LARGE EDDY SIMULATION OF NON-ISOTHERMAL TURBULENT FLOW PAST A CIRCULAR CYLINDER

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ABSTRACT

Understanding the thermal mixing of coolant jets in the lower plenum of High Temperature Gas-Cooled Reactors (HTGR) is very important to address certain design and safety issues. As a step towards developing an experimentally validated computational model for the lower plenum flow, turbulent flow and heat transfer around a circular cylinder is computed using large eddy simulation (LES) at three different Reynolds numbers (3000, 5900, 7400). In the range of the Reynolds number considered in this study, flow undergoes a rapid structural change with Reynolds number which significantly affects the heat transfer characteristics. The major difficulty of predicting turbulent heat transfer around a circular cylinder comes from turbulence modeling. To overcome this issue, a finite-volume solver with compressible flow formulations are used for the simulation. A sub-grid stress (SGS) model is chosen in such a way that LES can predict the physical characteristics of the flow and heat transfer. The LES results are found to be in good agreement with well-known experimental studies available in the literature. The main features of turbulent heat transfer in the subcritical regime are closely captured by LES, namely the thermal boundary layer and the sharp increase in both the mean and the r.m.s. Nusselt number in separation region. The dependence of these quantities on Reynolds number is also captured. The numerical results also confirm that the heat transfer characteristics is closely consistent with the structural change in the flow and is dependent on the Reynolds number. This research lays the groundwork needed to develop a high-fidelity experimentally validated computational model of the complex thermal mixing flow in the HTGR lower plenum.

KEYWORDS
Large eddy simulation, non-isothermal flow over cylinder, HTGR, thermal mixing

1. INTRODUCTION

Turbulent flow and heat transfer around a circular cylinder have fundamental relevance in various engineering applications and are also of practical interest in the lower plenum of High Temperature Gas-Cooled Reactors (HTGR). In HTGR coolant picks up heat from the core and then enters the lower plenum much like an array of jets. Due to the non-uniform heat generation in the core of a nuclear reactor, the temperature of these jets directed into the lower plenum can vary significantly. Once in the lower plenum, the flow of these jets changes directions by 90° and traverses across complex geometric features, including an array of cylindrical cross-sections, present as support posts. In order to more fundamentally understand the complicated flow and its influence on thermal striping in the lower plenum, it must be broken down into manageable subcomponents, where detailed experimental and computational studies can more easily be accomplished. The goal of this article is to computationally model non-isothermal flow past a cylinder as a fundamental benchmark in order to better quantify the physics behind thermal striping in the lower plenum. Detailed analysis will also provide the insight required to potentially modify the reactor design itself, and establish regulations for HTGRs.

In the range of Reynolds number which we focus on in this study, a laminar boundary layer is formed at the stagnation point of the cylinder, and then separates from cylinder surface and forms a shear layer which eventually establishes the wake downstream of the cylinder. In this subcritical regime, the Kelvin-Helmholtz instability along with the Karman vortex-shedding cause the separated shear layer to become unstable. As the Reynolds number increases in this range, the flow structure changes very fast, and the mixing of momentum as well as scalar mixing boost with this change. Consequently, heat transfer characteristics follow this flow structural change and sees much more improvement at the cylinder surface in the separated region.

Several experimental attempts have been made to investigate the unsteady heat transfer in the separated flow region of the cylinder. This investigation of unsteady heat transfer is very important to clarify since it aids in understanding the flow characteristics close to the cylinder body. Scholten and Murray [1] measured the unsteady heat transfer for a range of Reynolds numbers from 7000 to 50,000 while Nakamura and Igarashi [2, 3] also made several attempts to report measurements for a wide Reynolds numbers [2, 3]. Among those attempts, Nakamura and Igarashi [3] investigated this unsteady heat transfer from a circular cylinder to the cross-flow of air experimentally for Reynolds numbers from 3000 to 15,000. They measured fluctuating heat transfer on the cylinder surface using a heat flux sensor, and also measured time-spatial characteristics of the heat transfer by an infrared thermograph. Their circular cylinder had a diameter of d = 50 mm and a length of L = 150 mm, which was set horizontally in a wind tunnel. The wall condition of the cylinder was constant wall temperature and the temperature difference between cylinder surface and free stream was approximately 25 °C. In current study, we try to computationally mimic their experimental measurements.

