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Unsteady Reynolds Averaged Navier-Stokes and Large Eddy Simulations of Flows across Staggered Tube Bundle for a VHTR Lower Plenum Design

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1. Introduction

Computational fluid dynamics (CFD) is used in a design process of a very high temperature reactor (VHTR). Benchmarking the CFD code is inevitable for a reliability of such analysis. A study by Ridluan and Tokuhiro [1] shows that all the typical turbulence models do not sufficiently reproduce flow oscillating flow phenomena across tube bundles. Thus, a need is raised to investigate such limitations before application to Korean VHTR problems. In this work, behavior of unsteady and oscillating flow through a typical tube bundle array are analyzed by unsteady computations: 2D unsteady Reynolds averaged Navier-Stokes (URANS) and 3D Large Eddy Simulation (LES) and the results are compared with existing experimental data.

2. Methods and Modeling

Turbulent flow through a staggered tube bundle is a typical case to validate fluid dynamic behavior of the lower plenum flow mixing of a VHTR. A steady-state CFD analysis of this case was previously studied [3]. However, it showed that the typical turbulence models used to simulate steady turbulent flow do not sufficiently reproduce all the flow structures and phenomena. Unsteady turbulent flows are analyzed extending the authors' previous study [3]. Two types of unsteady computations are performed: 2D URANS and 3D LES.

The URANS usually uses standard k-ω turbulence model considering the characteristics of strong low Reynolds effect near the wall [2]. The LES simulates large scales of turbulence in space and models the effect of smaller scales by adding a sub-grid turbulent viscosity. Present analyses use Smagrinsky and Wall-Adapting Local Eddy-viscosity (WALE) models for the sub-grid eddies.

For all the analysis, 2nd order upwind scheme is selected for the solving transport equations. Acaled residual for all the flow properties are set at 1×10^{-6} for the standard k-ω and set at 1×10^{-4} for the LES. A time step is fixed at 1×10^{-4} seconds.

The existing staggered tube bundle used in the present analyses [4] is shown in Fig. 1 (tube diameter = 21.7mm, pitch = 45mm). Boundary conditions are all periodic. The LES computation is conducted with three dimensions (thickness of 5mm). The Reynolds number is 18,000 based on the diameter and the properties of liquid water used in the experiment [4]. The mean velocity upstream of the tube bundle is reported to be 1.06m/s. The meshes are shown in Fig. 2. The total number of cells is 42,952 in the URANS and 1,788,584 (2D 47,068) in the LES.

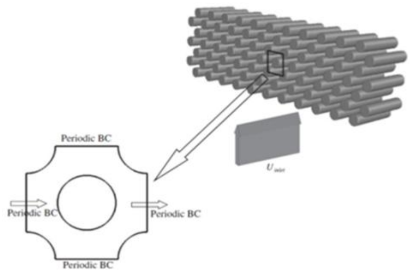
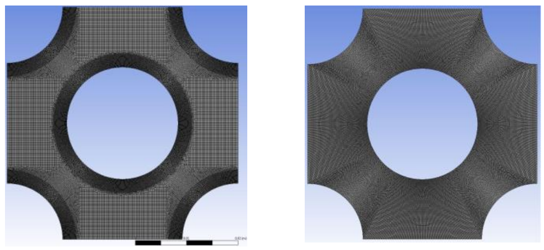


Fig.1 Geometries of the actual and simplified staggered tube bundle array by Simonin and Barcouda [4]



(a) URANS (b) LES
Fig.2 Meshes of URANS and LES computations

3. Results and Discussion

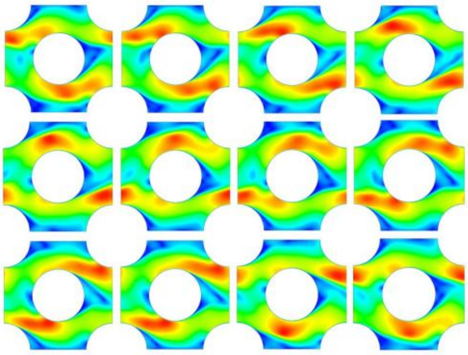
3.1. Unsteady RANS

Figure 3(a) shows velocity magnitude contours in sequence obtained from the URANS with the standard k-ω turbulence. This contour is flow streams during a cycle. The cycle is estimated as 0.032 seconds. It can be clearly shown that the wake flow is dynamically unstable and oscillating up and down. This oscillating wake is a kind of lumped flows. Fig.4 shows comparison of the analysis results with the experimental data [4] of the time mean x- and y-velocity profiles at x=0 and 11 mm. Here, the origin of coordination is the lower-left corner of the pitch. In some region, the velocities from the URANS are faster than experimental data. It is considered that this is due to inevitable neglect of actual physical flow phenomena or numerical error of the models.

