Large Eddy Simulation of Flow in LWR Fuel-Bundles

Advances in computational fluid dynamics (CFD), turbulence modeling, and parallel computing have made feasible the development of codes that can simulate 3-D flows and heat transfer in realistic LWR fuel bundle geometries. Although no single existing RANS (Reynolds averaging of the Navier Stokes equations) turbulence model predicts a sufficiently wide range of flows with accuracy adequate for engineering needs, at this time for most flows the k-ϵ models seem to be the best choice. In Ref. 1, it was shown that in LWR fuel-bundle flows the predictions of these models for turbulence intensity are in significant disagreement with experimental measurements. The objective of this work was to assess the predictive power of the constant-coefficient Smagorinsky Large Eddy Simulation (LES) model,[2] the simplest of the LES models, in a typical single-phase LWR fuel-bundle flow.

In an LES simulation, the large scales of motion, which contain most of the flow energy, are directly computed, while the small scales, which are much weaker, are modeled. Because statistics of small-scale turbulence are expected to be more universal than those of the large scale, LES which directly computes the large scales of turbulence and models only the small scales, is expected to be applicable to a wider range of flows and more accurate than RANS models.

The most commonly used LES models are of the Smagorinsky type. In these models, the influence of the unresolved (subgrid-scale) scales of turbulence on the resolved scales is treated as a turbulence viscosity, μ_{SGS}, given by

$$\mu_{SGS} = \rho C_s \Delta^2 \left(\overline{S}_{ij}\overline{S}_{ij}\right)^{1/2}$$

where

ρ	=	density
C_s	=	model coefficient
Δ	=	filter width
S_{ij}	=	the local strain rate tensor

In the constant-coefficient Smagorinsky LES model, the coefficient C_s is treated as a constant and the filter width is set to

$$\Delta = (\Delta x_1 \Delta x_2 \Delta x_3)^{1/3}$$

where Δx_i is the grid size in the i^{th} direction. However, C_s is not a strict constant. It may vary in the flow domain and may be different in different flows. To reduce the subgrid scale viscosity (μ_{SGS}) near the wall, the constant C_s is modified by using van Driest damping[3].

The available experimental information for the evaluation of turbulence models for the simulation of flows in reactor fuel bundles is very limited. In the mid-1970s a series of experiments were performed at Pacific Northwest Laboratories[4] to investigate turbulent flow phenomena in a model 7 x 7 fuel rod bundle consisting of 0.996-cm-diameter rods with a pitch of 1.369 cm. Axial components (main flow direction) of the local mean velocity and local intensity of turbulence were measured using a laser Doppler anemometer. The experiments were performed in water at 29.4°C and Reynolds numbers of 1.4×10^4, 2.9×10^4, and 5.8×10^4. The important features of the flow were not significantly dependent on the Reynolds number, and in this work the experiment with a Reynolds number of 2.9×10^4 (inlet velocity of 1.74 m/s) was used as benchmark.

Because the computational demands of LES are very high, a small section of the bundle, as shown in Fig. 1a, was simulated. This section has a length of 8.89 cm in the main flow direction, its left boundary is 1.05 cm away of the bundle wall, and is away enough from spacer grids to assure that the grids have no effect on the turbulence of the flow in this section. A variable computational grid of 616,000 cells was used. The cell size gradually increases as we move away of a rod surface, while the distance of the center of a cell adjacent to a rod is less than one y^+. In the spatial discretization the central differencing scheme was used, while temporal discretization was based on the Crank - Nicholson scheme. The computations were performed on eight processors of a Linux cluster.

Comparisons of code predictions with measurements were made for the turbulence intensity (local fluctuating axial velocity over local axial velocity) and the mean velocity (local mean velocity/velocity at the bundle inlet) at points on a line perpendicular to the bundle wall (long axis of symmetry of Fig. 1a) and on a plane perpendicular to the direction of the main flow. The measurement error for the velocity is ± 11% and for the turbulence intensity ± 16%.

Figure 1b shows axial velocity and turbulence intensity distributions. All k-ϵ models give nearly the same predictions. They overpredict the velocity around the center of the flow channel (area of velocity peaks) and underpredict it in the gap between the rods (area of velocity dips). The maximum discrepancy between predictions and measurements is about 10%. The turbulence intensity is low, about 5%. The k-ϵ models significantly overpredict the turbulence in the area of the gap. The maximum discrepancy between predictions and measurements is about 60%. Figure 1b also shows velocity predictions if the flow was considered to be laminar. The predicted velocity distributions with the k-ϵ turbulence and laminar models, and the turbulence intensity distributions indicate that the k-ϵ model does not work well in the area of the gap between the rods.

The LES prediction for the mean velocity distribution is nearly identical to the measured distribution. The predicted turbulence intensity in the gap region is in very good agreement with measurements. However, in the region around the center of the channel the turbulence intensity predicted by LES is about 30% lower than the measured value. As shown in Fig. 1a, the computational grid around the center of the channel is much coarser than closer to the rod surface. The effect of the grid size around the channel center on predicted turbulence needs to be investigated.

In conclusion, this work shows that the LES simulation of flows in LWR fuel-bundles is superior to that of κ-ϵ models, and LES may provide a quite faithful simulation of these flows.

