Direct Numerical Simulation of Vertical Rotating Turbulent Open-Channel Flow with Heat Transfer

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Abstract. Direct numerical simulation of vertical rotating open-channel flow with heat transfer has been carried out for the rotation number N_τ from 0 to 0.1, the Prandtl number 1, and the Reynolds number 180 based on the friction velocity of non-rotating flow and the height of the channel. The objective of this study is to reveal the effect of rotation on the characteristics of turbulent flow and heat transfer, in particular near the free surface and the wall of the open-channel. Statistical quantities, e.g., the mean velocity, temperature and their fluctuations, turbulent heat fluxes, and turbulence structures, are analyzed. The depth of surface-influenced layer decreases with the increase of the rotation rate. In the free surface-influenced layer, the turbulence and thermal statistics are suppressed due to the effect of rotation. In the wall-influenced region, two typical rotation regimes are identified. In the weak rotation regime with $0 < N_\tau < 0.06$ approximately, the turbulence and thermal statistics correlated with the spanwise velocity fluctuation are enhanced since the shear rate of spanwise mean flow induced by Coriolis force increases; however, the other statistics are suppressed. In the strong rotation regime with $N\tau > 0.06$, the turbulence and thermal statistics are suppressed significantly because the Coriolis force effect plays a dominate role in the rotating flow. To elucidate the effect of rotation on turbulent flow and heat transfer, the budget terms in the transport equations of Reynolds stresses and turbulent heat fluxes are investigated. Remarkable change of the direction of streak structures based on the velocity and temperature fluctuations is discussed.

Key words: Direct numerical simulation (DNS); rotating turbulent flow; turbulent heat transfer; thermal statistics; coherent structure.

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1   Introduction

Turbulent flows with heat transfer in a rotating frame exist in a variety of industrial, geophysical, and astrophysical applications. The rotation induces additional body forces, i.e., centrifugal and Coriolis forces, acting on the turbulent flow, so that the momentum transfer mechanism becomes more complex. Understanding the mechanism of turbulent flow and heat transfer in rotating system is of great importance. Usually, a simple and convenient way to investigate rotating turbulent flow is rotating channel flows, where the rotating axis can be chosen as that parallel to one of the three directions, i.e., the streamwise, spanwise and wall-normal directions [1].

The spanwise rotating turbulent channel flows have been studied experimentally and numerically [2-7]. With increasing rotation rate, turbulence is gradually enhanced on the pressure side and reduced on the suction side. Large-scale rotational-induced roll cells due to Taylor-Görtler instability occur in the cross-sectional plane of the channel [2, 3]. On the other hand, the streamwise rotating turbulent channel flows were also investigated numerically. Compared with the spanwise rotation effect, the influence of the streamwise rotation on turbulent channel flow is much weaker [1]. The streamwise rotation induces a mean velocity in the spanwise direction. The quasi-streamwise near-wall vortical structures rotating in the same direction are enhanced, whereas the opposite ones are reduced, and consequently the average spacing between the low- and high-speed streaky structures becomes much larger than that in a non-rotating channel flow.

In a wall-normal rotating channel flow, since the mean vorticity component is perpendicular to the rotating axis, turbulent channel flow is very sensitive to the wall-normal rotation, even though a slight system rotation can induce a significant spanwise mean velocity [1]. As a result, the absolute mean flow deviates from the initial streamwise direction, which redirects the mean shear and the turbulence structures. The interaction between the vorticity of coherent structures and the background vorticity due to imposed wall-normal rotation can significantly change the near-wall turbulence behavior [8, 9]. The statistical coherent structures are verified to be more sensitive to the Coriolis force effect induced by the wall-normal rotation.

It is well established that direct numerical simulation (DNS) is effective to explore the mechanism of turbulent flow and heat transfer and to provide detailed turbulence and thermal quantities which are essential to construct a turbulence model [7, 10, 11]. The determination of the thermal budget terms in the transport equations of turbulent heat fluxes is of great importance to the closure of the turbulent heat fluxes. Based on the DNS of turbulent channel flow with heat transfer, it is found that the temperature-pressure gradient correlation is a dominant term in the budget of wall-normal turbulent heat flux [12, 13]. The turbulent diffusion and dissipation terms in the budgets of turbulent heat fluxes are physically meaningful to the construction and assessment of the turbulence model involving heat transfer [7, 11]. Thus, it is highly tempting to investigate the effects of rotation on the budget terms of turbulent heat fluxes.

As described above, extensive investigations of the rotating two-walled channel flows