3D Analysis of the VHTR Lower Plenum Standard Problem Using Unsteady Reynolds Averaged Navier-Stokes and Large Eddy Simulations models

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1. Introduction

Very high temperature reactors (VHTR) can produce not only electricity but also hydrogen because these are operated at high temperature. The VHTRs are helium-cooled and graphite-moderated reactors, and a type of high temperature reactor (HTR) that can conceptually have an outlet temperature of approximately 1000°C. In the internals of the reactor, a helium gas coolant has the characteristics of high temperature and complicated turbulence. So, it is important to be able to simulate the turbulent phenomena of the coolant in the VHTR in order to ensure the large temperature gradients are not present in the coolant.

The objective of this study was to model a section of the VHTR reference design lower plenum and compare their results to experimental data obtained in the INL Matched-Index-of-Refraction (MIR) facility. The experimental data will comprise a validation data set to assess the applicability of CFD models to the analysis of flow in the VHTR lower plenum. The experiment provides instantaneous and ensemble-averaged velocities at discrete points in the flow, and is designed to simulate the flow in the central portion of the lower plenum, away from the outlet duct [1]. The present analysis is reproduced using FLUENT code based on this MIR experiment. Both 3D unsteady Reynolds average Navier-Stokes (URANS) and large eddy simulation (LES) models are used for present analysis. The Standard k-ε model is adapted in URANS models and Smagorinsky-Lilly model is adapted as a subgrid stress model for LES.

2. Methods and Modeling

The model consists of eight inlet jet ports above a symmetrical arrangement of five cylindrical columns along the centerline and ten half columns along the two parallel side walls. Only four of the eight inlet jets were operated during the MIR experiments. The columns extend throughout the full height of the model. Figure 1 shows the present geometry and measurement location of the computational and experimental data. The scaled model is 53.98mm wide, 485.42mm longs, and 217.5mm high. Diameters for the inlet jets and cylinders are 22.10mm and 31.75mm, respectively. The overall objective of the CFD analysis of the scaled model of the lower plenum has been to investigate issues related to the suitability of the experimental (MIR) data to be useful as a validation data set. The measurement location is at x-location=46.84, 95.12, 124.69 and 193.91mm, at y-location= -70 and –150mm with z-location along the centerline.

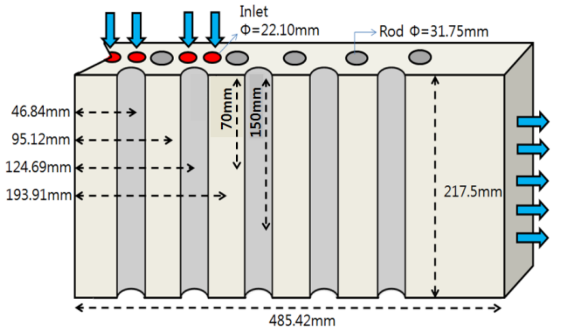


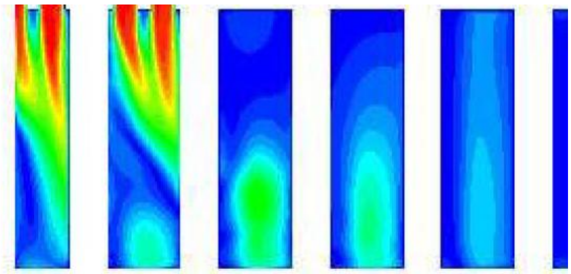
Fig.1 Geometry and measurement location of the lower plenum

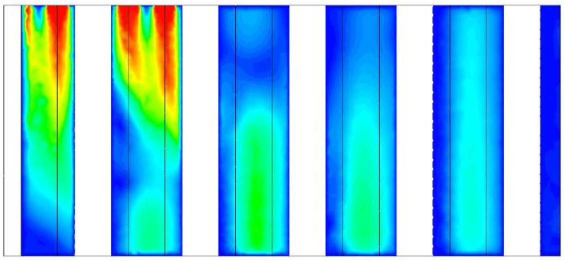
The working fluid in the MIR facility is mineral oil. Material properties for mineral oil were specified in the flow solver set up (e.g., a density of 831 kg/m^3 and a dynamic viscosity of 0.0118 kg/m·s). The average velocity across the inlets is approximately 3.2 m/s for cases with constant inlet velocity with an inlet jet Reynolds number of 4300. For all the analysis, 2nd order upwind scheme is selected for the solving transport equations. A calculated residual for all the flow properties is set at 1×10^{-4} and a time step is fixed at 1×10^{-4} seconds.