In spite of experimental attempts, surprisingly the reported computational simulation of the flow phenomena is limited in the literature. One major hurdle in simulating turbulent heat transfer around a circular cylinder stems from turbulence modeling deficiencies. Obviously, Reynolds-averaging is not capable to handle the real physics of a non-isothermal flow over a cylinder due to the laminar-turbulent transition as well as the active presence of both thermal and velocity fluctuations. Large eddy simulation (LES) is a more feasible approach, since the large scale structures are solved directly and the effect of small scales are modeled by an appropriate SGS (subgrid stress) model. Plenty of isothermal LES studies of flow around a circular cylinder exist in literature (see [4-6] for example), but for non-isothermal flow around a cylinder, only a single LES study can be found. Kim et al. [7] considered both the flow and the heat transfer in their LES study. They carried out LES of turbulence flow and heat transfer around circular cylinder in cross flow for three subcritical Reynolds number of 3900, 10,000 and 18,900 by Fluent. Although their LES predictions were in good agreement with the experimental data of Nakamura and Iragashi [3], their results in both the mean and the r.m.s. Nusselt number show undesired deviation from the experimental results. Our work presented here uses an appropriate SGS model and adequate domain size to provide direct validation using the experimental measurements of Nakamura and Iragashi [3].

2. Computational Model

The classical O-type grid as shown in Figure 1 and as used by Lysenko et al.[5] is employed for the simulation. The computational domain has a radius of 50 D. The domain has a span-wise extension of π D as was used by Lysenko et al.[5]. The domain has slightly more than 3M computational cells with 24 cells in the span-wise direction. Grid points are clustered near the surface of the cylinder ($\Delta r/D \approx 10^{-3}$) with a grid expansion factor of 1.025 in the radial direction. Cyclic boundary condition are used for the front and back faces in the span-wise direction. A non-reflective boundary condition is employed for outlet condition to prevent numerical waves coming inside of computational domain. Similar to the experimental set up, a constant wall temperature is used for the boundary condition. The temperature difference between the heated surface and incoming flow is fixed to 25 °C.

The Sub-Grid Scale (SGS) model selected for the LES simulation is the Dynamic Local-averaged Smagorinsky model based on the experience of model selection studies conducted in the previously study [8]. Compressible sets of Navier–Stokes equations are solved by OpenFOAM. Specifically, PIMPLE version of PISO (Pressure Implicit with Splitting of Operators) algorithm is employed as an efficient method to solve the Navier-Stokes equations in unsteady problems. The PISO algorithm is a pressure-velocity calculation method. The simulation is run for about 300 vortex shedding cycles. Time-averaging of the flow statistics is started after approximately 15 vortex shedding cycles. Turbulence intensity also has been matched to that reported from the experiment of [3], namely 0.5%, which is large by the standard of modern wind tunnel.

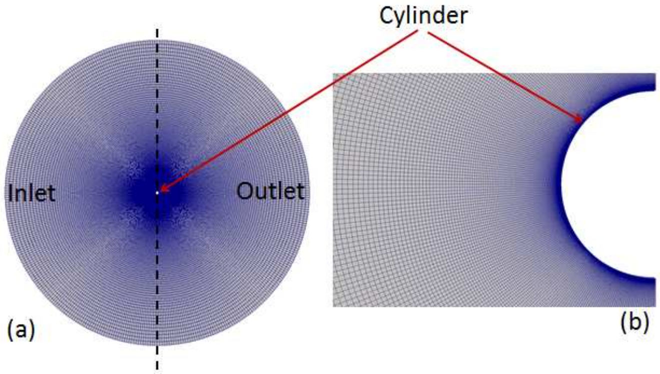


Figure 1. (a) The computational domain; and (b) Mesh near the surface of the cylinder

