ASSESSMENT OF MODELS FOR NEAR WALL BEHAVIOR AND SWIRLING FLOWS IN NUCLEAR REACTOR SUB-SYSTEM SIMULATIONS

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Abstract Accurate simulation of turbulence remains one of the most challenging problems in nuclear reactor analysis and design. Due to limitations in computing resources, Reynolds averaged Navier Stokes models (RANS) continue to play an important role in reactor simulations. The Consortium for advanced simulations of light water reactors (CASL) is a Department of Energy technology hub that is investing in research and development of a state-of-the-art computational fluid dynamics capability to meet the challenges of turbulent simulation of nuclear reactors. In this presentation, we assess several RANS eddy viscosity models appropriate for single-phase incompressible turbulent flows. Specifically, we compare the single equation Splalart-Allmaras to several variations of the $k - \varepsilon$ model. The assessment takes into consideration elements of full system reactor cores such as complex geometries, heterogeneous meshes, swirling flow, near wall flow behavior, heat transfer and robustness issues. The goal of this strategically oriented assessment is to provide an accurate and robust turbulent simulation capability for the CASL community. Metrics of performance will be constructed by comparing different models on a strategically chosen set of problems that represent reactor core sub-systems.

BACKGROUND

Hydra-TH is a hybrid finite-volume/finite-element incompressible/low-Mach number CFD module which is part of a multi-physics toolkit being developed for turbulent reactor core simulations. The toolkit is a suite of components that permits rapid application development, I/O interfaces to permit reading/writing multiple file formats for meshes, plot data, time-history and surface-based output. The toolkit also provides run-time parallel domain decomposition with data-migration for both static and dynamic load balancing. Linear algebra is handled through an abstract interface that permits use of popular libraries such as PetSC and Trilinos. The toolkit supports semi- and fully-implicit solvers for time-dependent and steady-state incompressible Navier-Stokes equations with heat conduction and tranport on heterogeneous unstructured meshes.

Currently, two RANS turbulence are mainly used; Spalart-Allmaras [7] and RNG $k - \varepsilon$ [9]. Several additional models are under consideration including the standard $k - \varepsilon$ [4], to provide a baseline, a non-linear model proposed by Baglietto and Ninokata [1] that has been shown to accurately reproduce sub-channel secondary flows, and and a realizable variation of the standard model [6] that is known to improve robustness by strictly enforcing realizability constraints. With the SA model, the normal distance to the wall is required for damping the eddy viscosity near walls. The normal distance is computed as a pre-processing step by solving a specialized Eikonal equation [8]. A value of $y+ \approx 1 - 5$ is necessary for accurate solutions. The $k - \varepsilon$ models employ a y*-insensitive wall function (sometimes call scalable wall function) [3]. The wall function requires the normal distance in the first cell adjacent to a wall. This is computed using the geometry of the cell. While not precise, the mesh resolution restriction is much looser for the y*-insensitive model. The usual recommendation for a lower limit of $y*$ is typically between $20 \leq y* \leq 30$. In this approach the $k-$equation is solved in the entire domain while the ε equation is solved only up to the wall-adjacent cells. In the wall-adjacent cells, ε is prescribed based on the near-wall flow behavior given by the law-of-the-wall.

NEAR WALL BEHAVIOR

As an example, consider the estimation of the Nusselt number for fully developed turbulent pipe flow. In this simple example, using the SA model, the mesh is designed to produce $y+ \approx 1.7 - 6.0$. The the same flow is solved using the RNG model on a grid with $y* \approx 15 - 59$. The solutions are obtained for three different Reynolds numbers based on pipe diameter. The flow is driven by a specified pressure drop. Turbulence model dependent variables; $(\widetilde{\nu}, k, \varepsilon)$ are assumed to have zero gradients in the axial direction and thus evolve to steady values at the inflow and outflow. The temperature profile evolves from a cold inflow through convection and conduction from the pipe wall. Nusselt numbers derived from the two model solutions are compared with correlations of Kays&Crawford [5] shown in Figure 1. The "ref." key refers to the specified boundary condition value and "calc." refers to computing surface gradients from the temperature solution. Both models with significantly different near wall resolutions predict well Nu when the wall bc is well prescribed. However, care must be taken when computing gradients and using wall functions on realtively coarse grids.

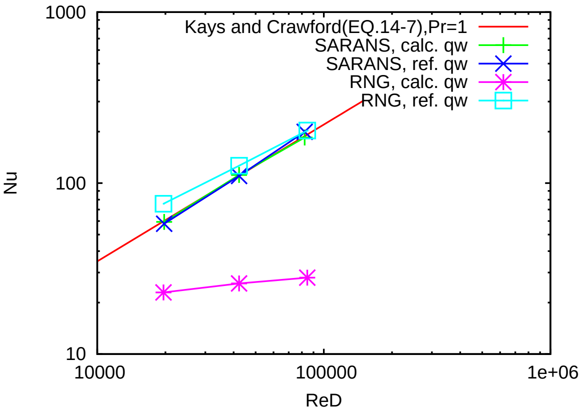

Figure 1. Nusselt number in fully developed turbulent pipe flow with constant heat flux.

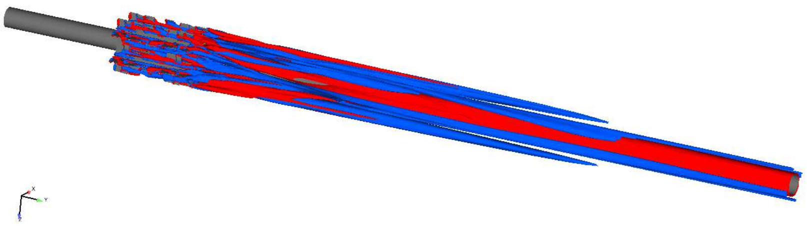

Figure 2. Helicity transport downstream from mixing vanes for a single span of a rod/spacer grid sub-assembly model, positive orientation (red) value=1000, negative orientation (blue) value=-1000.

SWIRLING FLOWS

Another important consideration for reactor flows is swirl. Reactor core rod bundles are held in place by "straps" called spacer grids. Mixing vanes are appended to the straps. These mixing vanes are designed to produce swirling flow to enhance mixing in order to produce uniform heat transfer and eliminate hot spots. Swirling flow persists in sub-channels (the space between rods) many rod diameters down stream of the mixing vanes. Determining the strengh is important to accurately predicting fuel rod performance. Swirling flow in the 3x3 rod/spacer grid model of Elmahdi et al. [2] is shown in Figure 2. The rod length to diameter $L/D \approx 42$ and Reynolds number was $ReD = 192,866$. Hydra-TH was run with a fully-implicit solver strategy using Picard iterations and a maximum CFL=300. The helicity is shown colored red for positive and blue for negative. The long tube-like swirling structures can be seen to persist far downstream. Comparison of structure and strengh will be made between the different models. Several additional strategic sub-assembly "stress test" problems that represent sub-system reactor core flows will included in the final presentation.

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