Active Control of Turbulent Convective Heat Transfer with Plasma Actuators

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Abstract We study an array of streamwise-oriented Dielectric Barrier Discharge plasma actuators as an active control technique in turbulent flows. The analysis aims at elucidating the mechanism of interaction between the structures induced by the DBD-plasma actuators and the convective heat transfer process in a fully developed turbulent boundary layer. The employed flush-mounted DBD-plasma actuator array generates pairs of counter-rotating, stationary, streamwise vortices. The full three-dimensional, velocity field is measured with stereoscopic PIV and convective heat transfer at the wall is assessed by calibrated infrared thermography. The plasma actuator forcing diverts the main flow, yielding a low-momentum region that grows in the streamwise direction. The suction effect promoted on top of the exposed electrodes confines the vortices in the spanwise direction. Eventually, the pair of streamwise vortices locally reduces the convective heat transfer with a persistence of several outer length scales downstream of actuation.

1 Introduction

The irruption of computational tools and novel control strategies is opening new research opportunities in the field of turbulent flows and their application to the industrial field. The need for efficient control devices in compact spaces is fostering the development of advanced heat-transfer control strategies. Heat-transfer control applications are found in several fields such as cooling of electronics or film-cooling in turbomachinery [5].

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A common solution for convective heat transfer enhancement in turbulent flows consists of using passive vortex generators. Some designs induce pairs of counter-rotating streamwise vortices, whereas others produce co-rotating vortices. The production of near-wall streamwise vortices that persist over a significant downstream distance promotes cross-stream momentum transfer within the boundary layer. This serves to transport high-momentum fluid from the outer region towards the wall which make this kind of devices ideally suitable for heat-transfer or mixing enhancement. Conversely, if the objective is to reduce heat transfer, it is known that a sufficiently powerful, stationary vortex embedded in a turbulent boundary layer and aligned to the streamwise direction, may substantially reduce turbulent wall fluxes according to the persistence theory of turbulence, described by Cotel and Breidenthal [2].

Even though passive methods do not require neither external power source nor complex devices, there are many applications in which the control is required at very specific or off-design conditions, making active techniques the most suitable option for overall efficiency. This study proposes the usage of Dielectric Barrier Discharge (DBD) plasma actuators to actively control convective heat transfer in turbulent flows. The DBD-plasma actuators are flush, surface-mounted active flow control devices used to promote a body force vector field. Indeed, past studies have successfully employed DBD-plasma actuators [4, 3] to introduce streamwise vortices in order to control turbulent boundary layers. Wicks et al. [6] investigated the vorticity generation mechanism of a streamwise-oriented array of plasma actuators in an operational manner analogous to vortex generators. The authors conclude that both the wall-normal vorticity introduced by the array as well as the boundary layer vorticity are re-oriented towards the streamwise direction.

By combining the ideas brought forward by persistence theory and the observations of the various investigations mentioned above, the present work aims to generate stationary streamwise vortices within a fully-developed turbulent boundary layer, with the final goal of reducing convective heat transfer downstream of the control location. The boundary layer hereby considered develops on a zero pressure gradient (ZPG) flat plate. A series of streamwise-oriented DBD plasma actuators with opposing actuation directions are utilised to produce the required streamwise vortices on the wall surface (similarly to Wicks et al. [6]). The assessment of the effect of the stationary vortices on the surface convective heat transfer process is carried out by means of infrared (IR) thermography over a Joule-heated printed circuit board (PCB). This combination is used as a heat-flux sensor, located downstream with respect to the plasma-actuator array. Stereoscopic PIV measurements aim to capture the three-dimensional features of the introduced stationary vortices and the interactions that lead to the observed patterns in the convective heat transfer distribution.

2 Experimental set-up and methodology

The experimental campaign was carried out in the anechoic vertical wind tunnel (A-Tunnel) at Delft University of Technology. A turbulent boundary layer develops

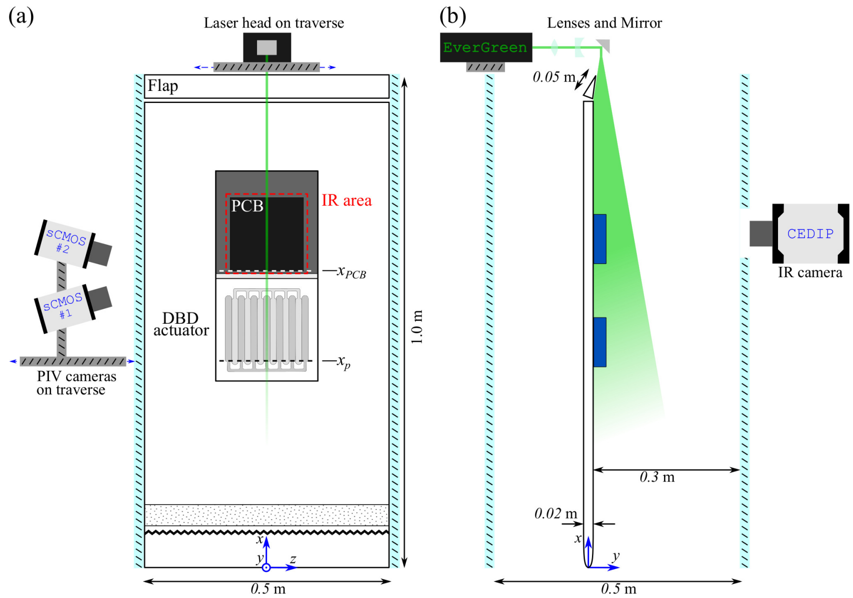

Fig. 1 Schematic of the experimental setup. (a) Front view; the measurement area of infrared thermography is indicated (– –). (b) Side view.; the field of views of the stereo-PIV measurements are highlighted (■).

