Large-eddy simulation of turbulent mixed convection in a vertical annulus with rotation of the inner cylinder

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Abstract: A large-eddy simulation of mixed convection in a vertical annular pipe flow with rotation of the inner cylinder is performed at Re=8900 and Pr=0.71. The objective of the present study is to perform a large-eddy simulation of vertical turbulent annular pipe flow with rotation of the inner cylinder, and to investigate the combined effects of buoyancy and rotation on the turbulent structures. The incompressible filtered Navier-Stokes equations are solved using a second order accurate finite difference method. Isoflux wall boundary conditions with low and high heating (Bo = 0.18 and 0.5) are imposed. Two rotation rates (N = 0.1716 and 0.2574) are used and the radius ratio (R') is 0.5. Many turbulent statistics are obtained to analyze the near-wall turbulent structures. The results show that the strong heating with a stationary inner wall causes distortions of the flow structure resulting in reduction of turbulent intensities, shear stress, and turbulent heat flux, particularly near the wall. In contrast, a substantial reduction in turbulent statistics is suppressed in the presence of inner wall rotation.

1. Introduction

Mixed convection in a vertical annular pipe flow with rotation of the inner cylinder is often encountered in engineering applications such as turbo machinery, rotating-tube heat exchangers, and the drilling of oil wells. In addition to the practical implications of achieving a better understanding of this type of flow, the study of turbulent rotating flows in concentric annuli provides insight into the general problem of three-dimensional turbulent boundary layers (TBLs).

The centrifugal force caused by the swirl induces stabilization or destabilization of the flow, depending on which wall of an annulus is rotating. When the inner wall of an annulus is rotated, enhancement of the turbulence is observed (Chung and Sung, 2005). The rate of heat transfer in annular pipe flow is also increased in the case of forced convection. In thermal system where forced flow and buoyancy-induced motion are encountered together, the mode of heat transfer is described as mixed convection. An explanation of the effects of buoyancy on turbulent heat transfer in vertical passages is given by Petukov and Polyakov (1988). When the motion near a heated surface is aided by buoyancy, the velocity is increased and the flow has a greater convective capacity. This is called ‘external’ effect. However, in the case of buoyancy-aided flow, the shear stress near the wall is reduced. Then, turbulence near the wall is suppressed. This is called ‘structural’ effect. In practice structural effect dominates and heat transfer is impaired. There is a significant disparity between inner wall rotation effect and structural effect on turbulence.

The objective of the present study is to perform a large-eddy simulation of vertical turbulent annular pipe flow with rotation of the inner cylinder, and to investigate the combined effects of buoyancy and rotation on the turbulent structures. A schematic diagram of the flow configuration is shown in Fig. 1. Isoflux wall boundary conditions with low and high heating are imposed. Two rotation rates (N = 0.1716 and 0.2574) are used and the radius ratio (R') is 0.5. The Reynolds number based on the bulk velocity \( V_m \) and the hydraulic diameter \( D_h \) is 8900. Many turbulent statistics are obtained to analyze the near-wall turbulent structures.

2. Numerical method

The incompressible filtered Navier-Stokes equations are written using Boussinesq approximation. The physical properties are regarded as constant except for the buoyancy term. Two Buoyancy numbers \( \text{Bo}(8*10^4 \text{Gr}/(\text{Re}^{2.425}\text{Pr}^{0.8}))=0.18 \text{ and } 0.5) \) are chosen for low and high heating. The working fluid is air, so that the Prandtl number (Pr) is 0.71. A dynamic localized subgrid-scale stress model (Piomelli and Liu, 1995) is used to account for the subgrid-scale turbulence. The governing equations are integrated in time using the fractional step method with the implicit velocity decoupling procedure proposed by Kim et al. (2002a).

Periodic boundary conditions are applied in the axial and circumferential directions for the velocity and temperature components, and a no-slip boundary condition is imposed at the solid wall. The inner wall of
the annular pipe is heated with constant heat flux. Zero temperature fluctuation at the inner wall is imposed. The adiabatic boundary condition \( q_w = 0 \) is applied for the outer wall. The computational domain is taken as one-quarter of the full cross-section of the concentric annular pipe. In all cases the computational length in the streamwise direction is \( L_z = 62.5 \delta \). The adequacy of the above computational domains is confirmed by calculating two-point correlations of the fluctuating streamwise velocities and temperature in the streamwise and azimuthal directions for all cases. The time step used is \( 0.03 \delta / V_c \) and the total averaging time is \( 1200 \delta / V_c \) in all cases, where \( V_c \) is the laminar maximum velocity of the non-rotating flow. In the wall-normal direction, grid points are clustered according to a hyperbolic tangent distribution. The number of grid points in the \( r \), \( \theta \), and \( z \) directions, respectively, is \( 65 \times 64 \times 320 \) for non-rotating cases, and \( 65 \times 64 \times 384 \) for rotating cases.

