Friction Drag Reduction Mechanism Under DBD Plasma Control

X. Q. Cheng, C. W. Wong, Y. Z. Li and Y. Zhou

Abstract This work aims to understand the mechanism behind friction drag reduction in a dielectric barrier discharge (DBD)-plasma-controlled flat-plate turbulent boundary layer (TBL). Streamwise-oriented DBD plasma actuators are deployed to generate streamwise counter-rotating vortices in the TBL. The variation in the local friction drag is measured using a single hotwire, and the change in the flow structure is captured using a high-speed PIV. At a voltage V_a of only 4.25 kV, the drag reduction over an area (90 mm long and 200 mm wide) behind the plasma actuators reaches 14%. In fact, the drag reduction area stretches longitudinally to about 300 mm or 2000 wall units. The drag reduction is found to be linked to the decrease in the near-wall turbulent kinetic energy production, pointing to that the plasma-actuator-generated streamwise vortices interrupt effectively the turbulence generation cycle, thus stabilizing near-wall velocity streaks and resulting in friction drag reduction.

Keywords Turbulent boundary layer · Drag reduction · Control mechanism DBD plasma control

1 Introduction

Drag reduction in turbulent boundary layers (TBL) has received widespread attention in the literature and its potential benefits in various engineering applications cannot be overlooked. Plasma-based TBL control is attractive to many researchers due to ease in implementation and possible large friction drag reduction.

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Choi et al. [1] developed two DBD plasma actuator configurations for generating spanwise wall oscillation and spanwise travelling waves in TBL. They suggested that the plasma-actuator-generated spanwise oscillation and travelling waves could lead to a drag reduction of 45%, though the drag change was not measured in their experiments. Whalley and Choi [2] observed based on the PIV data a wide ribbons of low-speed streamwsie velocity in the viscous sublayer due to the plasma-actuator-generated spanwise travelling waves. They conjectured that the drag reduction is associated with the near-wall flow structures change.

Wong et al. [3] investigated experimentally the effect of plasma-generated streamwise vortices in a flat-plate TBL and achieved a drag reduction of 20% over an area (100 mm long and 200 mm wide) behind the actuators. The drag reduction was found to be enhanced by increasing the voltage V_a of actuators. However, the mechanism of drag reduction was not explained. This work aims to study the drag change under plasma control and the flow control mechanism that is responsible for the drag reduction.

2 Experimental Details

Experiments were conducted in a closed-circuit wind tunnel, which has a test section with $L \times W \times H = 5.6 \times 0.8 \times 1.0$ m. With its leading-edge tripped, a smooth Perspex flat plate (4.8 m long and 0.78 m wide) generates a fully developed TBL under zero streamwise pressure gradient. The TBL thickness δ is 85 mm at 3.2 m downstream from the leading edge of the flat plate, where most measurements are performed (Fig. 1). The x-, y- and z-axis are along the streamwise, wall-normal and spanwise directions, respectively, with their origin at the trailing edge and half-way between the second actuator pair. The freestream velocity $U_\infty = 2.4$ m/s and the Reynolds number $Re_\theta = 1450$, based on the momentum thickness. Each DBD plasma actuator comprises two copper electrodes and a

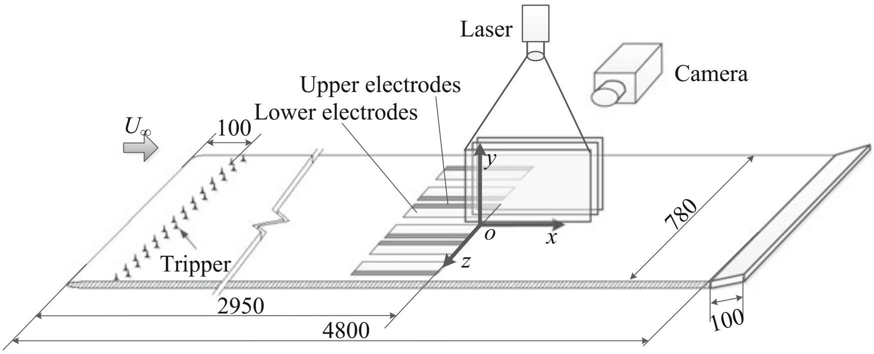

Fig. 1 Schematic of the experimental setup (not to scale; dimensions are in mm)

dielectric panel (one layer of mylar tape sandwiched between two layers of kapton tapes). In the present study, the actuators, required working long hours for detailed flow measurement, are operated at a small V_a (4.25 kV) to avoid breakdown. The streamwise-oriented actuators (configuration B in [3]) generate counter-rotating vortex pairs in the TBL.