3. Results and Discussion

Figure 2 portrays instantaneous vorticity magnitude contours in the near-wake of the cylinder at the three Reynolds numbers. Even though the difference between Reynolds numbers are not very large, yet the structural change in the cylinder wake as the Reynolds number increases is visible with comparison of these contours. It can be seen that, as the Reynolds number increases, particularly if Reynolds numbers 7400 is compared with two other Reynolds number studies, the location at which the separated shear layer becomes destabilized moves upstream. Moreover, large-scale vortex-shedding is observed at all three Reynolds numbers.

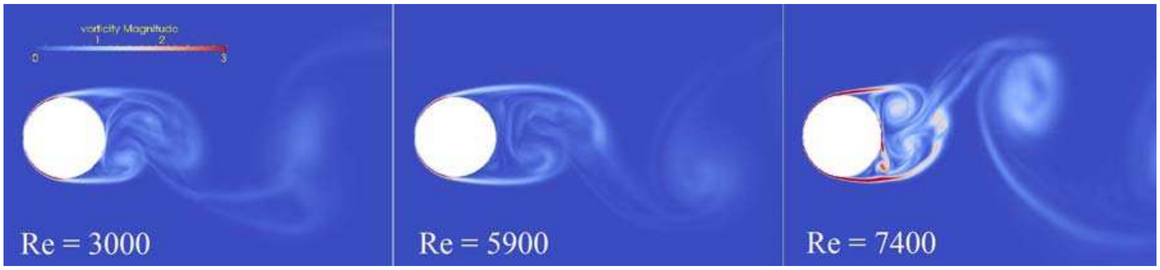


Figure 2. Contours of instantaneous vorticity magnitude in the near-wake for different Reynolds numbers

Instantaneous temperature fields are portrayed in Figure 3 in the near-wake region of the cylinder. The contour plots well portray the separated shear layer location. As we can see shear layer becomes instable and mixing of momentum leads to mixing of scalar and consequently as discussed before it cause heat transfer enrichment.

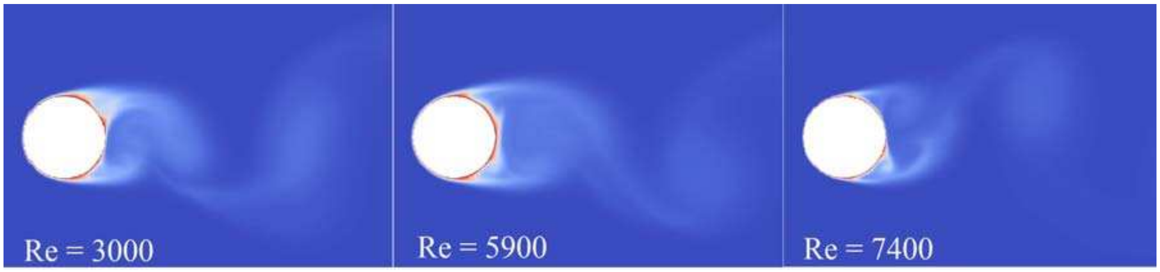
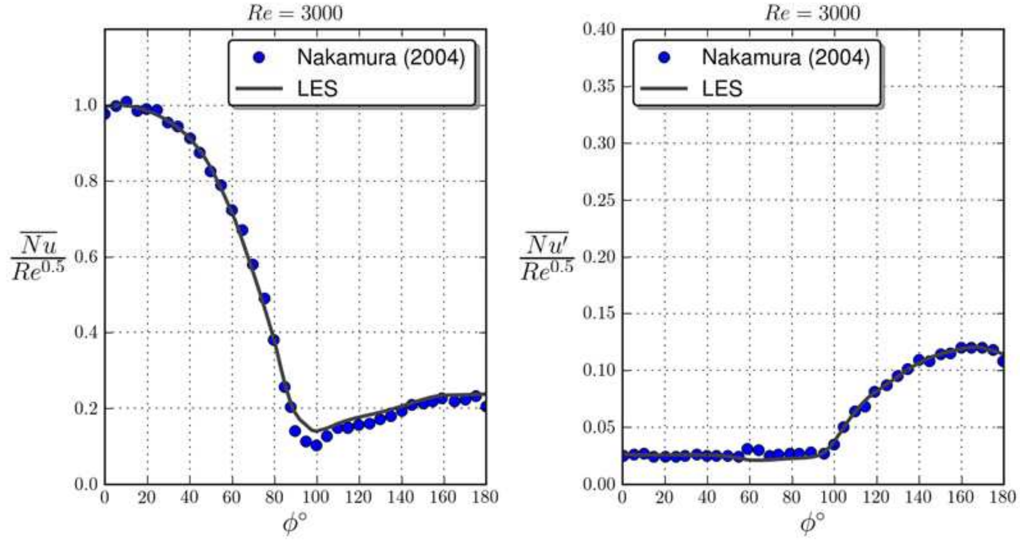