on a smooth aluminum flat plate of 1m length and 20mm thickness, spanning the entire width of the squared (50 × 50cm) test section. The flat plate is installed between two parallel, side-walls to ensure two-dimensional flow. Two main inserts are flush-mounted into the flat plate, namely the plasma actuator and the heat-flux sensor (see Figure 1). A movable trailing-edge flap is used to modify the position of the stagnation point. The boundary layer is tripped close to the leading edge with zig-zag turbulators in combination with a strip of silicon carbide grit downstream. The experiments are carried out for a single inflow velocity, $U_\infty = 11.8$ m/s.

The DBD-plasma actuator array is constructed as a repeated pattern of 6 double actuators with a spanwise wavelength $\lambda = 26$mm and streamwise length $L = 128$mm. The electrodes are manufactured by silver particle deposition on a polymethacrylate plate of 3mm thickness. The discharge is initiated by a continuous sinusoidal signal at a frequency of 2kHz and a peak-to-peak discharge voltage fixed at 20kV.

Stereo-PIV velocity-field measurements are performed in two regions of interest: the plasma actuator and the heat-flux sensor. Seeding particles are produced using a glycol-water solution with mean droplet diameter of 1μm. Illumination is provided by a dual cavity Nd:Yag Quantel Evergreen laser (200mJ/pulse at 10Hz). Two LaVision Imager sCMOS CLHS cameras equipped with Nikkon NIKKOR 60mm focal distance lenses are used. The cameras and the laser head are mounted on an automated traverse system to scan 3D effects in the spanwise direction.

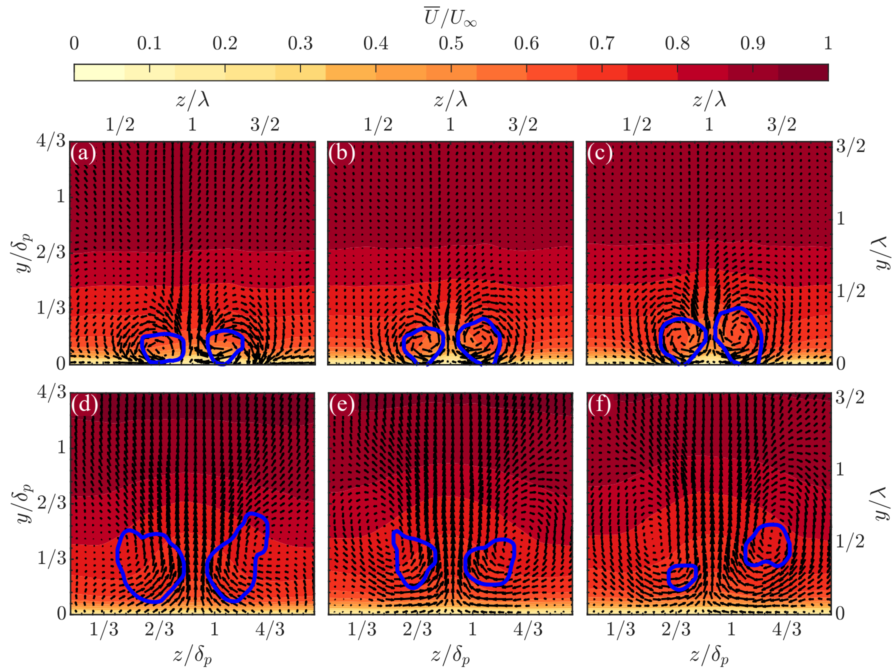

Fig. 2 Evolution of plasma actuation in the $y-z$ plane at $\hat{x} = \delta_p$ (a), $3\delta_p$ (b), $5\delta_p$ (c), $14\delta_p$ (d), $16\delta_p$ (e), $18\delta_p$ (f). The contour depicts the streamwise velocity distribution at each plane. The quiver represents the flow motion based on $\overline{V}$ and $\overline{W}$ velocity components. Negative λ_2 isolines (——) illustrate the locations of vortical flow structures.

