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Large-eddy Simulation of Turbulent Square Duct Flow

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1. Introduction

Turbulent duct flows occur in many industrial applications, including combustion and air-conditioning systems. Contrary to the simple geometry, turbulent duct flow has a complex behavior. This complexity is due to the secondary motions forming in the vicinity of the corners (see Figure 1). Secondary flows are comprised of four corner vortex pairs, which rotate in opposite directions. Previous investigations indicate that turbulent shear stress gradients in the direction normal to the bisectors is responsible for the formation of these secondary flows.

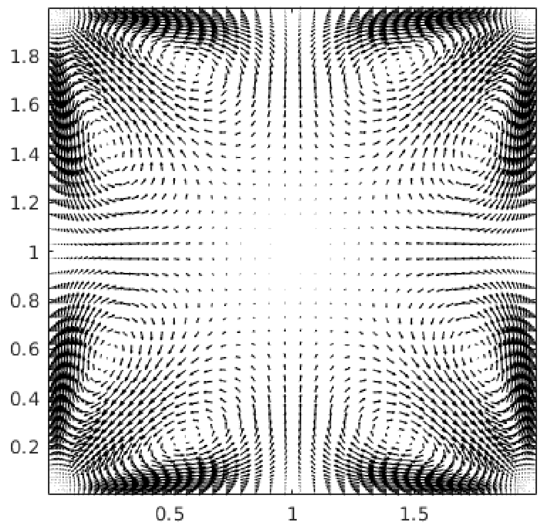

Figure 1. Vector plot of the mean velocity in a y-z plane

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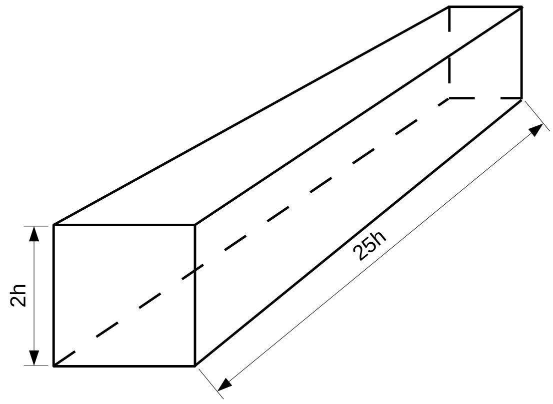

Figure 2. Schematic of the duct geometry.

Large-eddy simulation (LES) is an invaluable tool for numerical simulation of turbulent flows. Similar to direct numerical simulation (DNS), LES can provide instantaneous velocity and pressure fields. Although, it is computationally less expensive, its predictions are not as accurate as DNS. It is also well known that accuracy of LES predictions largely depends on the subgrid-scale model (SGS) formulation and flow complexity. In this respect, turbulent duct flow would be a good candidate for testing performance of SGS models for the prediction of complex turbulent flows. There has been a number of previous DNS and experimental studies on turbulent duct flows, but only a few LES studies. Hence, more LES studies on the performance of different SGS models for this type of flow seem to be necessary.

In the present study, LES is carried out for a turbulent square duct flow. Accuracy of LES prediction is assessed using a reference DNS data. To determine the effect of the SGS model on LES predictions, a simulation is also carried out without an SGS model. Results show that LES predictions have an appreciable improvement over no SGS model prediction for mean velocity and Reynolds stress quantities. But, the Reynolds stress anisotropy is not well-predicted for this type of flow.

2. Numerical method, geometry and SGS model

LESs are carried out using an open-source unstructured finite volume solver. The spatial and temporal discretization is carried out using a second-order scheme. The SIMPLEC algorithm is used for velocity-pressure coupling and Rhie-Chow interpolation is used to avoid oscillations in the solution.

The grid used in the simulations has a uniform spacing in the streamwise direction, whereas it is stretched in wall-normal directions, using a tangent-hyperbolic distribution, to capture the near wall turbulence structures. The LESs are carried out at a moderate resolution. Resolutions in wall units, i.e.

using wall friction velocity u_τ and kinematic viscosity υ, are given in Table 1.

Table 1. Simulation specifications. Resolutions are given in wall units: $\Delta x^+ = \Delta x u_\tau/\upsilon$, $\Delta y^+ = \Delta y u_\tau/\upsilon$ and $\Delta z^+ = \Delta z u_\tau/\upsilon$. $Re_\tau = hu_\tau/\upsilon$ is the friction Reynolds number.

Re_τ	Δz^+	Δy^+	Δx^+	SGS model	Case
142.1	9	9	35	Dynamic Smagorinsky	DS-SGS
154.8	11	11	28	−−	No-SGS
148.3	9	5	10	−−	DNS

The conventional dynamic Smagorinsky model is used as the subgrid-scale (SGS) model. Simulations are carried out at a fixed bulk Reynolds number $Re_b = h_b/\upsilon = 2800$. The flow geometry is shown in Figure 2. The simulation box length is 25 times the duct half width to accommodate for large turbulent structures that are formed in the duct.

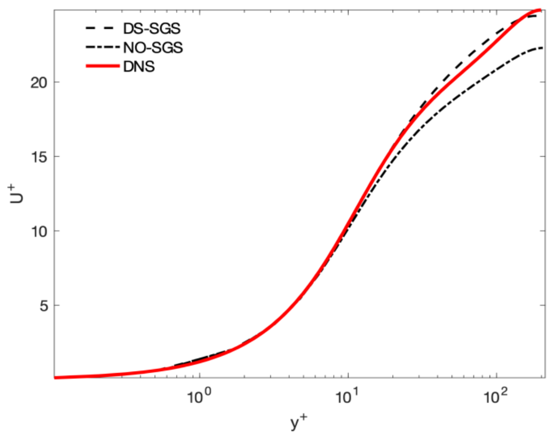

Figure 3. Mean velocity profiles U^+ in wall-units

3. Large-eddy simulations

Mean velocity profiles, at the center of the duct, are given in Figure 3. The DS-SGS simulation, with the dynamic Smagorinsky model, shows a good agreement with the reference DNS data at this point. There is a remarkable difference between the no-SGS model, prediction with the reference DNS data. The difference in the predictions is due to the over-prediction of the wall shear stress in this simulation. This is the situation often encountered in no-SGS model situations, where turbulence is not damped due to the lack of an SGS model.

Analysis of Reynolds stresses shows a similar behavior, like what is observed for the mean velocity profiles, for the streamwise and shear Reynolds stress profiles. Other components of the Reynolds stresses are only reasonably predicted by the dynamic Smagorinsky model. Hence, The Reynolds stress anisotropy is not correctly predicted by this model.

4. Conclusion

Large-eddy simulation (LES) of a turbulent square duct flow is carried out at a moderate resolution at the bulk Reynolds number $Re_b = u_b h/\upsilon = 2800$. LES is carried out using the conventional dynamic Smagorinsky subgrid-scale (SGS) model. Predictions are compared to a reference direct numerical simulation (DNS) and LES without an SGS model. LES showed a good agreement with the DNS data for the mean velocity and Reynolds stresses. Comparison with the no SGS model simulation showed that the SGS model makes an appreciable improvement in LES predictions of the mean velocity and Reynolds stresses over the no SGS model simulations. It was also observed that the Reynolds stress anisotropy was not captured properly. This was reflected in the excellent prediction of the streamwise and shear stress predictions, whereas other Reynolds stresses were predicted only reasonably acceptable. The reason for this behavior of the dynamic Smagorinsky model was argued to be due to its isotropic formulation. It is expected that at lower resolutions, where the SGS anisotropy becomes more pronounced, the differences in LES predictions with the DNS, become more prominent.