Figure 3. Contours of instantaneous temperature in the near-wake for different Reynolds numbers

The distribution of the time-averaged Nusselt number and its r.m.s. value are key metrics to compare with experimental data. Figure 4 shows the results of this comparison and reveal excellent agreement for both quantities. The LES data accurately captures the laminar flow region where $\phi < 80°$, where ϕ is the angle from the stagnation point of the cylinder. The magnitude of the Nusselt number fluctuations is very small in the region as well, both experimentally and as suggested by the LES data. For all three Reynolds numbers, a significant increase in the value of the r.m.s. Nusselt number can be seen in the neighborhood of $\phi = 70° – 80°$. This is likely due to the flow fluctuations resulting from the separated shear. This is more apparent for Reynolds number 7400. In the following separated region where $\phi > 90° – 100°$ the value of Nusselt number fluctuations is as high as half of the time averaged Nusselt number. The fluctuating Nusselt number in the separated flow region increases toward the rear stagnation point $\phi = 180°$ which is qualitatively similar to the time-averaged Nusselt number. The sharp upswing in heat transfer is repeated twice for a Reynolds number of 7400, where a plateau is observed in the data in the region of $100° < \phi < 130°$, which indicates that the alternating reattached flow at the rear of the cylinder initiates at Reynolds number around 7400. The plateau in the Nusselt number distribution is the production of the formation of the reattached flow at the rear of the cylinder. A fluctuating pressure distribution around a circular cylinder has a local maximum at $\phi = 105°$, at which the reattached reverse flow separates. This maximum disappears below Re = 6000-8000, corresponding to the range for which the reattached flow disappears [3, 9].



