FINE SCALE EDDIES IN TURBULENT TAYLOR-COUETTE FLOW UP TO RE = 25 000

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Abstract Reynolds number effects on fine scale eddies in the turbulent Taylor-Couette flow have been investigated by high accuracy direct numerical simulations from *Re* = 8000 to 25 000. The Reynolds number dependency of the mean torque changes near *Re* = 10 000, and the transition is closely linked to the turbulence characteristics. As the Reynolds number increases, the fine scale eddies are more densely populated and take more various tilting angles. The joint probability density function of the tilting angle and the radial position exhibits a preferential pattern corresponding to the large scale motion of Taylor vortices. The present results suggest that in this Reynolds number range, the fine scale eddies progressively prevail a large part of the domain, and their contribution to the fundamental statistics such as the Reynolds shear stress becomes more evident.

INTRODUCTION

Taylor-Couette flow has been investigated because of its significance in engineering applications. The Reynolds number dependency of the mean torque exhibits a transition near *Re* = 10 000, as is described by the Wendt's empirical function [1]. The transition is considered to be linked to the change in the flow structures. As the Reynolds number increases, the small scale turbulence structures develop and contribute more to flow characteristics. Recent experimental [2] and numerical [3] studies found that high Reynolds number Taylor-Couette flows approach to the fully developed turbulent state. However, the characteristics of fine scale eddy in high Reynolds number conditions and their relation to the torque transition have not been fully understood. In this study, direct numerical simulations (DNS) of the Taylor-Couette flow have been conducted with a high accuracy spectral method to clarify Reynolds number effects on the fine scale eddies.

NUMERICAL METHODS

DNS of the Taylor-Couette flow with a rotating inner cylinder and a fixed outer cylinder is conducted using the same method as in our previous study [4]. The governing equations are the incompressible Navier-Stokes equation and the continuity equation in a cylindrical coordinate system. These equations are normalized by the rotation speed of the inner wall U_{in} and the gap width d. The periodic boundary condition is applied in the axial direction. For the spatial discretization, the Fourier-Chebyshev spectral method is adopted. The time integration is implemented with Adams-Bashforth method for non-linear terms and backward-Euler method for the other terms to satisfy the continuity equation with the influence matrix method. For the calculation conditions, the radius ratio η and the height of the computational domain h are fixed to 0.8 and $5d$ respectively. The DNS have been performed at different Reynolds numbers *Re* (= dU_{in}/ν) = 8000, 12 000, 20 000 and 25 000, where the Reynolds number dependency of the mean torque changes.

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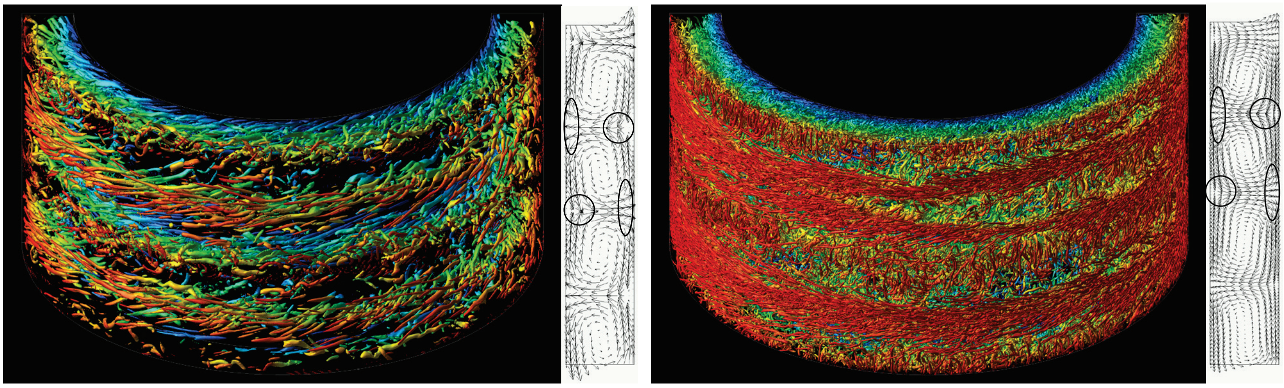
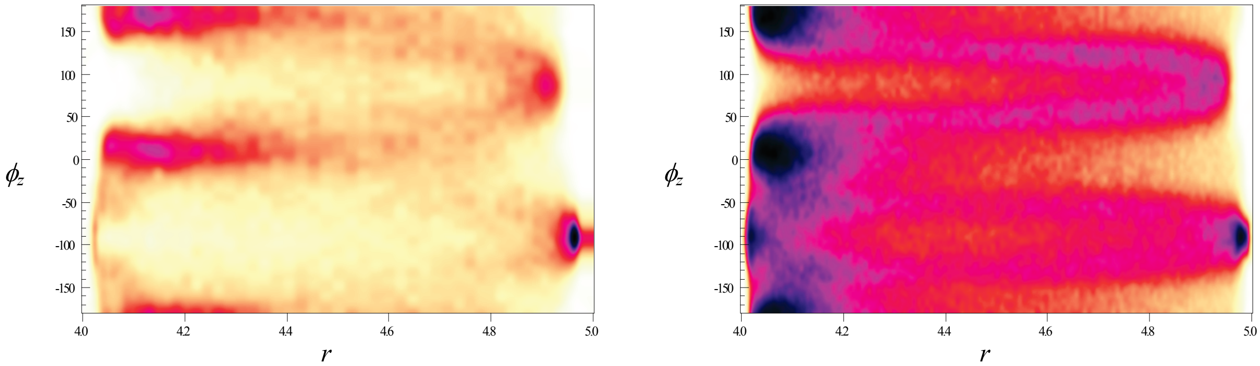
Figure 1 shows iso-surfaces of the second invariant of the velocity gradient tensor Q and the mean velocity field in r - z plane at *Re* = 8000 and 25 000. In the mean velocity field, two pairs of Taylor vortices are observed in the both Reynolds number cases. At *Re* = 8000, the fine scale structures visualized by the iso-surfaces of Q, are found mostly in the ejection region where the fluid moving away from the wall. On the other hand at *Re* = 25 000, bifurcation of Taylor vortices occurs and the fine scale structures distribute in the whole domain including in the sweep region where the fluid impinges toward the wall. In the sweep region, the number density of the fine scale eddies is relatively sparse, and the eddies tend to align in the axial direction. Note that the axially aligning eddies are found in all the Reynolds number cases including the one with bifurcation of the Taylor vortices.