Infrared thermography is used to measure the convective heat flux at the wall. A thermally-thin PCB is used as heated-thin-foil sensor. A constant heat-flux by Joule effect q_j'' is provided to the PCB by a stabilized power supply. The convective heat transfer distribution is expressed in non-dimensional form in terms of Nusselt number ($Nu = h\delta_p/k_{air}$) where k_{air} is the air thermal conductivity, h is the convective heat-transfer coefficient, and δ_p is the boundary layer thickness at the plasma onset x_p. The computation of h is performed through a steady-state energy balance, modeling the PCB as a heated-thin-foil sensor [1]. The temperature measurements are performed with a CEDIP-SC7300 Titanium IR camera (320 × 256 pixel MCT sensor and Noise Equivalent Temperature Difference (NETD) < 25mK).

3 Plasma actuation effects on flow fields and heat transfer

The 3D flow field is reconstructed in a region covering two opposing actuators. Figure 2 depicts the average streamwise velocity $\overline{U}$ on the $y-z$ plane at $\hat{x} = \delta_p$, $3\delta_p$, and $5\delta_p$ along with a superimposed vector plot of the corresponding $\overline{V}$ and $\overline{W}$

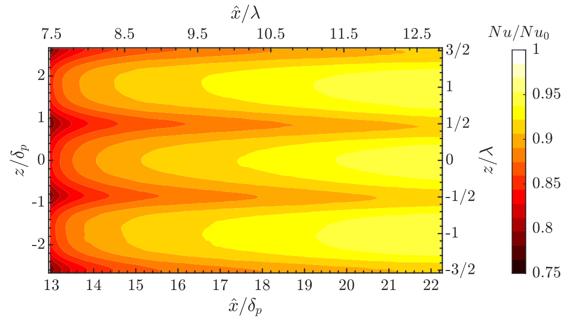

Fig. 3 Nu/Nu_0 contour map for plasma actuated flow.

velocity components (being $\hat{x} = x - x_p$). On the most upstream location of actuation ($\hat{x} = 0$), the fluid ejected laterally by the discharge is replenished by entertainment from above the exposed electrodes. This generates a circulation leading to a vortical motion. At $\hat{x} = \delta_p$, the streamwise vortices are already developed and begin to depart from the wall; their core is located at approximately $y \approx \delta_p/10$. The location of the vortex core is identified by the roll-up in the vector field and by λ_2 isolines. The counter-rotating, streamwise vortices mutually interact at $z/\lambda = 1$ pushing the fluid away from the wall while the suction effect on top of the exposed electrodes sustains the entrainment towards the wall at $z/\lambda = 1/2$ and $3/2$. The vortices are then progressively displaced away from the wall and grow in size, an indication of vortex strength reduction, in agreement with Wicks et al. [6]. It must be noted, however, that the pair of counter-rotating, streamwise vortices is confined for several outer scales in the space between two consecutive, opposing, exposed electrodes, i.e. $1/2 < z/\lambda < 3/2$ according to figure 2, suggesting vortex persistence.

Moving further downstream, the effect of the plasma actuation is still persisting (figure 2 d-f). Note that the upstream edge of the heat-flux sensor is located at x_{PCB}, i.e. $\hat{x} = 13\delta_p$. The induced structures are strong enough to divert the flow, affecting also the outer region of the boundary layer. The pairs of counter-rotating vortices generated upstream by the plasma actuation are less evident due to dissipation. The vortices progressively expand in the spanwise direction and lose strength. Nonetheless, the mutual interaction between the pair of vortices yields a significant wall-normal velocity that clearly persists and which is progressively expanded over a wider area in the spanwise direction. The ejected fluid out of the wall is then replenished by fluid from the outer region of the boundary layer.

The induced action of the vortices has evident effects on the convective heat transfer distribution. The time-averaged Nusselt number map is shown in Figure 3, computed from IR measurements over a region covering two pairs of opposing plasma actuators to show its uniformity. The results are normalized with the Nusselt number at reference flow conditions Nu_0 (i.e. without plasma forcing). The plasma forcing is composed of two main effects on the heat-transfer distribution: a uniform reduction over the whole region where the actuator array is deployed, and a localized, predominant decrease at the location where the plasma plumes lift-off to promote out-of the wall motion. Eventually, the plasma forcing provides a reduction of 9% in convective heat transfer within the region covered by the heat-flux sensor, far downstream the DBD-plasma actuator.

4 Conclusions

The usage of DBD plasma actuators for heat-transfer control in a well-developed TBL has been studied experimentally. The plasma actuator array was designed to induce pairs of counter-rotating, streamwise vortices. The results from stereo-PIV confirm the formation of such vortices which are locally confined by the suction effect promoted by the plasma discharge along the electrodes. The local confinement prevents the vortices to expand in the spanwise direction, making them stationary and hence persistent along the DBD actuator array. Downstream of the actuation, the vortices reduce their intensity but a strong up-wash motion at the plasma-jet impingement location ($z/\lambda = 1$) persists. At this spanwise location, a wide ribbon of heat-transfer deficit is observed from IR thermography measurements. The local velocity deficit at this location as a consequence of the flow blockage promotes the reduction of Nusselt number even several δ_p downstream the actuation. An average reduction of 9% in Nusselt number is achieved over a wide region of interest confirming the effectiveness of the plasma-induced large scales structures to control heat transfer.

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