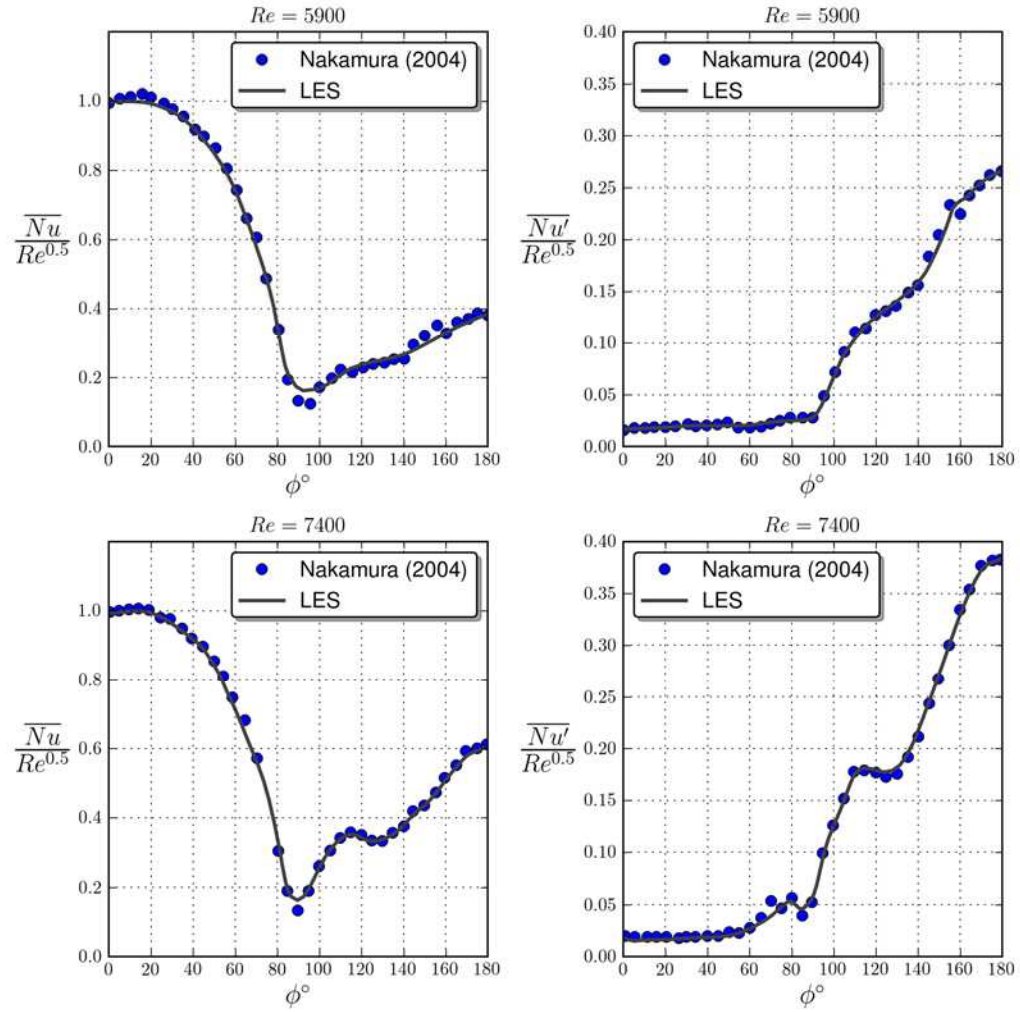


Figure 4. Time-averaged and r.m.s Nusselt number distributions around a circular cylinder for Reynolds number of 3000, 5900 and 7400.

Figure 5 shows time traces of the fluctuating Nusselt number at Reynolds number of 5900 where Nakamura and Iragashi [3] reported similar data at same Reynolds number. The data is collected at several azimuthal location at the mid-span of cylinder. As can be seen at $\phi = 70°$ the point is in the laminar region since there is no fluctuations present. As go further downstream of the cylinder, both flow feature and heat transfer affected by the instability of separated shear layer and vortex shedding. As boundary layer instability grows $150° < \phi < 180°$ the fluctuations Nusselt number become much larger. Same observation for both trend and magnitude of the fluctuations of Nusselt number experienced in Nakamura and Iragashi [3].

4. CONCLUSIONS

The LES of turbulent flow and heat transfer around a circular cylinder was conducted using OpenFoam at three Reynolds numbers (*Re* = 3000, 5900, 7400). From all three Reynolds numbers results, it can be seen that the physics of the heat transfer are captured very closely. The heat transfer characteristics of the laminar boundary layer upstream of the separation point as well as the entire region behind cylinder is accurately modeled. Excellent agreement is seen with the experimental data regarding time-averaged and r.m.s. Nusselt numbers. The sharp increase both in the mean Nusselt number and the r.m.s. fluctuating Nusselt number is also reproduced faithfully. Strong correlation between the heat transfer characteristics and the underlying flow characteristics is also confirmed.

Future and more detailed LES related studies should also be conducted. In particular, other LES studies should be done with higher Reynolds numbers and quantifying the metrics of importance as a function of upstream turbulence intensity. Also, the effect of the span-wise cell divisions should be considered. These additional studies will serve to better understanding of such both fundamentally and practical important problem.

