Near-wall streaky structure in a turbulent boundary layer on a cylinder

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A near-wall streaky structure has been identified in a turbulent boundary layer on a cylinder in axial flow. A platinum wire looped around a cylinder moving in a tank of quiescent water was used to generate hydrogen bubbles near the wall of the cylinder. The streaks that were visualized correspond to high-speed streaks identified by Kline *et al.* [J. Fluid Mech. **30**, 741 (1967)]. The appearance, motion, and spacing of the streaks appear similar to the streaky structure in a planar boundary layer, suggesting a similarity in the mechanism for the generation of turbulence in the boundary layers on a flat plate and on a cylinder.

The streaky structure near the wall in a turbulent boundary layer on a flat plate was first investigated in detail by Kline *et al.*[1] using a fixed, spanwise bubble wire very near the wall. The streaky structure in a wall-bounded turbulent flow appears to result from streamwise vortices, perhaps related to the legs of hairpin vortices, collecting low-speed and high-speed fluid into parallel streams.[1-4] Although the streamwise streaks are intermittent in space and time, they appear on the average at a regular transverse spacing. The appearance of low-speed streaks is the first step in the bursting cycle.[5-7] Briefly, a low-speed streak lifts away from the wall, becomes unstable, oscillates, and violently breaks up generating turbulent velocity fluctuations. The bursting cycle appears to be responsible for most of the turbulence generated near the wall in the turbulent boundary layer on a flat plate.[5]

The purpose of this Brief Communication is to describe a streaky structure near the wall in the boundary layer on a cylinder in axial flow where the boundary layer thickness is much larger than the radius of curvature of the cylinder. Event-detection techniques such as the UV-quadrant analysis and variable interval time averaging (VITA) suggest that a burst cycle similar to that in a planar boundary layer occurs in a boundary layer on a cylinder.[8,9] Thus it is likely that a near-wall streaky structure associated with the burst cycle should be apparent in a boundary layer on a cylinder.

In the experiments described here, the turbulent flow field of a cylinder moving through a tank of quiescent water was visualized using the hydrogen bubble technique. The cylinder, a continuous loop of 0.318 cm diam Buna-N cord (O-ring), was mounted on four pulleys at the corners of a rectangular frame, as shown in Fig. 1. One of the upper pulleys was driven by an electric motor, and the two lower pulleys were submerged in the water tank so that the O-ring axis was centered in the tank. The submerged pullies were each enclosed in a plastic box to minimize secondary flows due to pulley rotation. The pulley enclosures were mounted at the end of vertical tubes so that the O-ring moved through the tubes isolating the vertical O-ring motion from the water in the tank. The O-ring slid over the edge of a hole in the pulley enclosure to enter or exit the enclosure in order to minimize O-ring vibrations excited by the pulleys. During operation, the amplitude of vibration was nearly imperceptible and is thought to be unimportant in these experiments. The frame of the flow visualization photographs is indicated in Fig. 1.

Since there is no leading edge to the O-ring and there are no streamwise gradients in this flow, it may not be considered a boundary layer in a strict sense. However, the near-wall structures in this flow are likely to be similar to those in a boundary layer on a cylinder. The boundary layer thickness on the O-ring δ was estimated by flow visualization using a straight bubble wire oriented along a radial line of the cylinder and extending out of the boundary layer. The boundary layer thickness was about 16 times the radius of the cylinder a for a cylinder velocity of $U = 52.9$ cm/sec. The friction velocity was estimated based on analytical predictions[10,11] and empirical results.[9] For the experiments described here, the nondimensional cylinder radius[12] is $a^+ = 42$ and $R_a = Ua/\nu = 879$.

Hydrogen bubbles were generated at a 0.0076 cm diam platinum wire formed into a 0.64 cm diam loop around the O-ring. Although the use of a smaller diameter bubble wire would have produced smaller bubbles and minimized bubble buoyancy effects, smaller wires tended to vibrate because of the turbulent velocity fluctuations and could not be used. The distance between the bubble wire loop and the wall of the O-ring was $y^+ = 41$. It was necessary to keep the bubble wire about 0.16 cm away from the O-ring to prevent O-ring oscillations upon start-up from breaking the bubble wire. Although the streaky structure becomes less obvious at this distance from the wall, it is still evident at wall-normal distances of $y^+ = 38$ and $y^+ = 57$ in the boundary layer on a flat plate.[1,13] We attempted to pulse the bubble wire current to generate time lines. While both pulsed and continuous bubble wire currents provide similar qualitative results, continuous bubble production provides the clearest photos of the streaky structure.

The streaks that are visualized in Figs. 2 and 3 are high-speed streaks. In most streak visualization studies (for example, Ref. 1), a fluid flows over a fixed surface and a fixed bubble wire marks the flow with bubbles. Bubbles accumulate to form streaks in low-speed regions of flow, whereas they are quickly dispersed in high-speed regions. In this study, the bubble wire is fixed to the quiescent fluid as the O-ring moves past the wire. Bubbles accumulate and form streaks in regions where the flow is slow with respect

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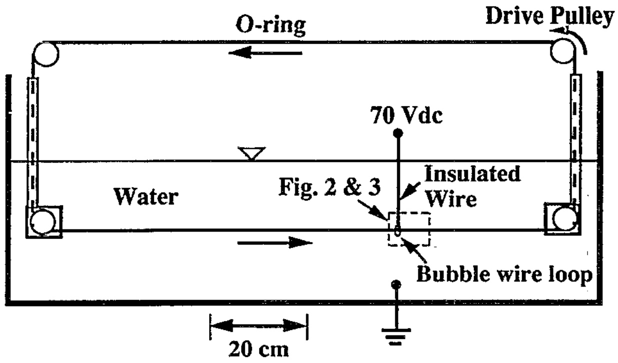

