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LARGE EDDY SIMULATION AND REYNOLDS-AVERAGED NAVIER-STOKES APPROACHES OF RIB ROUGHENED CHANNEL

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ABSTRACT
In this paper, rib roughened channel are investigated numerically by large eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) approaches. Results are compared with each other in streamlines and velocity components. During the present analysis, working domain is considered as three-dimensional (3-D) and the flow is assumed fully turbulent. Domain geometry and grids are generated by using a pre-processor of GAMBIT and then solved iteratively by a commercially available CFD code of FLUENT 6.2.16. Main purpose of this study is to show the capability of the CFD solver and the effect of the rib on the flow by comparing two different solution techniques.
Keywords: groove, rib, CFD, turbulence, channel, pipe

1. INTRODUCTION

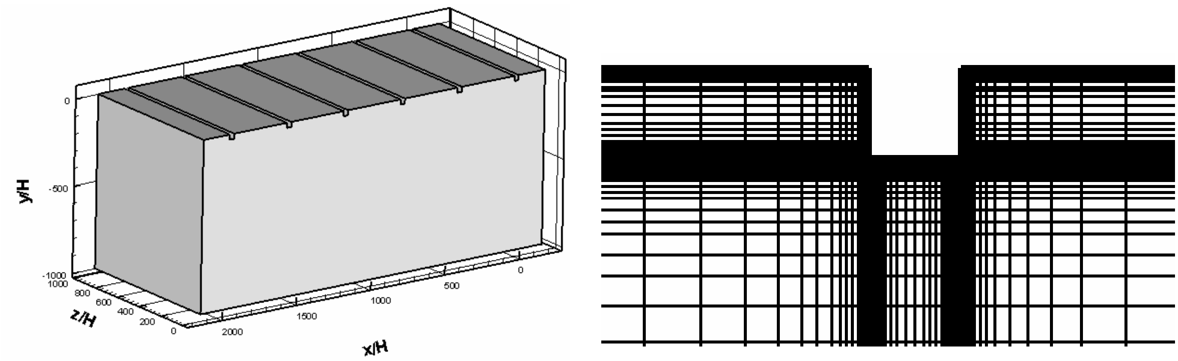
Turbulent flow over a rib-roughened wall is an important problem in industrial applications such as in the internal cooling of turbine blades, electronic cooling devices and heat exchangers and vegetation canopies. Use of a rib-roughened channel is one of the basic and effective tools for the enhancement of internal flow convective heat transfer. The flow field characteristics are strongly dependent on the length-to-depth ratio of the cavity, the freestream conditions, the approach boundary layer, and the characteristics of cavity components, etc. Navier-Stokes (N-S) equations that govern the flow are non-linear partial differential equations and in most cases cannot be solved analytically so direct numerical simulation (DNS) and large eddy simulation (LES) are used for numerical studies because they are the most accurate. There are two different types of roughness; k-type and d-type, respectively. k being the roughness height and d the boundary layer thickness, pipe diameter or channel height (Cui et al., 2003)[1], (Tani, 1987)[2].

In the past numerous experimental and numerical studies are performed to investigate heat transfer characteristics of rib-roughened channels that focus on channel cross-sectional shape on the effectiveness of surface ribs for heat transfer. Because of its importance, rib-roughened wall have been studying over the years and many experimental and numerical studies have been conducted. (Kim et al., 2004)[3] used Reynolds averaged Navier-Stokes solver (RANS) to optimize the shape of 2-Dimensional (2-D) channel with demonstrated rib mounted walls to enhance heat transfer. (Tatsumi et al, 2003)[4] adopted RANS approach in a 3-D numerical simulation for the flow in a duct accompanying longitudinal vortices. One recent study is reported by (Tomoaki and Durbin, 2007)[5] who performed direct numerical simulation (DNS) on a rectangular ribs mounted channel. Based on their DNS results, they tested 2-D RANS approach and they revealed that RANS models under estimate the drag acting on rough wall elements and cannot represent the modified log-law. A 3-D analysis of two-equation eddy viscosity (EVM) and Reynolds stress (RSM) turbulence models and their applications to solve flow and heat transfer in rotating rib-roughened internal cooling channels is performed by (Sleiti and Kepat, 2006)[6]. They reported that for both stationary and rotating channels RSM in predicting the flow field and heat transfer is the best. The another study to assess the capability of Navier-Stokes codes to predict flow and heat transfer in coolant channels with 45^0 ribs is reported by (Benhoff et al., 1999)[7] The similar observation is showed that RSM results are more consistent with their experimental results obtained by using Particle Image Velocimetry (PIV) than k-ε results. (Miyake et al., 2002)[8] analyzed a rib-roughened wall with DNS and they revealed that a tiny vortex pair to a hairpin vortex in rough wall flow demonstrate that near-wall is affected by the roughness quality.

