computational costs allow the CRM to be employed as the structure solver of the twFSI scheme to calculate the complex deformations of a large number of flexible fibers.

Chapter 4 develops a twFSI coupling scheme as the temporal and spatial coupling scheme of the structure motions and the surrounding fluid flows. For the temporal coupling, the partitioned algorithm utilizing individual solvers for fluids and structures with the explicit coupling scheme for data communication is employed owing to the simplicity and efficiency of the algorithm. With this approach, the fluid and the structure solvers are solved once within each time step and the subsequent data communication to exchange coupling quantities. The collision detection algorithm utilizing the binary tree data structure and the bounding volume hierarchy (BVH) is combined in the coupling scheme to significantly reduce the computing time of data communication. For the spatial coupling, combination of a spatially uniform Eulerian grid to solve the fluid flow and a Lagrangian expression to solve the structure motions is employed. This approach has advantages of a simple algorithm, no grid regeneration for the fluid solver independent of complex geometries or large deformations of the fluid-structure interfaces and high efficiency of the fluid solver owing to the regular grid. To represent the fluid-structure interface with spatially uniform grids, the level set method with the fluid-structure boundary reconstruction (fsBR) scheme is employed. This technique reconstructs the original smooth fiber shape from a zig-zag Eulerian grid configuration by the level set functions indicating the normal distances from the interface between two phases. Thus, the common fluid-structure interface can be defined between the fluid and structure solvers. The constrained-based collision model is employed to take into account simultaneous collision/contact behaviors of a large number of fibers.

Chapter 5 discusses the individual verification and validation (V & V) of the fluid and the structure solvers. The V & V cases presented in this chapter cover the scope of applications focused on in this thesis, namely the effect of the flow-induced deformation of fibrous porous media on the filtration efficiency. For the V & V of the fluid solver, the LBM is verified and validated by computing the permeability of the well-known geometries of cylinder arrays and nonwoven fabrics produced by the industrial hydroentanglement process. The first benchmark confirms that the lattice resolution of six in the cylinder diameter at low Reynolds numbers is good enough to calculate the permeability. Utilizing the above knowledge, the second benchmark validates the applicability of the LBM to calculate the flow permeation through fibrous porous media. The LBM though predicts the permeability trend of six types of nonwoven fabrics in good accuracy, this method underestimates the overall permeability compared with the experimental results. During the flow permeation experiment, the fibers are oriented to the flow direction due to the hydrodynamic forces generated by the fluid flows through nonwoven fabric samples, resulting in the relatively high-permeable fiber geometry compared with the initial one before the measurement. Thus, the direct numerical method is relatively reliable to predict the flow permeation physics of nonwoven fabrics by handling the realistic fiber structures while the effect of the flow-induced deformations and orientations of the fibers is required to be considered. For the V & V of the structure solver, the deformation of the Timoshenko cantilever beam (TCB) is compared between the CRM and the analytical solution of the TCB theory. The results show good agreement and that the CRM well represents the complex rod physics of bending elasticity, rotary inertia and shear deformations.

Chapter 6 presents the validation of the developed numerical twFSI scheme (LBM-CRM-twFSI scheme) for three wind tunnel experimental benchmark tests. The first benchmark confirms that the present scheme accurately calculates the equilibrium state of the fiber exposed to uniform airflows at the Reynolds numbers of 29.1 and 55.6. In the second benchmark, the time-dependent oscillatory motions of the filament and the fluid velocity fluctuation at the downstream of the filament at the Reynolds number of 673 are reasonably captured by the present scheme. The third benchmark validates the flow-induced collision/contact behaviors of the flexible fiber and the rigid filament. To provide the reference data, flow-induced deformations of a single flexible fiber and collision/contact behaviors of multiple filaments in a wind tunnel are experimentally measured in this study. The results show that the collision/contact behaviors of the maximum bending and the equilibrium contact states between the simulations and the experiments are in good agreement. These validations confirm the practicability of the LBM-CRM-twFSI scheme for calculating the flow-induced motions of a single and multiple fibers with collision/contact behavior.

Chapter 7 discusses to investigate the effect of the flow-induced deformation of nonwoven fabric face masks on the filtration performance by utilizing the LBM-CRM-twFSI scheme. Especially under the worldwide COVID-19 pandemic environment, investigating the filtration performance of face masks has recently been of great importance for the general public health as well as the research topics. The surrogate nonwoven fabric model is employed to obtain fiber structures of spunbonded lay-down nonwoven fabrics often utilized in the outer and inner layers of face masks. The fluid flows mimicking coughing through the fiber structures are calculated to obtain the porosity-permeability relationship. The results show that the permeability tends to be overestimated without considering the effect of the flow-induced deformation, and the maximum prediction difference of the permeability is 20.7%. The prediction difference is due to the dynamic change in the fiber orientations along the flow direction from the initial state, induced by the flow permeation. The LBM-CRM-twFSI scheme proposed in this study can take into account the dynamic flow-induced deformations of the fiber structures, and thus is practically useful for fundamental evaluation and designing the nonwoven fabric filtration product.

Chapter 8 summarizes the concluding remarks and the suggestions for the future work.

審査結果の要旨

本論文は繊維多孔体の流動誘起変形を対象とした，流動と柔構造の動的双方向連成解析手法の開発と，開発した手法を用いた不織布の動的性能評価を目的とした研究成果をまとめたものであり，以下の成果を得ている．

(4) 流動解析に格子ボルツマン法，繊維構造の解析にコセラット・ロッドモデルを用いる，新たな連成解析手法を開発した．そこでは，流動から構造，および構造変化から流動への双方向の影響が動的に考慮されるように構成されている．
(5) 流動と単繊維の挙動に関する文献データに基づいたベンチマークテストを行い，開発した流体－構造双方向連成解析手法の正確性を確認した．さらに，多数繊維の相互干渉モデルに関し，気流中の繊維同士の干渉運動に関する実験を行い，解析結果を評価することにより，開発した手法の妥当性を実証した．
(6) 開発した解析手法を用いて，繊維の流動誘起変形により，マスク用不織布のフィルター性能がどのように変化するかを解明した．そして 95%以上の空隙率の場合，人が咳をする条件では，フィルター性能が最大20%低下するが，繊維密度が高くなり，不織布の空隙率が 83%を下回る条件では，咳をするしないにかかわらず，性能に変化が起きないことを明らかにした．

以上の成果は，流動と繊維構造の動的双方向連成解析手法を確立したばかりではなく，不織布の設計指針に寄与できるものであり，その機械工学に対する貢献度を高く評価できる．さらに，これら成果は明確に目的達成に直結しており，申請者が自立して研究計画を立て，研究を遂行するに十分な能力と学識を有することを証している．学位論文審査委員会は，本論文の審査および最終試験の結果から，以上のことを確認したので博士（工学）の学位を授与することを適当と認める．