The total number of cells is 7,548,917. Previously, Johnson analyzed this case using a URANS model with fewer cells that meet enough mesh dependence but here many cells are for calculations using the LES model [1, 2]. A tetrahedral mesh of almost the same size is used.

3. Results

The following Figure 2 show the velocity contour at centerline(y=0mm). The present results are compared with the analysis results of Johnson [1]. Each figure shows (a) the URANS Standard k-ε results of the Johnson analysis, (b) URANS Standard k-ε results and (c) LES with Smagorinsky-Lilly results of the present analysis. The URANS Standard k-ε results have smooth contours but the LES with Smagorinsky_Lilly results body out turbulence eddies. Particularly, in third inlet, small eddies appear in the LES result but is not the case in the URANS results. It is the numerical characteristics of URANS models.


(a) URANS Standard k-ε (Johnson)


(b) URANS Standard k-ε (Present)

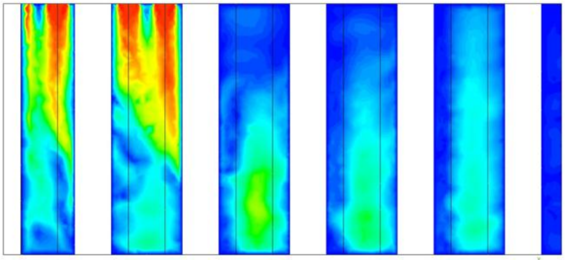

(C) LES + Smagorinsky-Lilly (Present)

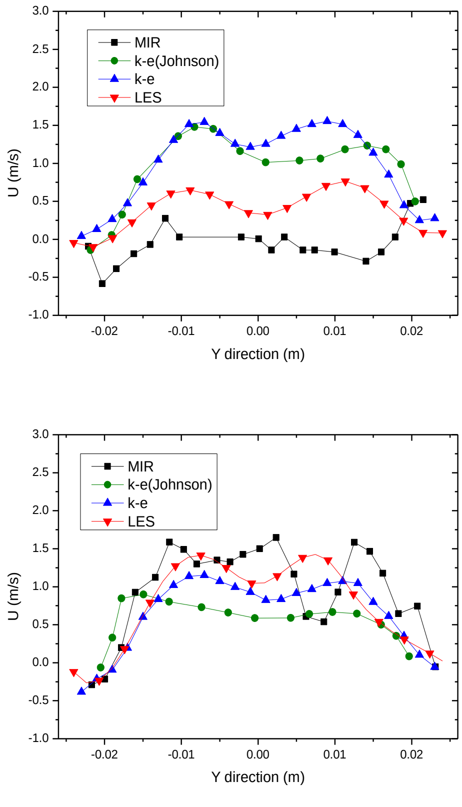
Fig. 3 Velocity magnitude contour

Figure 3 is time average velocities at (a) x=46.84mm, (b) 91.12mm, (c) 124.69mm and (d) 193.91mm. These are compared with the MIR experiment results. y=0 is the centerline and each plot is the velocity magnitude at z=-150mm (top) and z=-70mm (bottom). The black line is the result of the experiment, and the green line is the FLUENT analysis results of Johnson. He was also using the URANS Standard k-ε model, but some figures are not the average data because of his interim report results.

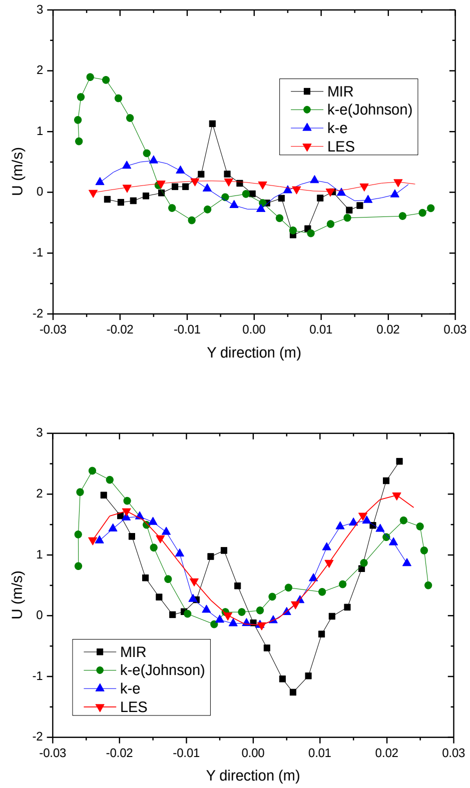
Figure 3 (a) shows the velocity profile of x=46.82mm and the lower part of the inlet. All analysis results are different from the experimental results. The LES Smagorinsky-Lilly model is relatively close to the experimental data.