In the present work LES with sub-grid-scale (SGS) model and RANS solutions are employed to simulate turbulent flow in a 3-D channel with rib and it is aimed to show the differences between LES and RANS solutions and the effect of the rib on the flow.

2. NUMERICAL MODEL

In this paper rectangular ribs mounted on one side of a channel to represent roughness are employed while the bottom wall of the channel is left smooth as shown in Fig.1a. Grid structured applied to the domain is seen in Fig.1b. As can be seen from this figure the numerical grid is densely allocated near the rib-roughened channel to resolve the flow characteristics around the ribs.



(a) **(b)**

Figure 1. Working domain (a), and mesh structures around the rib (b)

As a turbulence closure large eddy simulation (LES) and Reynolds averaged Navier-Stokes (RANS) approaches are considered. As it is well known that in LES solution, spectrum of turbulent eddies in the N-S equations is filtered which is a function of grid size. In this study eddies smaller than the grid size are removed and modeled by a SGS model. Filtered N-S that is the governing equations in LES are as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad \ldots(1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j} \qquad \ldots(2)$$

Sub-grid scale stress (SGS) which must be modeled:

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j \qquad \ldots(3)$$

$$\overline{u_i u_j} = \overline{\bar{u}_i \bar{u}_j} + \overline{\bar{u}_i u'_j} + \overline{u'_i u_j} + \overline{u'_i u'_j} \qquad \ldots(4)$$

The continuity and momentum equations for RANS solver are given as follows:

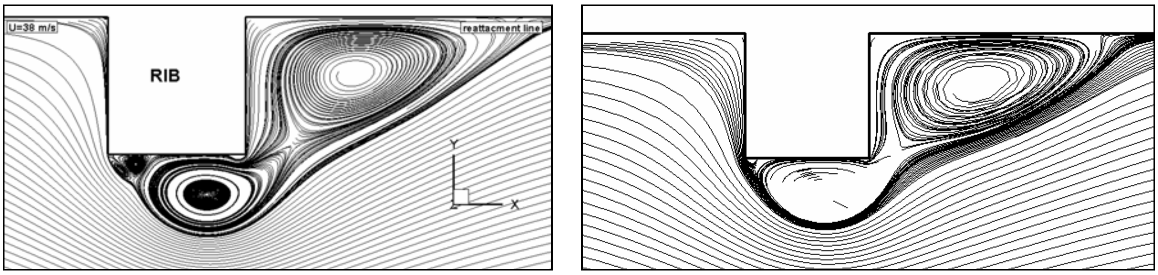
$$\frac{\partial U}{\partial x_i} = 0 \qquad \ldots(5)$$

$$\frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho}\left(\frac{\partial P}{\partial x_i} + \delta_{ij}\frac{\partial \langle P \rangle}{\partial x_1}\right) + \frac{\partial}{\partial x_j}\left(\upsilon \frac{U_i}{\partial x_j} - \overline{u_i' u_j'}\right) \qquad \ldots(6)$$

where U_i and P are Reynolds-averaged velocity and pressure, respectively. <P> is constant pressure gradient and ν is the kinematics viscosity. The last term is Reynolds stresses which must be modeled.

