Augmentation of Partially-Averaged Navier Stokes Method using Non-Linear Eddy Viscosity Closure

In recent years partially-averaged Navier-Stokes (PANS) method has emerged as a viable bridging method of turbulence. PANS is a filtering based, scale-resolving bridging method. The PANS method has been successfully evaluated in a variety of both canonical and practical flows of interest. Conventional PANS method employs linear eddy viscosity based closure for unclosed turbulent stress terms. PANS based on linear closure (linear PANS) overcomes the scale-resolving inadequacies of the Reynolds-averaging, but still suffers from the limitations arising from linear constitutive modeling of turbulent stresses. In linear models, unclosed turbulent stresses are modeled as a linear function of the mean strain-rate tensor. Experimental and computational works report that linear constitutive modeling is insufficient to capture essential flow physics in a variety of turbulent separated flows. In non-linear eddy viscosity models, unclosed turbulent stresses are related to the higher-order terms involving mean strain-rate and mean rotation-rate tensors as well, besides the linear terms. The non-linear models are reported to perform better than the linear models in case of Reynolds-averaged Navier Stokes (RANS) simulations of many complex turbulent flows.

In our attempt to enhance the performance of the PANS model for separated turbulent flows, the specific tasks taken up in this thesis can be listed as:

1. Extraction of non-linear eddy viscosity based PANS closure.

2. Sensitization of thermal flux terms using non-linear stresses.

3. Ordinary differential equation (ODE) based analysis of the non-linear PANS model in the absence of the transport terms.

4. Implementation of PANS methodology in computational fluid dynamics (CFD) solver packages like ANSYS FLUENT® and OpenFOAM®.

5. Comparative evaluation of the linear PANS vs. non-linear PANS in canonical flow test cases.

Among various higher-order models available, in this work, we choose the non-linear model proposed by Shih *et al.* (1993). Shih's non-linear model uses the standard k-ϵ RANS model and a non-linear algebraic equation for unclosed Reynolds stress tensor. We have extracted non-linear PANS based on Shih's non-linear closure using the definition of the filter parameters and underlying PANS assumptions. Besides modeling the turbulent stresses, we have proposed a novel

non-linear sensitization of the thermal flux to account for the effect of non-linearity in temperature equation as well.

An ODE-based analysis of the extracted non-linear PANS model is performed to examine the production-dissipation dynamics in the absence of transport processes. This analysis involved an extensive examination of the influence of PANS filter control parameter and type of resolved velocity gradient tensor on: (i) the magnitude of the turbulent stress; (ii) anisotropy of the turbulent stress tensor, and (iii) relative orientation of turbulent stress tensor and the resolved strain-rate tensor.

Further, validation and assessment of the non-linear PANS methodology developed in this research are performed using open-source CFD tool OpenFOAM®. Code development for OpenFOAM involved the inclusion of near-wall resolving treatment, changes in the solver to include energy equation and re-writing of existing RANS models' library to accommodate both linear and non-linear PANS. Implementation of linear PANS methodology in commercial CFD solver ANSYS FLUENT®, required for one sub-study, is done with the help of available RANS model structure.

Performance of non-linear PANS is subjected to evaluation in two canonical flow fields − flow past a square cylinder and flow past a sphere. Assessment is performed by comparing the performance of linear PANS vs. non-linear PANS. The influence of the reduction in the value of the filter control parameter is also examined. Evaluations are performed in terms of both hydrodynamics quantities (like drag coefficient, pressure coefficient, skin friction coefficient, velocity profiles, vortex structures, wake contours) and heat transfer aspects (like Nusselt number variation, temperature profiles). Comparison is made against the available experimental, direct numerical simulation (DNS) and large eddy simulation (LES) results. The results of these comparisons highlight the enhancement in the performance of the PANS due to non-linear closure over the conventional linear based closure in the considered test-cases of separated flows.

Bridging methods are computationally cost-efficient, and improvement in their predictive accuracy will widen their applicability for other variety of complex flows. The author believes that this study will motivate more users to further explore and evaluate the integration of bridging methods like PANS with other non-linear and even explicit algebraic Reynolds stress models (EARSMs) as well.