Abstract

Understanding the structure of turbulence in flow after transition to turbulence in soft walled microchannels.

After transition in a soft-walled microchannel

In comparison to the flow in a rigid channel, there is a multi-fold reduction in the transition Reynolds number for the flow in a microchannel when one of the walls is made sufficiently soft, due to a dynamical instability induced by the fluid-wall coupling. The flow after transition is characterised using Particle Image Velocimetry (PIV) in the $x-y$ plane where $x$ is the stream-wise direction and $y$ is the cross-stream co-ordinate along the small dimension of the channel of height $0.2 - 0.3$ mm. For the two different soft walls of shear modulus 18 kPa and 2.19 kPa, the transition Reynolds number is about 250 and 330 respectively. The deformation of the microchannel due to the applied pressure gradient is measured in the experiments, and is used to predict the laminar mean velocity profiles for comparison with the experimental results. The mean velocity profiles in the microchannel are in quantitative agreement with those predicted for the laminar flow before transition, but are flatter near the centerline and have higher gradients at the wall after transition. The flow after transition is characterised by a mean velocity profile that is flatter at the center and steeper at the walls in comparison to that for a laminar flow. The root mean square of the stream-wise fluctuating velocity shows the characteristic sharp increase from the wall and a maximum close to the wall, as observed in turbulent flows in rigid-walled channels. However, the profile is asymmetric with a significantly higher maximum close to the soft wall in comparison to that close to the hard wall, and the Reynolds stress is found to be non-zero at the soft wall, indicating that there is a stress exerted by fluid velocity fluctuations on the wall. The turbulent energy production profile has a maximum at the soft wall, in contrast...
to the flow at a rigid surface where the turbulent energy production is zero at the wall (due to the zero Reynolds stress). The maximum of the root mean square of the velocity fluctuations and the Reynolds stress (divided by the fluid density) in the soft-walled microchannel for Reynolds numbers in the range 250-400, when scaled by suitable powers of the maximum velocity, are comparable to those in a rigid channel at Reynolds numbers in the range 5000-20000. The near-wall velocity profile shows no evidence of a viscous sub-layer for \((y v_\star/\nu)\) as low as 2, but there is a logarithmic layer for \((y v_\star/\nu)\) up to about 30, where the von Karman constants are very different from those for a rigid-walled channel. Here, \(v_\star\) is the friction velocity, \(\nu\) is the kinematic viscosity and \(y\) is the distance from the soft surface. The surface of the soft wall in contact with the fluid is marked with dye spots to monitor the deformation and motion along the fluid-wall interface. The measured displacement of the surface in the stream-wise direction, which is of the order of 5–12\(\mu\)m, is consistent with that calculated on the basis of linear elasticity. Low-frequency oscillations in the displacement of the surface are observed after transition in both the stream-wise and span-wise directions, indicating that the turbulent velocity fluctuations are dynamically coupled to motion in the solid.

**Modification of soft-wall turbulence in a microchannel due to the addition of small amounts of polymer**

The modification of soft-wall turbulence in a microchannel due to the addition of small amounts of polymer is experimentally studied using Particle Image Velocimetry (PIV) to measure the mean and the fluctuating velocities. The microchannels are of rectangular cross-section with height about 160 \(\mu\)m, width about 1.5 mm and length about 3 cm, with three walls made of hard Polydimethylsiloxane (PDMS) gel, and one wall made of soft PDMS gel with an elasticity modulus of about 18 kPa. A dynamical instability of the laminar flow
due to the fluid-wall coupling, and a transition to turbulence, is observed at a Reynolds number of about 290 for the flow of pure water in the soft-walled microchannel (Verma and Kumaran, J. Fluid Mech., 727, 407-455, 2013). Solutions of polyacrylamide of molecular weight \(5 \times 10^6\) and mass fraction up to 50 ppm, and of molecular weight \(4 \times 10^4\) and mass fraction up to 1500 ppm, are used in the experiments. In all cases, the solutions are in the dilute limit below the critical concentration where the interactions between polymer molecules become important. The modification of the fluid viscosity due to addition of polymer molecules is small; the viscosity of the solutions with the highest polymer concentration exceed those for pure water by about 10\% for the polymer with molecular weight \(5 \times 10^6\), and by about 5\% for the polymer with molecular weight \(4 \times 10^4\). Two distinct types of flow modifications below and above a threshold mass fraction for the polymer, \(c_{\text{threshold}}\), which is about 1 ppm for the polyacrylamide with molecular weight \(5 \times 10^6\), and about 500 ppm for the polyacrylamide with molecular weight \(4 \times 10^4\). As the polymer mass fraction increases up to the threshold value, there is no change in the transition Reynolds number, but there is significant turbulence attenuation — the root mean square velocities in the streamwise and cross-stream directions decrease by a factor of 2, and the Reynolds stress decreases by a factor of 4 in comparison to that for pure water. When the polymer concentration increases beyond the threshold value, there is a decrease in the decrease in the transition Reynolds number by nearly one order of magnitude, and a further decrease in the intensity of the turbulent fluctuations. The lowest transition Reynolds number of about 35 for the solution of polyacrylamide with molecular weight \(5 \times 10^6\) and mass fraction 50 ppm. For the polymer solutions with the highest concentrations, the fluctuating velocities in the streamwise and cross-stream direction are lower by a factor of 5, and the Reynolds stress is lower by a factor of 10, in comparison to pure water. Despite the significant turbulence attenuation, a sharp increase in the intensity of the
fluctuating velocities is evident at transition for all polymer concentrations.