3. RESULTS

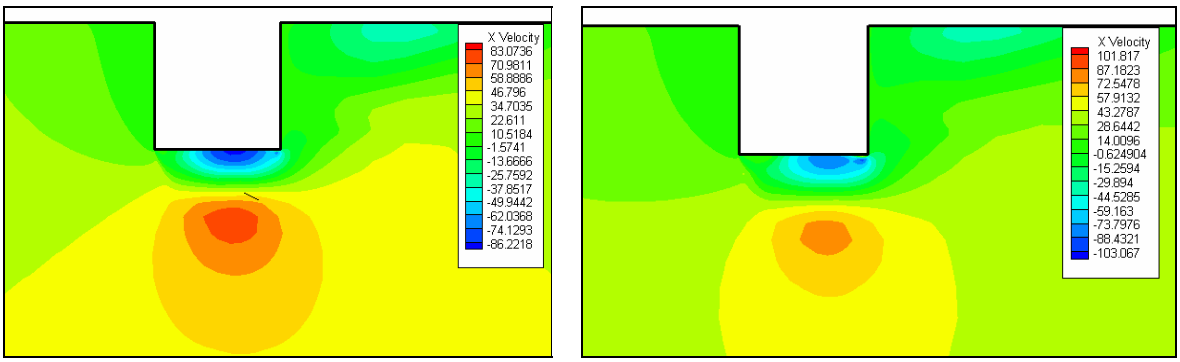
The streamlines of averaged three-dimensional velocity field of LES and RANS results are showed in Fig.2a and Fig.2b, respectively. These streamlines of the time-averaged flow in the region around the rib and at the center plane of the flow. A great deal of information about the flow can be discerned from this plot. In the LES case, several recirculation regions are developed upstream. At the leading edge of rib these two zones can be seen clearly.



(a) **(b)**

Figure 2. Streamlines generated by (a) LES and (b) RANS.

In the upstream corner there is no any separation zone but after the rib, at the downstream, a recirculaiton region is seen clearly. The head of the arch vortex occurs at approximately half-rib height from the upper wall.

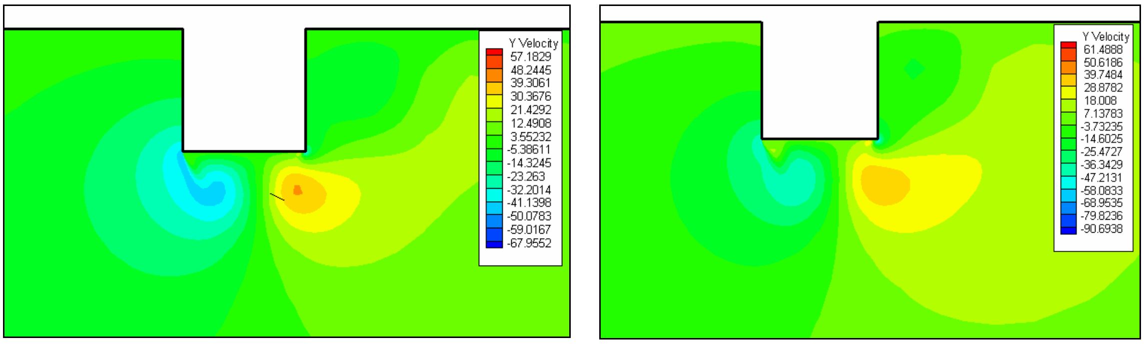


(a) **(b)**

Figure 3. Streamwise velocity contours generated by (a) LES and (b) RANS.

About two times of rib length reattacment line can be seen. Below the body, there are three different-size recirculaiton zones, two of them in upstream and another big one is at the downstream. These types of flow characteristics was reported by Shah and Ferziger, 1995[9] who studied flow around a wall-mounted cube. Compared with the LES solution, RANS shows different result because besides two main recirculation regions, the small zones occurred at the bottom of the ribs are not seen.

In addition to the streamlines x-velocity contours and y-velocity contours are presented in Fig.3 and fig.4, respectively. As can be seen from LES and RANS approaches, LES and RANS solution give different value and distribution. While y-velocity components give the similar value, x-velocity values are very different from each other. Fig.3 and Fig.4 show how the rib treated as an obstacle induces a strong acceleration of the flow approximately at the bottom of the rib. The sudden expansion after the rib leads flow separation and wide recirculation region as seen in Fig.2. It is clear that LES provides a gret deal of information about the flow.



(a) **(b)**

Figure 4. Vertical velocity contours generated by (a) LES and (b) RANS.

4. CONCLUDING REMARKS

In this paper, rib roughened channel are investigated numerically by LES and RANS solution. From the results it is seen that LES and RANS give different velocity fields and streamlines. Taken into account some reports seen in open literature about this kind of flow, it can be said that RANS model used here gives underestimate velocity fields and streamlines. Although LES approaches take more solution time and needs more efforts than RANS solution, it gives the best results as in reported in open literature.

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