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論　　文　　名	「Large Eddy Simulation and Turbulence Modelling of Porous Medium Flows」
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論文要旨

Chapter 1 summarises the introduction, the literature survey and the outline of this thesis. Due to the interconnected voids and large area/volume ratios, porous media have significantly large heat and mass transfer rates. Porous materials are thus often applied to industrially important devices such as catalytic converters and metal foam heat exchangers. Moreover, porous medium flows are also seen in environmental fields such as in vegetated or urban canopy flows. Hence, understanding and modelling those flows around and inside porous media have been important engineering issues. Therefore, the main objectives of this thesis are understanding and modelling of porous medium turbulent flows.

Chapter 2 introduces the mathematical formulation of fluid flows. This chapter derived the Reynolds and volume (double) averaged turbulence equations which are the governing equations of the macroscopic turbulence model for porous medium flows. The macroscopic model doesn't treat the porous structure directly but solves volume averaged flows in porous media. Hence, due to the low computational costs, it is very promising for engineering applications and this thesis attempts to develop it. However, the double averaged Navier-Stokes equation produces unknown second moments which are the macro- and micro- scale Reynolds stresses and the dispersive covariance. To model those second moments, it is essential to consider the transport equations of those moments. However, those transport equations include many further unknown correlations and thus understanding the turbulent transports are not straightforward. To understand them, although the computational costs are not low, the pore-scale numerical simulations which faithfully treat the porous structures are considered. Due to the simplicity of the wall treatments and the high computer efficiency, the lattice Boltzmann method (LBM) is considered for pore scale simulations. Although the LBM has been widely used for flow or scalar field simulations, the shortcomings which should be particularly noticed in turbulent flow simulations have been reported. They are insufficient isotropy and numerical stability for high Reynolds number flows.

Chapter 3 discusses the LBM to overcome those shortcomings. To understand the reason of insufficient isotropy, the truncation error analysis is firstly carried out. Although there are several discretizing models such as D3Q15, D3Q19 and D3Q27 for the LBM, for turbulent flow simulations with curvature or circular boundaries, it is confirmed that the D3Q27 model is preferable. It is because the D3Q15 and D3Q19 models produce false forces originated from the error terms including the Reynolds stresses and they cause unphysical spurious currents. The spurious currents of D3Q27 are sufficiently weak since the magnitudes of the error terms are less than two percent of those by the D3Q15 and D3Q19 models. Thus the D3Q27 discrete velocity model is chosen for turbulent flow simulations. Then, to ensure the numerical stability in high Reynolds number flow simulations by D3Q27 model, multiple-relaxation-time (MRT) lattice Boltzmann equation for the D3Q27 model is evaluated through the applications to the turbulent pipe and channel flows and complex porous medium flows. It is confirmed that the D3Q27 MRT LBM can overcome above mentioned shortcomings and the prediction performance is sufficiently reliable.

Chapter 4 performs high resolution large eddy simulations of homogeneous porous medium flows by using the scheme (D3Q27 MRT LBM) evaluated in Chapter 3. The porous structures considered in this thesis are square rod arrays, staggered cube arrays, fractal cube arrays and body centered cube foam. Using the simulation results, the budget term analysis of the transport equations of the second moments is performed. It is found that the micro-scale Reynolds stress and the dispersive covariance are mainly generated inside the porous media and the turbulent anisotropy and the magnitudes of the second moments are strongly influenced by the porous structures. It is also found that the dispersive covariance is produced by the drag force term and it is transferred to the micro-scale Reynolds stress by the mean dispersive shear production. The correlations between turbulent quantities and characteristic parameters are also investigated and it is revealed that the micro-scale turbulent kinetic energy and the dispersive kinetic energy show reasonable correlations to the Forchheimer coefficient and the hydraulic tortuosity, respectively.