The local skin-friction drag was estimated from the single-hotwire-measured mean streamwise velocity gradient in the viscous sublayer. An overheat ratio of 0.6 was used for the hotwire on the constant temperature anemometer. The hotwire signal was sampled at a frequency of 3 kHz (the cut-off frequency was 1 kHz). The sample duration was 40 s, long enough for the convergence of the streamwise mean and fluctuating velocities with and without plasma control. LaVison high-speed PIV system was used to measure the flow field in three *x*-*y* planes. The flow was seeded with the fog, with an average particle size of 1 μm in diameter, generated from peanut oil by a TSI 9307-6 particle generator. Flow was illuminated by a 1.0 mm thick laser sheet generated by a dual beam laser system (Litron LDY304-PIV, Nd:YLF) in conjunction with spherical and cylindrical lenses. A high-speed camera (Imager Pro HS4M) equipped with 180 mm lens was installed underneath the test section to capture PIV images at a framing rate of 300 frames per second. Each image covers an area of 70.46 mm × 70.46 mm, with 2056 × 2056 pixels. Over 2700 pairs of images were captured in each plane to ensure the convergence of the turbulent kinetic energy dissipation and production.

3 Results and Discussions

Since each pair of actuators is identical to another, it is expected that the drag variation is the same behind each pair of actuators when all actuators are operated simultaneously. Therefore, our results are presented only the second or middle actuator pair. In Fig. 2, the local wall shear stress τ_w downstream of the actuators is estimated from the streamwise velocity gradient in the viscous sublayer and the drag change $\Delta c_f = (\tau_{won} - \tau_{woff})/\tau_{woff}$ (where subscripts on and off denote with and without control, respectively). Through integrating the hotwire-measured Δc_f in both *z*- and *x*-directions, the estimated drag reduction over an area of 90 mm × 200 mm behind the plasma actuators agrees reasonably well with the measurement by a force balance [3], which may resolve the friction drag change up to the order of 10^{-4} N, and reaches 14% at a V_a of 4.25 kV. It is worth pointing out that the drag reduction may increase for a higher V_a. Figure 2a shows that the local drag reduction is non-uniform along the z-direction. The downstream variation in Δc_f is examined at three typical locations in Fig. 2a, i.e., the maximum drag increase region (R1), the maximum drag decrease region (R2) and the drag reduction plateau region (R3) which is between the actuator pair. At $x^+ = 167$ and $z^+ = 133$ (R1), the drag reduction is as high as 55%, due to the fact that the upwash side of the plasma-generated streamwise vortices pushes the near-wall low-speed fluid away

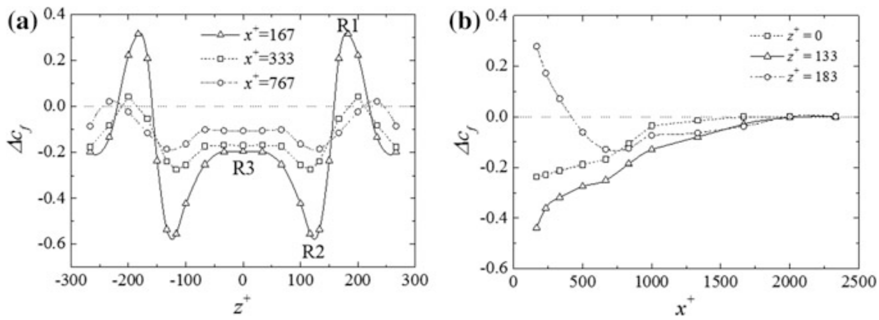

Fig. 2 **a** Spanwise distribution of Δc_f at $x^+ = 167$, 333, 767 downstream of an actuator pair. **b** Streamwise distribution of Δc_f at $z^+ = 0$, 133, 183 downstream of an actuator pair. Control parameters: $V_a = 4.25$ kV, $f = 11$ kHz

from the wall. On the other hand, the R1 occurs on the downwash side of the plasma-generated streamwise vortices due to the entrainment of high speed fluid in the near wall region. At R3, there is about 19% drag reduction; the corresponding turbulent kinetic energy (TKE) production is considerably reduced, as shown in Fig. 3b. The result seems consistent with the observation that the velocity streaks appear stabilized as evident from the flow visualization images captured at $y^+ = 24$ (not shown).