FIG. 1. Sketch of the tank and O-ring setup. The frame of photos appearing in Figs. 2 and 3 is noted.

to the bubble wire. Since the bubble wire is moving at the free-stream velocity with respect to the O-ring, the visible streaks mark high-speed regions. These streaks are similar to the high-speed streaks visualized by Smith and Abbott by traversing the bubble wire in the streamwise direction in a flat-plate boundary layer at a velocity of 0.77 times the free-stream velocity.[14]

Streaky flow structures are evident in Figs. 2 and 3 as light-colored bubbles streaming from the bubble wire loop. A streak is evident in Fig. 2 midway across the span of the O-ring to the right of the bubble wire. Other streaks are visible above and below the O-ring. The high-speed streaks shown in Fig. 2 appear to be similar to the low-speed streaks visualized by Kline *et al.*[1] in a planar boundary layer at a similar distance from the wall. The streaky structures are oriented in the streamwise direction and appear intermittently in space and time. Direct observation and video recordings of the flow indicate that the streaks appear to wave and oscillate randomly in the wall-normal and spanwise directions.

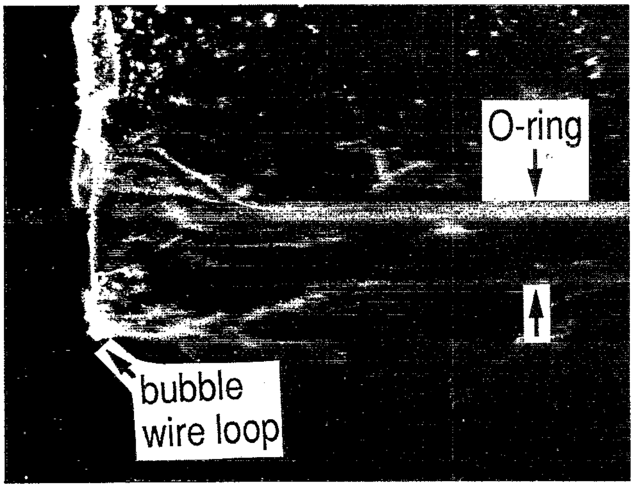

FIG. 2. Photo of streaky structure as the O-ring moves left to right. A streak is clearly visible at the center of the span of the O-ring to the right of the bubble wire.

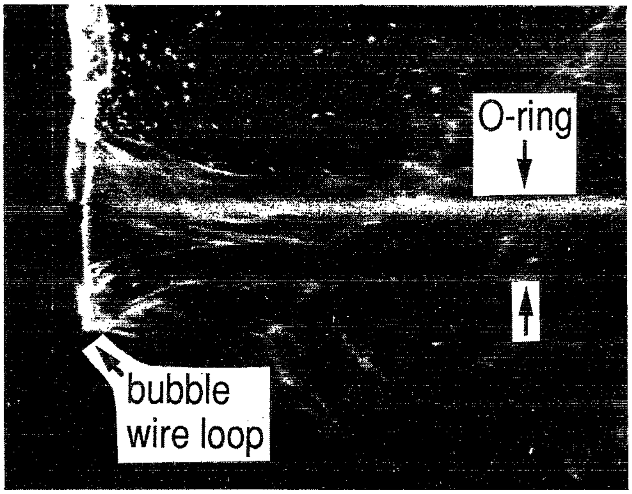

FIG. 3. Photo of a pair of streaks merging and entangling as the O-ring moves left to right.

The streak spacing cannot be determined exactly in these experiments, since part of the flow is hidden behind the cylinder. However, from photos and videos we estimate that, at the wall of the O-ring, the high-speed streak spacing is $50 \leqslant \lambda^+ \leqslant 140$. This is comparable to the low-speed streak spacing in a planar boundary layer of $\lambda^+ \approx 100$.[1,15,16] The width of a high-speed streak in the boundary layer on a cylinder is $\Delta z^+ \approx 15$, substantially smaller than that of high-speed streaks in a planar boundary layer.[6,13] It is unclear if this is a difference between the streak structures in the two flows, or if it is simply a consequence of differences in flow visualization schemes. The streak length in the boundary layer on a cylinder is typically $\Delta x^+ \approx 250$. Comparison with similar visualization results for a planar boundary layer[1,16] indicate that this streak length is not unusual, although low-speed streaks in a planar boundary layer may exceed $\Delta x^+ > 500$.[13,16]

Figure 3 shows two high-speed streaks merging midway across the O-ring diameter to the right of the bubble wire. Videos of the flow show that the streaks entangle and rotate around each other along a streamwise axis. Similar entanglement and merging of low-speed streaks has been noted in a planar boundary layer, particularly when the bubble wire is at a distance from the wall comparable to that in this study.[1,16]

The near-wall flow visualization of a boundary layer on a cylinder shows a streamwise streaky structure strikingly similar to that near the wall in a planar boundary layer. Although the streaks visualized in the boundary layer on a cylinder are high-speed streaks instead of low-speed streaks typically visualized in a planar boundary layer, their location, appearance, motion, and spacing are similar. Since a streaky structure near the wall is a precursor to the burst cycle, these results provide further evidence that the burst cycle plays a key role in the generation of turbulence in a boundary layer on a cylinder.

Note Added in Proof. Further evidence of a streaky structure in a turbulent boundary layer on a cylinder is given by Neves *et al.*[17] based on their direct numerical simulation of turbulent axial flow over a cylinder.

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