Chapter 5 discusses the macroscopic turbulence model for flow and thermal fields by utilizing the knowledge obtained in Chapter 4. For flow fields, although most of the models in the literature handled the second moments altogether using a single turbulent scale so far, the discussions in Chapters 2 and 3 reveal that the production and dissipation processes of those second moments are totally different. In homogeneous porous medium flows, the micro-scale Reynolds stress and the dispersive covariant are dominant, whereas the macro-scale turbulence is also expected to appear at the interface turbulence between the porous medium and the outer region. Hence it is readily recognized that the individual treatment of multi-scale turbulence is definitely essential for inhomogeneous turbulence in the interface region. Therefore, the individual modelling of those second moments is considered in Chapter 4. The presently considered model chooses to solve the total (macro and micro) Reynolds stress, the micro-scale Reynolds stress and the dispersive covariance. The two-component-limit pressure-strain correlation model is applied to model the total Reynolds stress equation along with the newly devised redistribution terms for the dispersion related production, whilst for the micro-scale turbulence the two-equation model is employed with an anisotropy correction to the eddy viscosity assuming the similarity to the total turbulence. The dispersive covariance is algebraically modelled by the decomposition into dynamic and structural parts using the Forchheimer tensor which is also decomposed into molecular and turbulence parts. To validate the developed model, it is applied to the fully developed porous medium flows, the porous channel flows and the aquatic vegetation canopy flows and the predicted results are compared with the experimental and numerical data. It is confirmed that the developed model can successfully predict the interface turbulence between the porous and clear regions and it can also reproduce the stress anisotropy inside the porous media. For thermal fields, the double averaged energy equations of solid and fluid phases are considered, which include the unknown correlations as well as the equations for flow fields. The volume averaged turbulent heat flux is modelled by the tensorial gradient diffusion model and the wall heat transfer is modelled by the analogy to the modelling strategy of the viscous drag term along with the flow fields. The evaluation of the present thermal model in the fully developed turbulent heat transfer flows inside square rod arrays confirms that the present thermal method is very promising in both in the conjugate and isothermal wall heat transfer conditions.

Chapter 6 develops a more industry-friendly macroscopic eddy viscosity turbulence model based on the model developed in Chapter 5 since the eddy viscosity model (EVM) is usually used in engineering applications. Both the total and micro- scale Reynolds stresses are modelled by the EVM. The developed model is applied to the porous rib-mounted channel flows which include the separation and reattachment flows. The results are compared with the experiments and it is confirmed that the overall agreement between the present predictions and the experiments is satisfactory, though the present model still inherits some shortcomings from the original two-equation eddy viscosity model.

Chapter 7 summarizes concluding remarks and the suggestions for the future work.

審査結果の要旨

本論文は多孔体の内部や周囲を流れる乱流現象の理解とその数学モデルの構築に関しての研究成果をまとめたものであり，以下の成果を得ている．

(1)　多孔体のような複雑な形状を有する物体周囲の乱流の詳細な 3 次元数値解析には，3 次元 27 方向速度モデルの多緩和時間格子ボルツマン法（D3Q27 MRT-LBM）が適切であることを理論的な誤差解析および既存のスペクトル法による数値解析結果と比較することで明らかにした．
(2)　D3Q27 MRT-LBM を用いた高解像度ラージ・エディ・シミュレーション(LES)によって多孔体内乱流物理の統計的性質を明らかにした．そこでは，多孔体の構造によって，時間・空間の二重平均輸送方程式に現れる乱流応力項と分散相関項がそれぞれ独立した挙動を示し，それらの大きさも同程度であることを始めて明らかにしている．
(3)　上記 LES から得られた知見とデータベースを駆使し，二重平均流動場での乱流の数学モデルを構築した．そこでは分散相関項は代数的モデルにより解くが，乱流応力は総応力とマイクロ・スケール応力に分割し，それぞれに関連したモデル化輸送方程式を解くことを行っている．総応力にはレイノルズ応力方程式を解くレイノルズ応力方程式モデルを，マイクロ・スケール応力には k-ε 渦粘性モデルを基礎にそれぞれモデリングを行い，文献中の実験データや数値解析結果と比較することでその有用性を示している．
(4)　以上のようにして構築された乱流の数学モデルを使い，多孔体内乱流温度場を正確に解析する熱輸送モデルや，より簡便に応用可能となるよう，総応力に関しても k-ε 渦粘性モデルを適用するマルチ・スケール k-ε 4 方程式モデルも構築するなど工学的な応用範囲を広げている．

以上の成果は，乱流の数値解析や，多孔体内流体物理の理解を広げたばかりではなく，多孔体を流路に含む流れ場の工学的数値解析の精度や応用範囲を広げており，その機械工学や環境工学に対する貢献度を高く評価できる．さらに，これら成果は有機的に関連しており，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．