The Δc_f of R2 and R3 is initially significantly negative and resumes gradually to the value of the natural state with increasing x^+ (Fig. 2b) due to the weakened plasma-generated streamwise vortices when advected downstream. Yet Δc_f measured at $z^+ = 183$ drops from a level appreciably positive to negative before approaching the natural state. It is also noteworthy that there is no overshoot after Δc_f reaching zero beyond $x^+ = 2000$.

The dissipation and production of TKE is closely associated with drag reduction in TBL since TKE is an essential element to sustain near-wall turbulence [4]. Figure 3a shows the distribution of $\overline{(du^+/dy^+)^2}$ in the wall-normal direction, extracted from the PIV data. It has been established that this quantity may account for nearly 80% of the total TKE dissipation in the near wall region [5]. Without control, this quantity coincides well with the DNS data obtained in a turbulent channel flow by Antonia et al. [5]. Under control, the $\overline{(du^+/dy^+)^2}$ deviates slightly from that without control at all three z^+ locations.

The maximum TKE production is 0.3 at $y^+ \approx 14$ without control and is larger than that of the controlled case at all three z^+ locations (Fig. 3b). The maximum TKE production is reduced, compared to 0.3, by about 34% at $z^+ = 133$, which corresponds to the largest local drag reduction but by only 10% at $z^+ = 183$, where the positive Δc_f occurs (Fig. 2a). It is noteworthy that the location of the maximum TKE production changes when the control is applied. For instance, at $z^+ = 133$, the maximum TKE production occurs at $y^+ = 18$, due to the upwash of the plasma-generated streamwise vortices but shifts toward the wall at $z^+ = 183$ due to

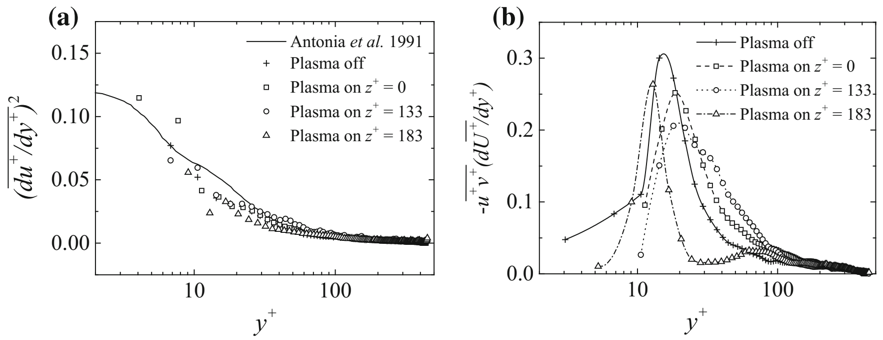

Fig. 3 Variation of **a** $\overline{(du^+/dy^+)^2}$ and **b** $-\overline{u^+v^+}(d\overline{U^+}/dy^+)$ with y^+ (at $x^+ = 167$). Control parameters: $V_a = 4.25$ kV, $f = 11$ kHz

the downwash of the plasma-generated streamwise vortices. One scenario is proposed. The plasma-generated streamwise vortices interact with the TBL, interrupting the turbulence generation cycle, and causing the TKE production to be decreased though not affecting much the TKE dissipation. As a result, the near-wall streaky structures are stabilized, which is consistent with the observed drag reduction.

4 Conclusions

(1) The present investigation demonstrates that the DBD plasma actuators are effective to reduce the skin-friction drag over a flat-plate TBL. At $V_a = 4.25$ kV applied on the actuators, a drag reduction of 14% is achieved over the control area (90 × 200 mm or 600 × 1333 wall units) behind plasma actuators. The percentage drag reduction could be increased further given a higher V_a [3].

(2) The decreased TKE production under the plasma control points to that the plasma-generated streamwise vortices may have altered the near-wall coherent structures and hence the turbulence generation cycle, causing a considerable decrease in the TKE production, though affecting little the TKE dissipation in distinct contrast to the observation made in Bai et al. [6]. As a result, the near-wall streaky structures are stabilized, which is fully consistent with the observed drag reduction.

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