Recent Developments in Turbulent Flow Control

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ABSTRACT
Recent developments in turbulent flow control are discussed through a presentation of experimental results from wind tunnel tests which have been carried out at the University of Nottingham in collaboration with AIST. A particular emphasis is given to the use of surface plasma for controlling turbulent boundary layers for skin-friction reduction, delaying or reattaching flow separation and enhancing flow mixing.

Key Words: Turbulent flows, drag reduction, separation control, surface plasma

1. Introduction

Surface plasma is an emerging technique in active flow control, which has unique ability to create a body force close to the wall in atmospheric pressure air. The actuators based on surface plasma principle are simple, lightweight, require no moving parts, and are extremely fast acting.

2. Surface Plasma Actuators

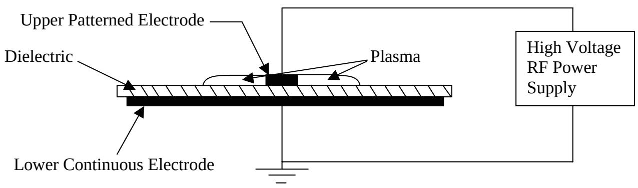


Fig. 1 Symmetric surface plasma actuator.

The electrode layout of surface plasma actuators consists of a pair of electrodes - one patterned and one usually continuous - separated by a dielectric layer (Fig. 1), across which a pulsed or oscillatory voltage is applied. Typical excitation is at several kHz and several kV. Electrode sheets that have been used here are made from Mylar, with a typical thickness in the 125-250μm range, double-sided with copper.[1] One or both sides can be etched.

3. Turbulent Drag Reduction

Two sets of electrodes are etched onto the upper surface of the electrode sheet with a common ground electrode between opposing pairs. On energizing one electrode set, the offset of the ground electrode confines plasma formation to one side of the exposed electrode only. At a later point in time the other electrode set is energized, causing plasma to form on the opposite side of these electrodes. By switching the electrodes at an optimum frequency, it is possible to produce spanwise flow oscillation in the near-wall region of the turbulent boundary layer.[2,3] We have observed up to 45% of skin-friction drag reduction in the downstream of the actuators. Figure 2 shows the time averaged velocity profile with and without plasma forcing. The plasma causes a large streamwise velocity deficit in the lower region of the boundary layer, extending for $0.1 < y/\delta^* < 2$ ($6 < y^+ < 110$). Within this region, the mean velocity has been reduced by as much as 40% at $y/\delta^* \approx 0.5$ ($y^+ \approx 30$).

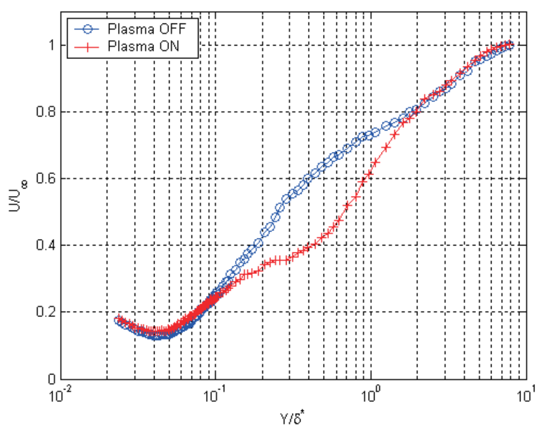


Fig. 2 Mean streamwise velocity profile with (+) and without (○) oscillatory surface plasma.

Figure 3 shows the turbulent intensity profile across the boundary layer. Velocity fluctuations have been reduced by as much as 30% for $0.1 < y/\delta^* < 0.55$ ($6 < y^+ < 30$). However, the magnitude of the fluctuations has been increased by up to 30% for $0.55 < y/\delta^* < 2.5$ ($30 < y^+ < 140$). This shift indicates that turbulence production has been reduced in the near-wall region, yet increased further out from the wall due to the change in local mean velocity gradient.

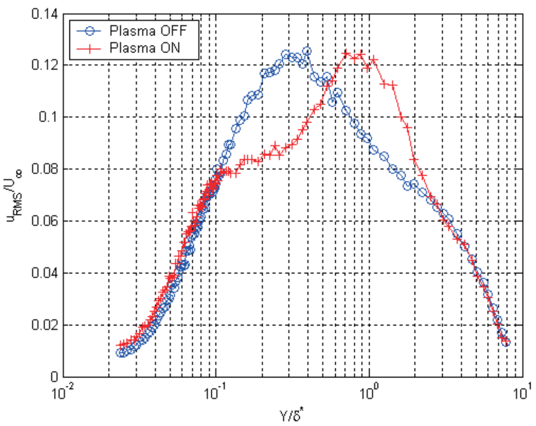
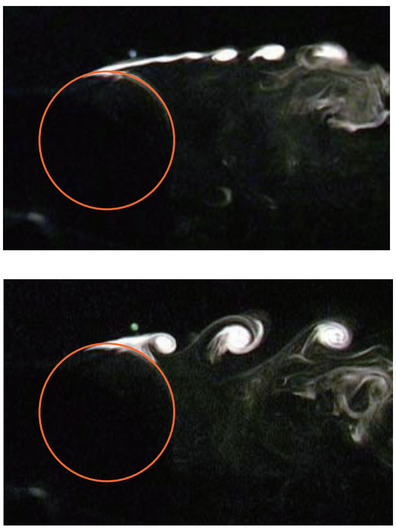


Fig. 3 Turbulent intensity profile with (+) and without (○) oscillatory surface plasma.

4. Flow Separation Control

For this experiment, a single plasma actuator was flush mounted within the circular cylinder. This consisted of two 17μm thick copper electrodes, separated by 250μm Mylar dielectric. The upper electrode was 1mm wide and offset relative to the lower. A high voltage (E = ±3.5kV) square-wave pulse train was delivered to the upper electrode. The circular cylinder was rotated about its axis so that the plasma forcing acted at several different azimuthal locations, θ, measured relative to the front stagnation point, where the freestream is from left to right. Plasma was created in 1ms duration pulses at various multiples of the Karman vortex shedding frequency (f_{plasma}/f_K = 0.5, 1, 2, 4, 8, 14). Note that the frequency of separated shear layer roll-ups occurs at f_{SL}/f_K = 5.6 at this Reynolds number.[4]



a)

b)

Fig. 4 Flow visualisation images at $Re_d = 3.3\text{x}10^3$. a) Without plasma; b) with plasma actuator at θ = 87°, pulsed at f_{plasma}/f_K = 4.

Figure 4 shows flow visualisation images of the flow around the cylinder with and without plasma forcing. Without plasma (Fig. 4a), it is shown that the free shear layers rolled up into Karman vortices. Plasma forcing (Fig. 4b), clearly caused a significant change in the global flow structure around and in the wake of the cylinder, causing a downstream shift in the separation point. The effectiveness of the plasma in reattaching the flow was dependant on the actuator location. The most dramatic change was observed when the actuator was placed at 87° (i.e. very close to the natural separation point), where the flow was significantly reattached for all plasma forcing frequencies. In fact, the flow appeared to become reattached to the rearward stagnation point when f_{plasma}/f_K = 14.

5. Conclusions

Surface plasma actuators are versatile devices for active flow control, which can be integrated into aeronautical structures, such as the surface of aircraft wings or nacelle. Many flow control applications are possible with these devices from skin-friction reduction to separation flow control as has been demonstrated in this paper. We have also shown that the actuator configuration is easily adjustable, making unique applications possible. It is hoped that this paper could give an opportunity to aerospace engineers to take a look at surface plasma actuators and to find out what they are capable of.

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