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Laminar-Turbulent Transition of a Boundary Layer by a Single Roughness Element in an Inlet Region of a Circular Pipe

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Abstract

An artificially triggered transition due to a local disturbance source in an inlet region in a circular pipe has been investigated experimentally. To create the disturbance, a single roughness element was installed on the pipe wall, thus forming a steady turbulent region downstream. Hot-wire measurements of the axial mean and fluctuating velocities were obtained. A peripheral development of the turbulent region was examined with the aid of an intermittency factor. The turbulent region was similar to a turbulence wedge formed downstream of a single roughness element in a flat-plate laminar boundary layer.

Introduction

Because pipe flows have been used in a wide variety of engineering fields, it is important to understand their properties. Flows within a pipe are limited not only by turbulence but also by transitions. For this reason, laminar-turbulent transitions in pipes have long been investigated since the work of Reynolds in 1883 [2].

From a variety of theoretical and experimental investigations [5,3], the flow in a fully developed region has been found to be stable in regard to axisymmetric and small non-axisymmetric disturbances. For this reason, the flow in an inlet region is important with respect to any transition in the pipe. There have not, however, been many investigations into a transition due to disturbances within the inlet region. Such investigations may generally be divided into one of two types: one is focused on the instability process from a perturbation to a hairpin vortex, and the other on established turbulent patches. A turbulent slug in a high Reynolds number and low-turbulence pipe flow, or a turbulent puff in a low Reynolds number and high-turbulence pipe flow corresponds to the turbulent patch. Both can be observed in the region downstream of various disturbances within the pipe, although they have also been observed in a developed flow in many experiments [6,7]. In addition, all such disturbances were constant or periodic in the azimuthal direction.

In the present experiment, however, a local point-like disturbance was introduced in the inlet region, and the resulting turbulent region just behind the disturbance was observed. A single roughness element was employed to create the disturbance. When such an element is introduced in a flat-plate laminar boundary layer, once the Reynolds number exceeds a certain critical value, a wedge-shaped turbulent region (turbulence wedge) is formed [4]. The vertex of the wedge is at the roughness position. The turbulence wedge does not propagate downstream but exists in a stationary state. In the present pipe flow, a stationary turbulent region was formed just behind the roughness, similar to the one in the flat plate. The present investigation is focused on the developing property in the turbulent region.

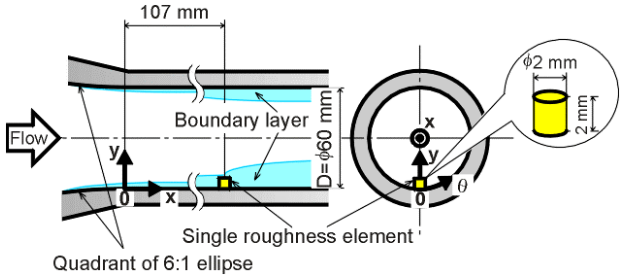

Figure 1. Coordinate system and single roughness element.

Experimental Apparatus and Methods

A Plexiglas pipe with a diameter, D, of 60 mm and a total length of approximately 6200 mm (=103D) was used in the experiment. A fan downstream of the pipe sucked air into the pipe. Figure 1 shows the coordinate system and roughness element. An axial coordinate, x, starts from a position where the curvature of an inlet bell-mouth curve becomes straight. The origin of that coordinate is 90 mm downstream from the inlet. The roughness element is a cylinder 2 mm both in diameter (d) and height (k), and is mounted on the pipe wall. The axis of the roughness element is perpendicular to the wall. The downstream distance of the roughness element from the coordinate origin, x_k, is 107 mm. The boundary layer at this position without the roughness element is laminar and has a thickness of 3.5 mm. Therefore, the top of the roughness element is kept within the boundary layer.

The Reynolds number based on the pipe diameter and the velocity averaged over the cross-section is 20000. The roughness Reynolds number based on the roughness height and the velocity at the top of the roughness is 610. The turbulent level at the pipe centerline is approximately 0.6%. The axial similarity of the velocity is satisfactory.

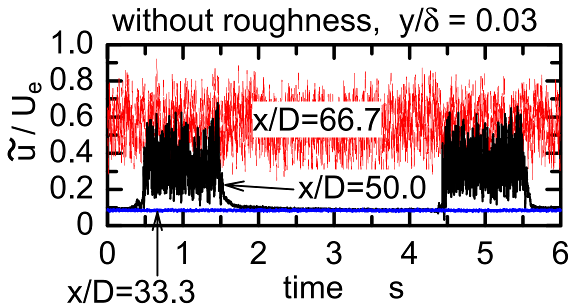

Figure 2. Instantaneous velocity signals.