References

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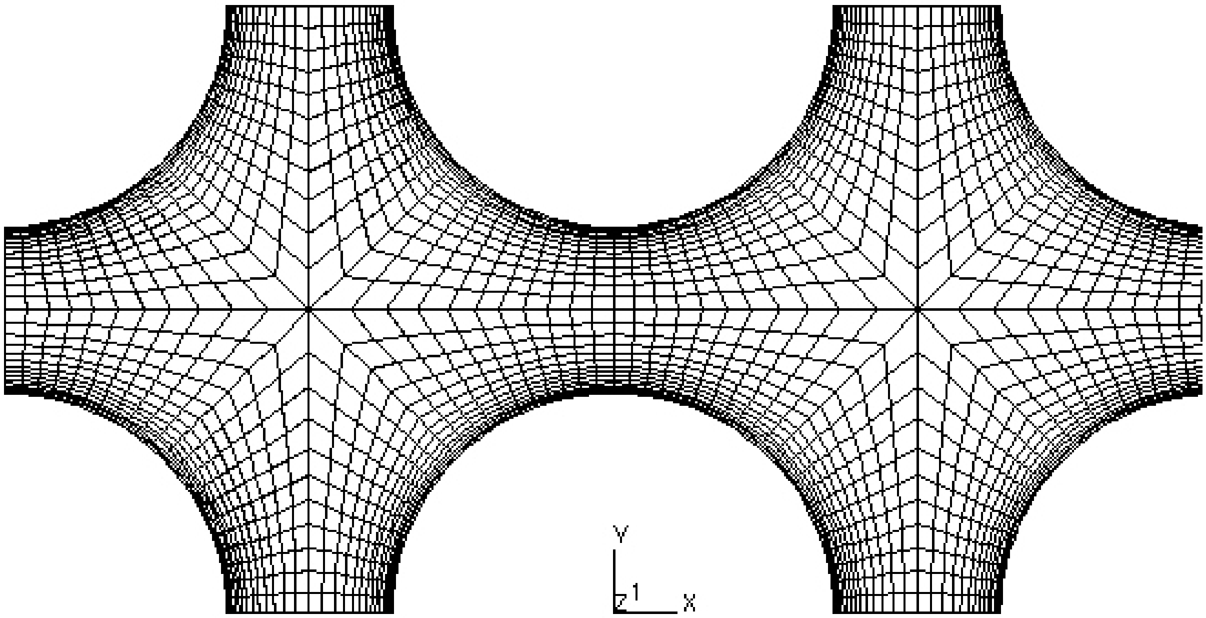
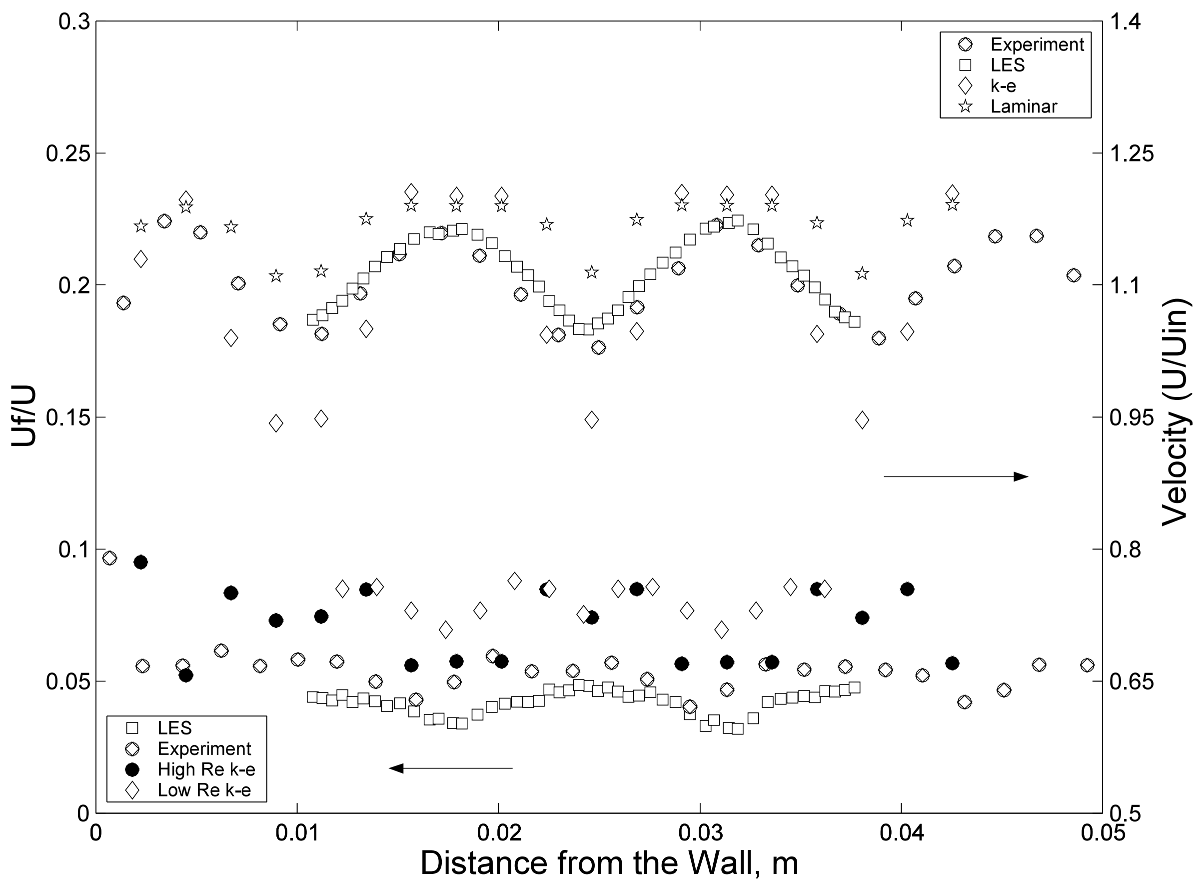


(a)



(b)

Figure 1. Velocity and Turbulence Intensity Distributions.