To investigate the spatial distribution and orientation of fine scale eddies, an eddy is identified by the local maximum of Q. The axis of the eddy is defined by the direction of the vorticity vector. The orientation of the eddy is evaluated by the tilting angle ϕ_z, which is defined as the angle between the tangential direction and the eddy axis projected on the θ - z plane. Figure 2 shows the distributions of conditionally averaged joint probability density functions (PDF) of ϕ_z and the radial position in the ejection region in the inner wall side. At *Re* = 8000, eddies with low tilting angle are dominant in the inner wall side. As shown in Figure 1(a), these eddies correspond to the herringbone streaks presented by Dong [5]. In the outer wall side corresponding to the sweep region, the majority of eddies exhibit the tilting angle at ±90 degrees. Note that these axially aligning eddies are relatively weak and less pronounced in Figure 1(a). These observations are consistent with our previous study [4] with the identification of the coherent fine scale eddy, which considers sub-grid



(a) $Re = 8000$ (b) $Re = 25\,000$

Figure 1. Iso-surfaces of the second invariant of the velocity gradient tensor ($Q = 1.0$, colored by the radial position) and time-azimuthally averaged mean velocity in r-z plane (circle: ejection regions, ellipse: sweep regions).



(a) $Re = 8000$ (b) $Re = 25\,000$

Figure 2. Joint PDF of the tilting angle, ϕ_z, and radial position, r, averaged in the ejection region in the inner wall side.

identification of the eddy location and confirmation of the swirling motion around its axis as well.

The pattern of joint PDF significantly changes in the higher Reynolds number conditions. Although the preferential alignment is still observed in both inner and outer wall sides, eddies take more various angles as the Reynolds number increases. This is also apparent from the visualization in Figure 1(b). These eddies are mainly populated in the ejection region as a result of the near wall turbulence production, and they are strong enough to prevail in a large part of the domain at $Re = 25\,000$. In the center region, the eddies with the tilting angles near ±50 and ±130 degrees are noticeable. These eddies tend to be found in the region between Taylor vortices, and they are convected and stretched in the shear layer between the Taylor vortices. Therefore, it is considered that the pattern of the preferential alignment of fine scale eddy across the domain is determined by the large scale Taylor vortex motion. Since the Reynolds stress in the middle of the domain contribute significantly to the mean torque, the change of the turbulence structures in this region is directly related to the torque transition.

CONCLUSION

A series of DNS of Taylor-Couette flow has been conducted with a high accuracy spectral method to clarify Reynolds number effects on the fine scale eddies from $Re = 8000$ to 25 000. As the Reynolds number increases, the number density of fine scale eddies significantly increases and the orientation of eddies takes more versatile tilting angles. The joint PDF of the tilting angle and the radial position shows a preferential distribution across the domain, which is closely related to the large scale motion of Taylor vortices. The present results suggest that the contribution of fine scale eddies on the fundamental statistics becomes more significant in this Reynolds number range.

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