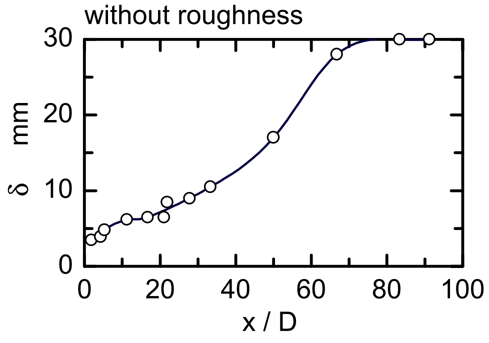

Figure 3. Boundary-layer thickness.

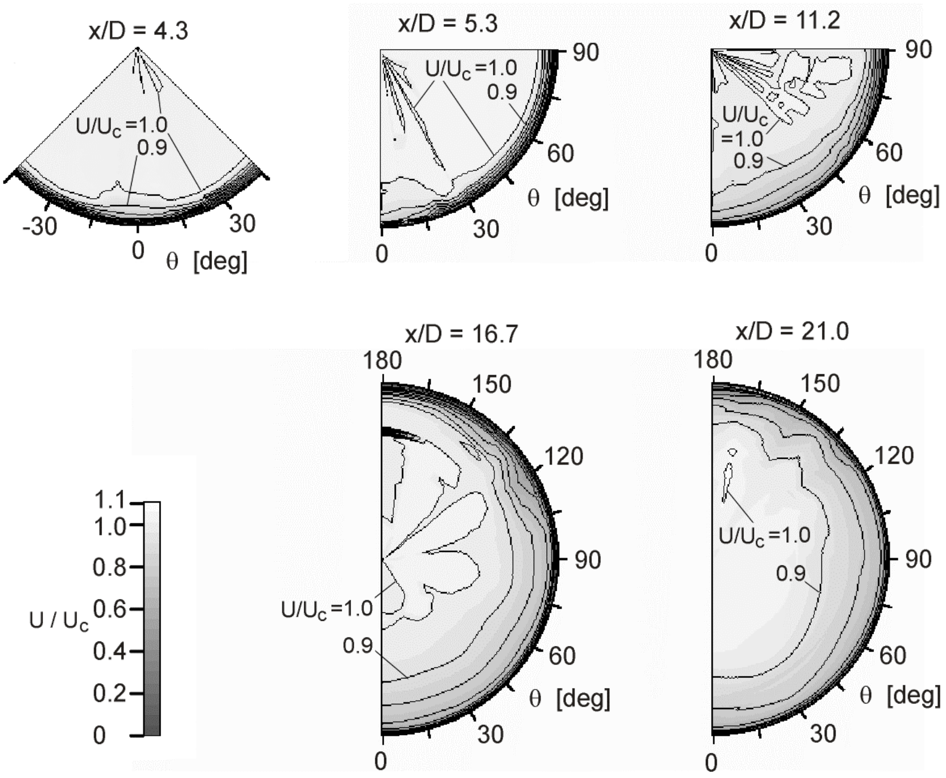

Figure 4. Isocontour maps of mean velocity.

