

MULTISCALE FLUID MECHANICS AND MODELING

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Multiscale phenomena are ubiquitous in fluid mechanics systems, which naturally emerge from the complex interaction among various scales due to the nature of the nonlinearity of fluid dynamics. Simulating or modeling multiscale fluid mechanics is difficult since it requires large computational resources. In recent years, there has been a tremendous growth of activity on multiscale modeling and computation. In particular, the multiscale hybrid numerical methods are those that combine multiple models defined at fundamentally different length and time scales within the same overall spatial and temporal domain.

Finding physically consistent solutions in hybrid numerical methods is crucial for various modeling and simulations of fluid mechanics. A framework for continuum and molecular dynamics multiscale hybrid method has been recently developed to simulate micro- and nano-fluid flows. In this approach, the continuum Navier-Stokes equation or the mesoscopic lattice Boltzmann method is used in one flow region and atomistic molecular dynamics in another. The spatial coupling between two methods is achieved through the constrained variation in an overlap region. The hybrid methods have been successfully used to study various fluid problems, including micro-nano fluid flows and heat transfer, singularity problems in the driven cavity, moving contact lines and electrowetting and other electrokinetics phenomena. All of those problems are difficult to tackle using traditional numerical modeling.

The similar idea of constrained variation has also been used in developing multiscale fluid turbulent models for constrained dynamic subgrid-scale stress model, Reynolds stress constrained large eddy simulation (RSC-LES) for wall-bounded turbulent flows with massive separation and heat flux constrained large eddy simulation. Using physical constraints on reduced set turbulent systems was first proposed by Kraichnan in the constrained decimation theory (Kraichnan 1985). In his approach, the effect of residual scales (subgrid scales) on the retained scales (large scales) is modeled by a stochastic forcing. To correctly calculate the mean energy flux or intermittency, the forcing term is constrained to satisfy certain constraint equations deduced from underlying physics, such as symmetry and conservation. In principle, the large eddy simulation method is equivalent to a physical space decimation method.

In the constrained dynamic subgrid-scale stress, we impose physical constraints in the dynamic procedure of calculating the SGS coefficients. The comparison between the large eddy simulation results in steady and decay isotropic turbulence using constrained and non-constrained SGS models and those from direct numerical simulation (DNS) will be presented. For RSC-LES, our model is able to solve the traditional log-layer mismatch problem in RANS/LES approaches and can predict mean velocity, turbulent stress and skin friction coefficients more accurate than pure dynamic large eddy models and traditional detached eddy simulation using the same grid resolution for turbulent channel flow, flow past a circular cylinder,

flow over periodic hills and other canonical flow systems. The application of the current model for simulating aerodynamics will also be discussed. Our results demonstrate the capability of multiscale simulation methods for complex fluid systems and the necessity of physical constraints on the multiscale methods.

Keywords: Multiscale fluid mechanics; Multiscale hybrid method; Constrained variation; micro-nano fluid flow; turbulence modeling;