### 3. Results and discussion

Figure 2 shows the variation of the normalized skin friction at the inner wall according to the buoyancy

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R' = \frac{R_1}{R_2}
\]

\[
N = \frac{V_{in}}{V_{m}}
\]
number. Comparison with the DNS result of turbulent mixed convection in a vertical pipe (You et al., 2003) is made to represent the difference between pipe and annulus. Here, $C_{f\theta}$ is the skin-friction coefficient for forced convection with non-rotating inner wall and is evaluated as $9.2 \times 10^{-3}$. For non-rotating cases, the trend of $C_{f\theta}$ with Bo is similar to that of vertical pipe flow. The skin friction first decreases and then increases with increasing Bo. For rotating cases, the skin friction coefficients are increased in comparison with non-rotating cases. Moreover, this tendency becomes more pronounced as N increases. This is attributed to the destabilizing effect of inner wall rotation.

The normalized Nusselt number is shown in Fig. 3 with the experimental results (Kim et al., 2002b) and the DNS results of vertical pipe flow. The Nusselt number for forced convection is calculated to be 26.35. The Nusselt numbers for non-rotating cases show good agreement with experimental results. It is interesting to note that the impairment of heat transfer for N=0.0 develops more gradually than those for pipe flow. The reason is that such influences are present only on the inner wall of the annulus whereas in a pipe the entire wall is affected (Kim et al., 2002b). For rotating cases, the distributions of Nusselt numbers show similar trend to those of the skin frictions. However, note that the Nusselt number is decreased with increasing Bo at a fixed N. This phenomenon is due to the minor effect of rotation relative to heating effect.

The logarithmic velocity profiles in the axial direction are shown in Fig. 4. The profiles for the rotating and non-rotating systems differ considerably in the buffer and logarithmic regions. This discrepancy becomes more distinct with increasing N. The difference in behavior observed is attributed to the effect of the rotation of the inner wall, which results in an increase in the frictional velocity.

To further find out the buoyancy/rotation effect on mean flow field, figure 5 depicts the calculated mean azimuthal velocities normalized by the rotational speed of the inner wall. The velocity gradient undergoes very abrupt changes near the walls and profiles near the walls show almost the same trend independent of N and Bo. Note that the deviation of profiles for N=0.2574 is smaller than that of N=0.1716. This result is consistent with the findings in mean streamwise velocity distributions.

Figure 6 exhibits the mean temperature distributions in wall coordinates. It is seen that temperature profiles are shifted upward with increasing Bo due to the strong external effect of buoyancy. Note that this tendency becomes relatively small for rotating cases. This verifies that inner wall rotation suppresses the external effect.

The wall-normal Reynolds shear stresses and turbulent heat fluxed are displayed in Figs. 7 and 8, respectively. The positions of zero shear are skewed toward the inner walls as pointed out by the previous study (Zarate et al., 2001). In addition, the magnitudes of Reynolds shear stresses and turbulent heat fluxes become smaller with increasing Bo. This is due to the strong structural effect of buoyancy. However, it should be noted that the values of shear stresses and
turbulent heat fluxes are promoted for rotating cases. This suggests that the inner wall rotation suppresses the structural effect. The structural effect arises from the turbulent density fluctuations in the gravitational field and is represented by the buoyant production term in the turbulent kinetic energy equation. In the case of upward flow like the present study, the structural effect brings reduced turbulence in the flow. The secondary mean shear produced by inner wall rotation makes production terms in the turbulent kinetic energy equations and this promotes turbulence. So, buoyancy and inner wall rotation has a competitive relation from each other.

4. Summary

In the present study, a LES has been performed for turbulent mixed convection in a rotating vertical concentric annulus at Re = 8900 and Pr = 0.71 for two buoyancy number (Bo=0.18 and 0.5) and two rotation rates (N=0.1716 and 0.2574). Main emphasis was placed on the combined rotation effect with buoyancy on near-wall turbulent thermal structures. At first, the skin friction coefficients and Nusselt numbers were represented to show and compare the mean thermal properties. It was found that the values of mean quantities for rotating cases were larger than those of non-rotating ones. The simulations showed that, when the inner wall was rotated, the slopes of the mean velocity and temperature profile near the inner wall were lower in the logarithmic region. Overall turbulent thermal statistics of rotating cases were larger than those of non-rotating cases due to the reduced structural effect. This tendency was more apparent for high rotation rates. The present numerical results showed that buoyancy and inner wall rotation has a competitive relation from each other.

References