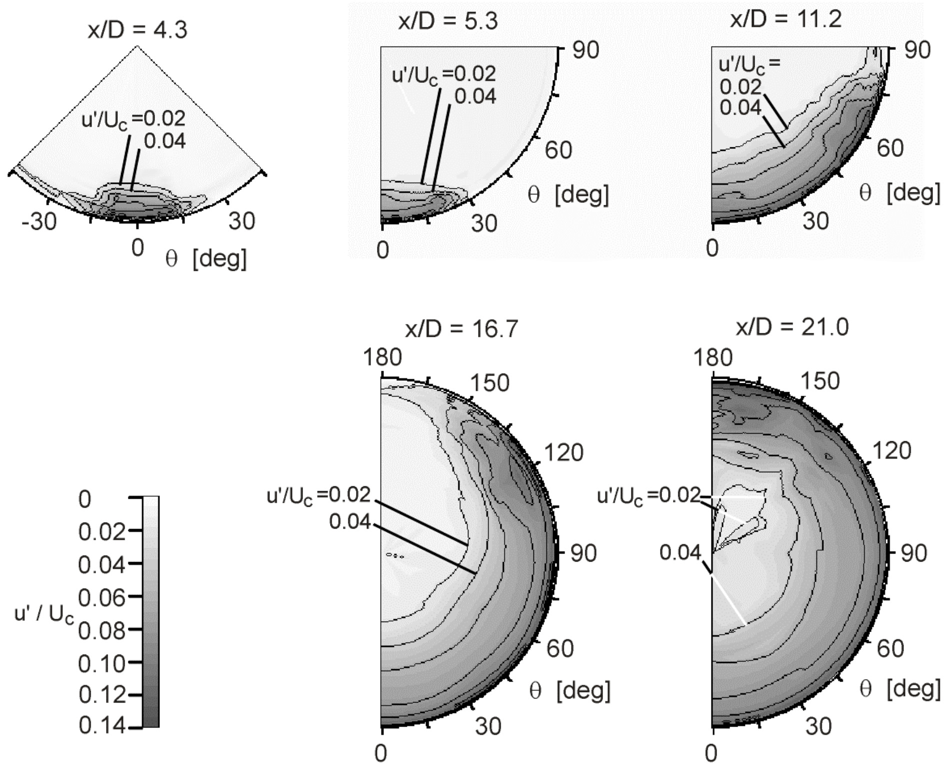

Figure 5. Isocontour maps of fluctuating velocity.

Measurements with a single hot-wire probe were made at five axial stations downstream of the roughness element, i.e., *x*/*D* = 4.3, 5.3, 11.2, 16.7 and 21.0. A single hot-wire probe with a tungsten sensing element 5 μm in diameter and 1 mm in length was used in the measurements. The output voltage from the hot wire had been digitized at a 5 kHz sampling frequency and a 52-second sampling period.

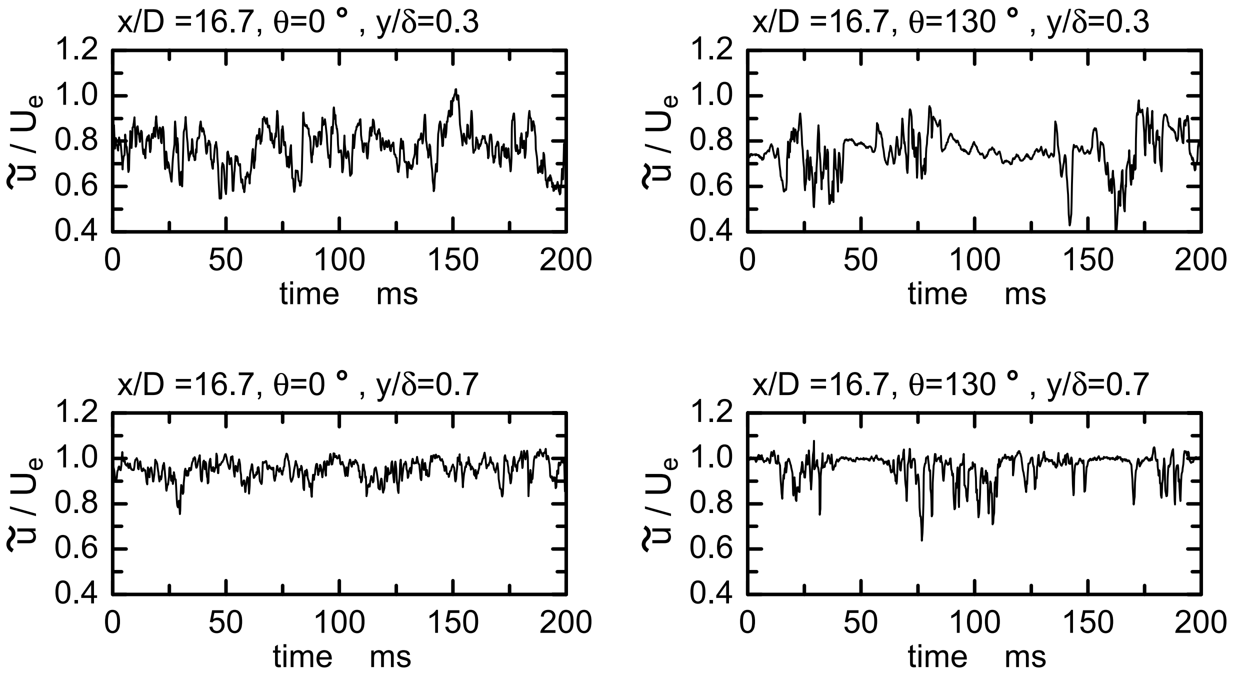

Figure 6. Instantaneous velocity signals.

