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Direct Numerical Simulation of Reverse Transition from Turbulence in Plane Poiseuille Flow

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ABSTRACT

Problems of transition from laminar to turbulent flow are important not only in engineering applications such as boundary layer control to avoid flow separation but also scientific fields connected with investigation of turbulent flows. In particular, reverse transition, namely relaminarization from turbulence, can be useful for finding out the nature of turbulence. This is because in the reverse transition, flow characteristics presented in turbulent region decay and disappear as Reynolds number becomes smaller, while in the normal transition, they suddenly appear and are difficult to analyze in detail. Therefore, researchers have recently made experimental and numerical investigations into relaminarization in plane Couette flow [1] and in pipe flow [2][3]. In the present study, the relaminarization in plane Poiseuille flow is investigated using Direct Numerical Simulation (DNS) method, and the threshold of the relaminarization is estimated. Also, dynamic behavior of the streaky structure is simulated in the relaminarization.

We consider an incompressible viscous fluid in a rectangular domain whose size is $4\pi b$, $2b$ and $2\pi b$ in the x-, y- and z-directions, respectively, where b is half width of the channel and chosen as a characteristic length hereafter. The governing equations are the continuity equation and the Navier-Stokes equations in non-dimensional form in Cartesian coordinates. The numerical method is the DNS based on a spectral method [4]. The no-slip boundary condition is used on the walls in the y-direction, and the periodic boundary condition is used on the sides in the z-direction. Also, the periodic boundary condition with pressure gradient is imposed at the inlet and the outlet in the x-direction. It should be noted that the pressure gradient is corrected at every time step so that the flow rate can be kept constant after reduction of Reynolds number [5]. The initial condition is given by turbulent flow velocity and pressure fields at Re = 1740 in the whole domain, where Re is the Reynolds number based on the

streamwise velocity at the centerline of the channel. Note that $\mathrm{Re} = 1740$ corresponds to $\mathrm{Re}_\tau = 100$ which is Reynolds number defined by the friction velocity on the wall. In the calculations, the time when Re is instantaneously reduced to a certain value between 800 and 1200 is reset to dimensionless time $t^* = 0$.

Figure 1 shows time variation of turbulent energy for different Reynolds numbers. The turbulent energy is normalized by the initial value at $\mathrm{Re} = 1740$. The symbols, □, △, + and ○, indicate the results at $\mathrm{Re} = 800$, 1000, 1100 and 1200, respectively. It is seen that the turbulent energies at $\mathrm{Re} = 800$, 1000 and 1100 decay and approach zero with time. In contrast to these results, the turbulent energy at $\mathrm{Re} = 1200$ falls at first and then it rises around $t^* = 60$. After $t^* = 150$, it decreases and increases repeatedly and finally approaches a certain value. These results mean that judging from the turbulent energy, the threshold of the relaminarization is expected to exit between $1100 < \mathrm{Re} < 1200$. Moreover, in the case of $\mathrm{Re} = 1100$, above which the relaminarization may occur, a relatively large peak of the turbulent energy can be seen around $t^* = 160$. Thus, we next investigate the relation between flow characteristics and the turbulent energy.

Figure 2 shows the flow structure on z-y plane for $\mathrm{Re} = 1100$ at $t^* = 160$. In this figure, the solid lines indicate the contour of streamwise velocity, and the vectors are composed of the wall-normal and spanwise velocities. From this figure, it is seen that ejections from the bottom wall occur around $z/b = \pm 0.75$ and that these spots correspond to positions where the low speed streaks appear. In addition, the ejections are not observed at $t^* = 60$ when the turbulent energy drops to the local minimum. Consequently, it is considered that the ejections around low speed streaks contribute to the rise in the turbulent energy at $\mathrm{Re} = 1100$.

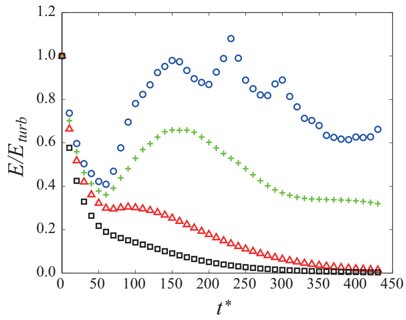

Figure 1: Time variation of turbulent energy: □, $\mathrm{Re} = 800$; △, $\mathrm{Re} = 1000$; +, $\mathrm{Re} = 1100$; ○, $\mathrm{Re} = 1200$.

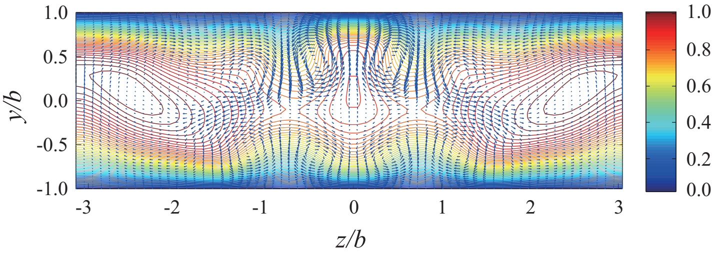

Figure 2: Flow strcture on z-y plane for $\mathrm{Re} = 1100$ at $t^* = 160$.

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