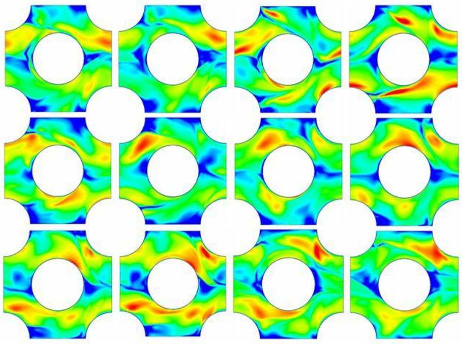
3.2. Large eddy simulation

As mentioned earlier, two sub-grid models are adopted for the LES. They are well-known

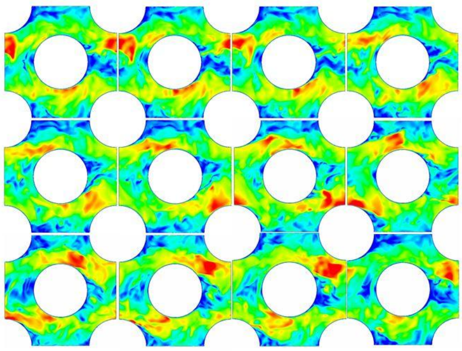
Smagorinsky model and the WALE. Figure 3(a) and 3(b) also show velocity magnitude contours in sequential order for the LES analysis. Like URANS, the wake flow is dynamically unstable and oscillating up and down. The strong coupling of accelerated flow along the lower side of the central cylinder and decelerated flow along the upper rear side of the lateral cylinder (bottom left) is also evident in the two computations. The cycle periods of these two models are 0.02 sec and 0.038 sec, respectively.



(a) URANS



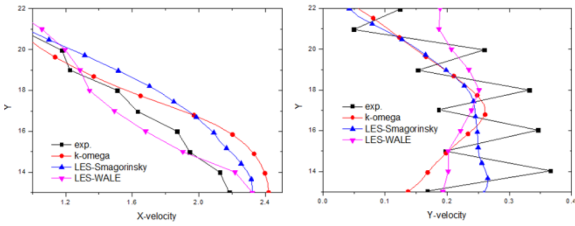
(b) LES/ Smagorinsky



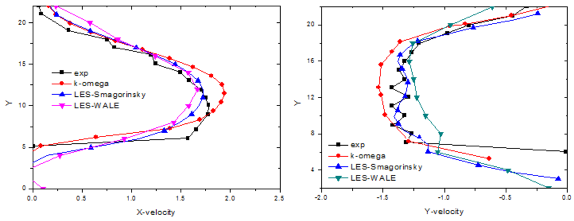
(c) LES/WALE

Fig.3 Subsequent velocity magnitude contours from each method

Velocity contours from the URANS shows stylized flow behavior whereas the LES with two sub-grid turbulence models) show similar overall behaviors but flows are more chaotic and tattered. In the LES-WALE calculation, the flow is most chaotic among the three types of computations. This difference comes from fundamental averaging methods in the RANS and the LES, e.g., time and spatial averaging, respectively. The data set available from Ref. 4 are only the x- and y-velocity along the lines at x = 0, 11, and 16.5mm and at y = 0, 22.5 mm. Figure 4 shows x- and y-velocity profiles at locations x=0 and 11mm from the present three computations and the measured data points [4]. The LES-Smagorinsky computation is closest to the experimental data.



(a) x-velocity and (b) y-velocity in x=0



(a) x-velocity and (b) y-velocity in x=11

Fig. 4. x- and y-velocity along the lines at x = 0, 11 mm

4. Conclusions

In order to confirm appropriateness and limitations of CFD applications in the Korean VHTR design, two types of unsteady computations are performed such as 2D unsteady Reynolds averaged Navier-Stokes (URANS) and 3D Large Eddy Simulation (LES) for the existing tube bundle array. The velocity component profiles are compared with the experimental data and it is concluded that the URANS with the standard k-ω model is reasonably appropriate for cost-effective VHTR lower plenum analysis. Nevertheless, if more accurate results are needed, the LES-Smagorinsky computation is recommended considering limitations in the time averaged RANS in capturing small eddies.

5. References

[1] A. Ridluan, A. Tokuhiro, Benchmark Simulation of Turbulent Flow through a Staggered Tube Bundle to Support CFD as a Reactor Design Tool. Part II URANS CFD Simulation, J. Nuclear Science and Technology, Vol. 45, No. 12, p. 1305, 2008.

[2] J. Kim, ANSYS CFD FLUENT, ANSYS Inc., Canonsburg, 2011.

[3] H. K. Choi, J. W. Park, A Study on the Feasibility of CFD Analysis in VHTR Gas Mixing Analysis, The Korean Nuclear Society, Div. Reactor System Technology, p. 3, 2012.

[4] O. Simonin, M. Barcouda, Measurements and Prediction of Turbulent Entering a Staggered Tube Bundle, 4^{th} Int. Symp. Applications of Laser Anemometry to Fluid Mechanics, Vol. 5, p. 23, 1988.