Results and Discussion

Outline of Transition without Roughness Element

First of all, an outline of the natural transition, i.e., the transition without a roughness element, is briefly discussed. Instantaneous velocity signals are shown in Fig. 2 at three axial positions, *x*/*D* = 33.3, 50.0 and 66.7, where *y* is a normal distance from the pipe wall. The intermittent turbulent patches in *x*/*D* = 50.0 appeared to be turbulent slugs based on the sharp leading and trailing edges of the patches and the present high Reynolds number of 20000. Figure 3 shows an axial distribution of a boundary layer thickness. The inlet region, which is fairly maintained downstream, is approximately 70 times the pipe diameter.

Artificial Transition due to Roughness Element

Next, the experimental results of the transition property due to the single roughness element are discussed. Isocontour maps of an axial mean and of fluctuating velocities in the five cross-sections are shown in Figs. 4 and 5, respectively. An azimuthal position, θ = 0°, corresponds to the roughness position. Positive and negative regions of θ are measured only in the section *x*/*D* = 4.3. In the other four sections, only the positive region of θ is measured, since the symmetry with respect to the position θ = 0° at *x*/*D* = 4.3 is satisfactory. The turbulent region originates from the position θ = 0°. As θ increases, the flow changes from turbulent to laminar. The turbulent region expands in both the radial and azimuthal directions in the downstream region, though the azimuthal expansion is faster.

The fluctuating velocity is higher, i.e., it is in the azimuthal region away from θ = 0° than in the region of θ = 0°, higher than at θ = 0° at θ = 10°, 20°, 60°, 120° and 140° in *x*/*D* = 4.3, 5.3, 11.2, 16.7 and 21.0, respectively. This is a remarkable characteristic that has also been observed in the turbulence wedge downstream of a single roughness element on a flat plate [1]. To examine the fluctuation at these azimuthal positions in detail, instantaneous velocity signals are shown in Fig. 6 at *x*/*D* = 16.7. The signals at θ = 0° always fluctuate, whereas those at θ = 130° show an intermittent occurrence of turbulent patches. To confirm that the fluctuating velocity is higher within the patches, conditional-averaged fluctuating velocity distributions are shown in Fig. 7. The condition was based on the criterion of whether an instantaneous flow is turbulent or not. Both turbulent and normal (non-conditioned) averages are shown. Both distributions of θ = 0° are quite similar except for those in the outer region of the boundary layer. This is because the flow is always turbulent at θ = 0°, so that the turbulent-averaged velocity is almost the same as the normal-averaged one. On the other hand, at θ = 130°, the fluctuating velocity of the turbulent average, i.e., within the turbulent patches, is much higher. The large turbulent average at θ = 130° makes the normal average greater than the normal average at θ = 0°.

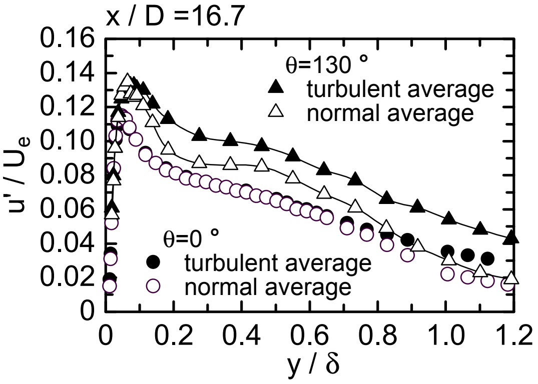

Figure 7. Conditionally averaged fluctuating velocity distribution.

Figure 8 shows isocontour maps of an intermittency factor, i.e., time fractions of the turbulent flow. The discrimination between turbulence and non-turbulence was determined according to whether a time derivative of an instantaneous velocity exceeds a prescribed threshold level. The azimuthal expansion is faster than the radial expansion both in the fluctuating velocity in Fig. 5 and the intermittency factor in Fig. 8. At *x*/*D* = 21.0, contour lines whose value exceeds 0.3 fail to reach the pipe center. The lines, however, reach the position of θ = 180°, i.e., the turbulent region in the positive θ area merges with it in the negative θ area and covers the entire periphery of the pipe.

