Turbulence maintenance limitation at low Reynolds number in annular Couette flow with very small radius ratios

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We investigated turbulence maintenance limitation in annular Couette flow (ACF) with very-small radius ratios, such as pipe geometries, at the subcritical transition for $Re = O(10^2)$, where the typical turbulent puff was observed. In ACF, a fluid between coaxial double cylinders is driven by axial sliding of the inner cylinder. The channel geometry is defined by the radius ratio η ($\equiv r_{\text{in}}/r_{\text{out}}$), with $\eta \to 1$ indicating a planar flow (PCF) while $\eta \to 0$ a pipe geometry. The linear stability of ACF is extremely high compared to the present targets, with the critical Reynolds number of linear stability $Re_L \to \infty$ for $\eta \geq 0.1415$, and $O(10^5)$ for lower η[1]. The shear stress becomes intensely strong only near the inner cylinder wall due to the shrinking of the inner cylinder's radii as shown in the curved laminar velocity distributions (Figure 1(a)).

In the present study, the very high curvatures as $\eta = 0.0001$, 0.001, and 0.01 were targeted, leading to wall-bounded boundary layer flows that developed to a statistically steady state. Note that in the present simulations of Navier–Stokes equations for the incompressible Newtonian fluid, the direct numerical solutions were applied.

Typically, turbulent puffs form global intermittently in ACF with $\eta = 0.1$ for $Re = 400$[2], and similar results were obtained for $\eta = 0.01$. Whereas, with much smaller radius ratios ($\eta = 0.0001$ and 0.001), weak turbulence including quasi-periodic vortices maintained a statistically steady state at even lower Reynolds numbers $Re = 100$, shown in Figure 1(b). This staggered structure of weak turbulence with obliquely aligned streaks (Figure 1(c)) is similar to the periodic structure that appears in the annular flow as a gap instability due to the eccentricity of a double cylinder[3]. Turbulence statistics and correlations will be discussed for the staggered structure.

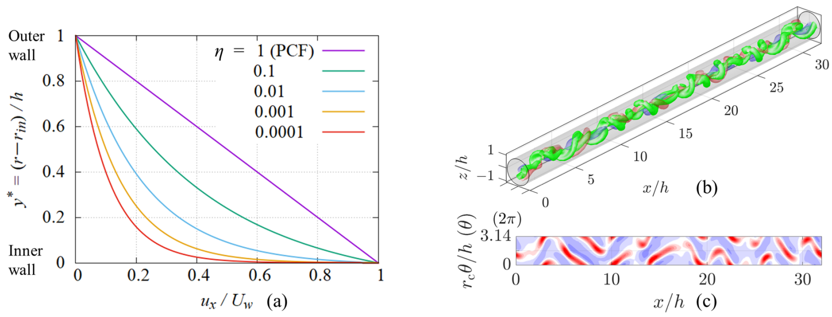

Figure 1: (a) Laminar flow profiles of mean streamwise velocity $u_x(y)$ in annular Couette flow (ACF) with different radius ratios. Turbulent structures in ACF with $\eta = 0.0001$ for $Re = 100$ in (b) 3D view and (c) (r–θ) plane at the central gap $r_c = (r_{\text{in}} + r_{\text{out}})/2$. In the 3D view, the green shows the second invariant of the velocity gradient tensor with $q^* = -1.5 \times 10^{-8}$, and the red/blue indicates the streaks as the axial velocity fluctuation $|u_x'^*| = 0.025$. In the (r–θ) plane, red/blue indicates the radial velocity $|u_r'^*| = 0.05$.

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