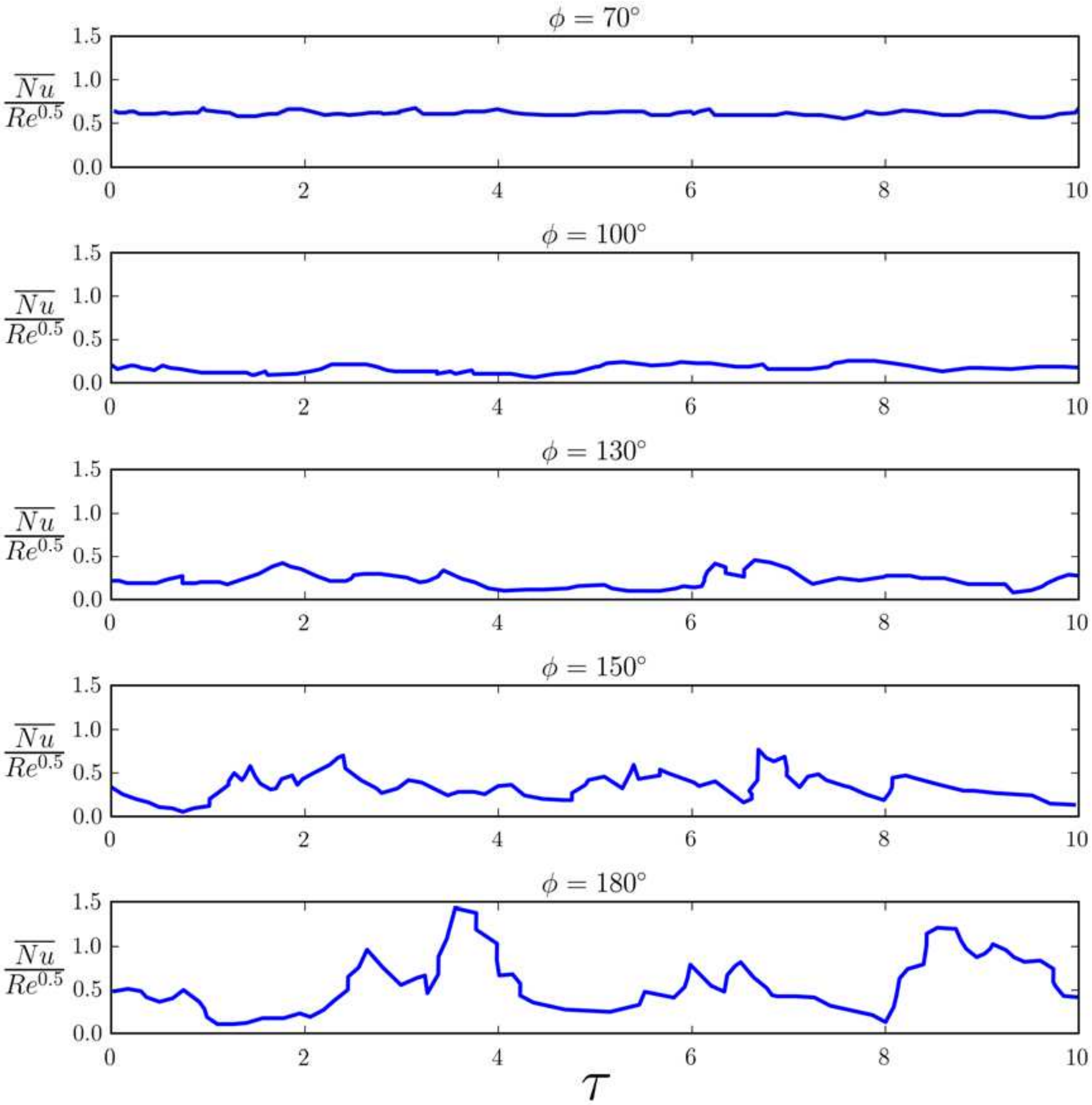


Figure 5. Time-histories of the instantaneous r.m.s Nusselt number for Re=5900.

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