Figure 3 (c) is the velocity magnitude of x=124.69mm. Almost all analysis results are similar to the experiment data, especially the LES with the Smagorinsky-Lilly model is similar to the experimental data. However the analysis results of Johnson is not the average results in z=-15mm. Compared to other figures, the LES with the Smagorinsky-Lilly model results are suitable. The velocities are similar to the experiment results except for bilateral symmetry in the results of the LES with the Smagorinsky-Lilly model.

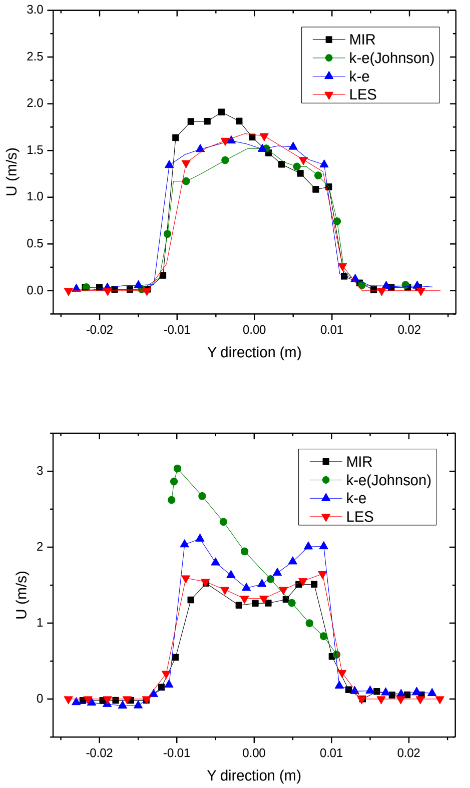
The verification of the accuracy of the LES and RANS models was carried out for flow in the VHTR lower plenum. The LES and URANS models can be applied to 3D MIR experiments. It evaluates that LES with the Smagorinsky-Lilly model is the most suitable in terms of accuracy as well. However, this model has a lot of computation time and requires a grid point. Therefore, the capacity of the computer must overcome the limitations.



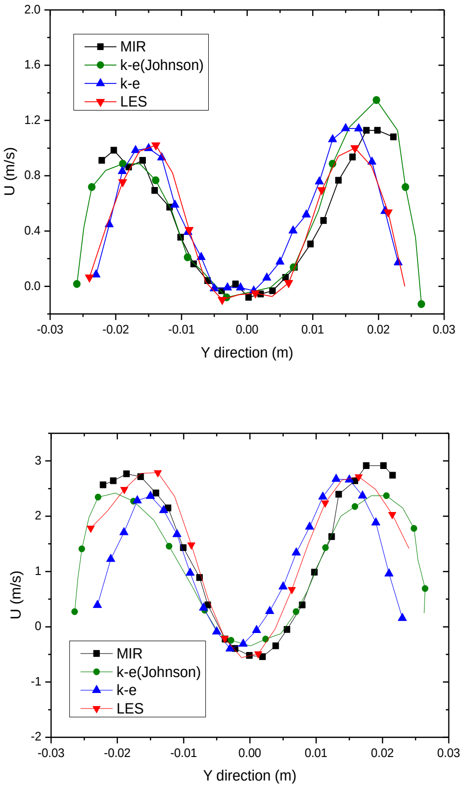
(a) MIR x=46.84mm



(b) MIR 91.12mm



(c) MIR 124.69mm



(d) MIR 193.91mm
Fig. 4 veolcity magnitude contour

4. Conclusions

In order to confirm the limitations of a CFD application to Korean VHTR problems, INL MIR case is analyzed by using FLUENT, and they are compared with the existing analysis and experimental data. The velocity component profiles are compared with the experimental data and it is concluded that the URANS with the standard k- ε 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] R. Johnson, D. Guillen, T. Gallaway, Investigations of the Application of CFD to Flow Expected in the Lower Plenum of the Prismatic VHTR, Idaho National Laboratory, 2006

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[3] H. K. Choi, J. W. Park, Unsteady RANS and LES of Flows across Staggered Tube Bundle for a VHTR Lower Plenum Design, The Korean Nuclear Society, 2012