**Transitions to different kinds of turbulence in a channel with soft walls**

The flow in a rectangular channel with walls made of soft polyacrylamide gel is studied to examine the effect of soft walls on transition and turbulence. The width of the channel is much larger than the height, so that the flow can be considered approximately two-dimensional, the wall thickness is much larger than the channel height (smallest dimension), the bottom wall is fixed to a substrate and the top wall is unrestrained. The fluid velocity is measured using Particle Image Velocimetry, while the wall motion is studied by embedding beads in the soft wall, and measuring the time-variation of the displacement both parallel and perpendicular to the surface. As the Reynolds number increases, two different flow regimes are observed in sequence. The first is the ‘soft-wall turbulence’ resulting from a dynamical instability of the base flow due to the fluid-wall coupling. The flow in this case exhibits many of the features of the turbulent flow in a rigid channel, including the departure of the velocity profile from the parabolic profile, and the near-wall maxima in the stream-wise root mean square fluctuating velocity. However, there are also significant differences. The turbulence intensities, when scaled by suitable powers of the mean velocity, are much larger than those after the hard-wall laminar-turbulent transition at a Reynolds number of about 1000. The Reynolds stress profiles do not decrease to zero at the walls, indicating that the wall motion plays a role in the generation of turbulent fluctuations. There is no evidence of a viscous sub-layer close to the wall to within the experimental resolution. The mean velocity profile does satisfy a logarithmic law close to the surface within a region between 2-30 wall units from the surface, but the von Karman constants are very different from those for the hard-wall turbulence. The wall displacement measurements indicate that there is no observable motion perpendicular to the surface, but displacement
fluctuations parallel to the surface are observed after transition, coinciding with the onset of velocity fluctuations in the fluid. The fluid velocity fluctuations are symmetric about the center line of the channel, and they show relatively little downstream variation after a flow development length of about 5 cm. As the Reynolds number is further increased, there is a second ‘wall flutter’ transition, which involves visible downstream traveling waves in the top (unrestrained) wall alone. Wall displacement fluctuations of low frequency (less than about 500 rad/s) are observed both parallel and perpendicular to the wall. The mean velocity profiles and turbulence intensities are asymmetric, with much larger turbulence intensities near the top wall. There is no evident logarithmic profile close to either the top or bottom wall. Fluctuations are initiated at the entrance of the test section, and the fluctuation intensities decrease with downstream distance, the fluctuation intensities first rapidly increase and then decrease as the Reynolds number is increased. For a channel with relatively small height (0.6 mm), the transition Reynolds number for the soft-wall instability is lower than the hard-wall transition Reynolds number of about 1000, and the laminar flow becomes unstable to the soft-wall instability leading to soft-wall turbulence and then to wall flutter as the Reynolds number is increased. For a channel with relatively large height (1.8 mm), the transition Reynolds number for the soft-wall instability is higher than 1000, the flow first undergoes the hard-wall laminar-turbulent transition at a Reynolds number of about 1000, the turbulent flow undergoes the soft-wall transition leading to soft-wall turbulence, and then to wall flutter.