These peripheral expansions of the turbulent region unfolding on a flat plane are shown in Fig. 9. The peripheral distance *l* is

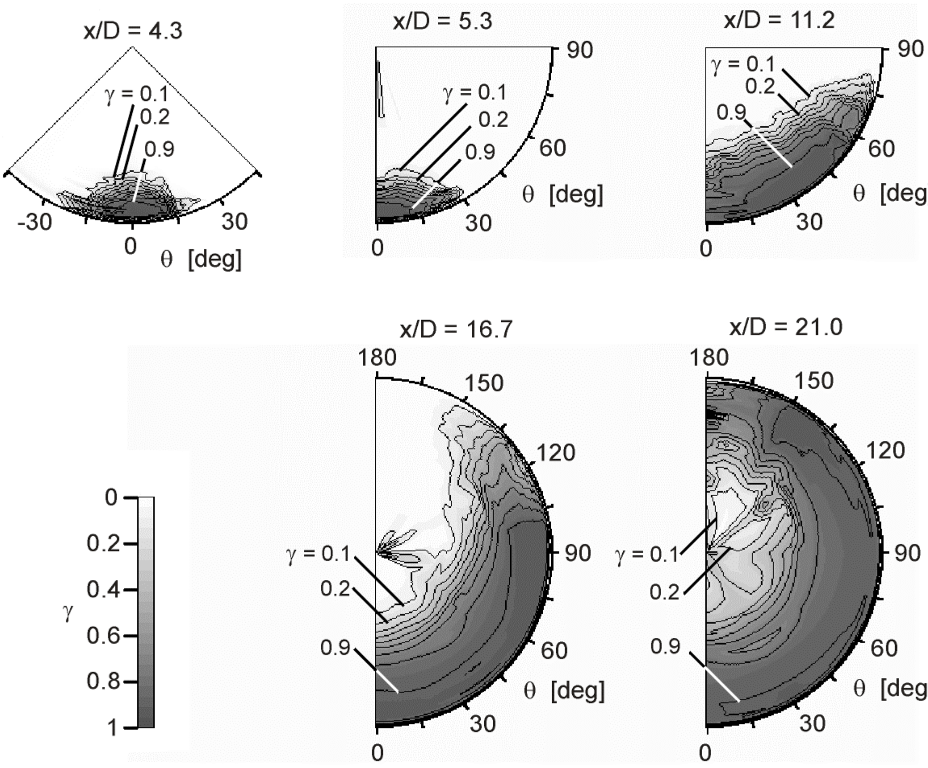

Figure 8. Intermittency contour maps.

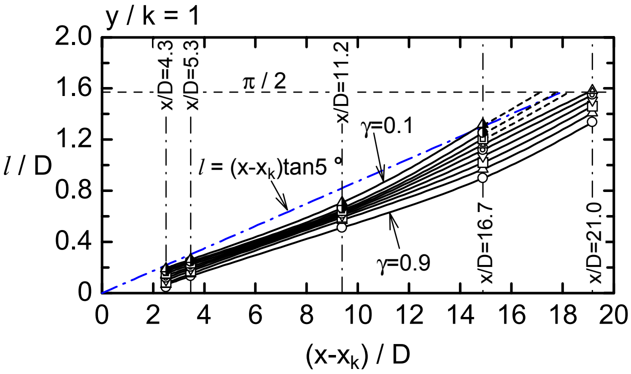

Figure 9. Peripheral expansion of turbulent region.

shown across the axial distance from the roughness element x - x_k. Note that both scales are different. The contour lines are wedge-shaped. The lines, which are initially straight, then curve to the outside. This condition is similar to that of the turbulence wedge on a flat plate [1]. If the lines are extrapolated to the upstream region, they reach the position x - x_k = 0, i.e., the virtual origin of the turbulent region equals the roughness position. The present author has found that the half-angle of the lines at the virtual origin 4.8° and 6.0° at y/k = 0.25 and 2.5, respectively [1]. A line corresponding to 5° is also shown in Fig. 9. The present turbulent region expands at approximately the same angle and is similar to the turbulence wedge on a flat plate.

Conclusions

Experiments were performed to investigate the effects of a single roughness element on a boundary-layer transition in an inlet region in a circular pipe. When the roughness element was absent, turbulent slugs were observed in the transition process; when it was present, however, a stationary turbulent region was formed downstream. The contour lines of the turbulent region were wedge-shaped once they unfolded onto a flat plane. The lines, which were initially straight, then curved to the outside. This condition is similar to that of the turbulence wedge on a flat plate. The fluctuating velocity was as its maximum not at the center of the region but at a region away from the center. Intermittent turbulent patches existed in the region, and the fluctuation within those patches was large.

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