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Flow Control at Subsonic Speeds using Serpentine Plasma Actuators

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The use of plasma actuators for flow control applications is fast becoming the subject of many research campaigns. A drawback of this technique is the relatively low flow speeds that the plasma induced jet exhibits. One method of enhancing the influence of such actuators, is to devise novel actuator configurations that despite their low induced speeds still have the ability to considerably manipulate the flow characteristics. The objective of the current study is to apply the newly developed serpentine plasma actuator to a standard backwards facing step model in a low-speed wind tunnel operating at 15m/s. The influence of the actuator on the separated shear layer is examined using PIV. The results show that due to the three-dimensional flow induced by the actuator, the shear layer exhibits different characteristics along the span wise direction. It is believed that using plasma actuators with three-dimensional flow characteristics has the ability to create greater control authority at the relatively low plasma induced velocities.

Nomenclature

h	Boundary layer height, mm
St	Strouhal number
V	Voltage, v

Subscript

$p-p$	Peak-to-peak

I. Introduction

The single dielectric barrier discharge (SDBD) plasma actuator consists of two electrodes flush-mounted on the opposite faces of a dielectric plate: one is exposed to the flow and the other is placed under the bodys surface and insulated by a dielectric material.[1,2] A high AC voltage is applied to the exposed electrode using a particular waveform, usually sine or square waveforms.This results in a weakly ionised region above the dielectric, referred to as surface non-thermal plasma discharge. The electrochemical interactions between air and plasma lead to complex plasma kinetic phenomena resulting in production of a wall tangential jet flow due to a self-sustaining process involving high rate of collisions between neutral and charged particles. Ramakumar and Jacob[4] showed, in their experiments with quiescent flow, that sine waveforms perform better than square and sawtooth waveforms in terms of plasma induced velocities; this is also confirmed by Jolibois and Moreau[3] which discourages the use of high-sloped waveforms such as square or sawtooth. The high AC applied ionises the atmospheric air adjacent to the exposed electrode creating plasma which, due to the electric field gradient, results in a body force inducing airflow along the actuator surface.

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Balcon et al.[5] in a study on plasma actuators performed in absence of flow, evaluated the time required by the plasma induced airflow to reach a stationary state (using a fixed 1 kHz sine wave at an amplitude of 20 kV); PIV flow investigation aimed to an evaluation of turbulent kinetic energy, have shown that for short unsteady actuations (<100ms) a vortex is created and convected downstream and after 400ms the flow can be considered in a steady state.

Most of the literature refer to experiments aimed at delaying separation on general aviation airfoils and turbine blades, particular interest is given to unsteady actuation of plasma devices specifically by varying the frequency and duty cycle. Huang et al.[6] applied an SDBD actuator on a turbine blade for separation control for Reynolds number ranging from 10000 to 100000, both steady and unsteady actuation were studied. Steady actuation resulted in a decrease of the separation bubble size proportional to the voltage increase. Unsteady excitation caused vortical structures that are thought to bring more momentum to the fluid, hence helping to withstand adverse pressure gradients. The optimal forcing frequency was found corresponding to a Strouhal number St = 1 and this was confirmed by the improved pressure coefficient on the airfoils suction side for St = 1. Benard et al.[7] studied both steady and unsteady actuation on a NACA 0015 airfoil in a free stream velocity of 20m/s, resulting in a Reynolds number, based on the chord length of approximately 2.6×10^5. For a steady actuation the results showed an increase in the stall angle between 1^o and 2^o (linearly with the increasing voltage amplitude), an increase of C_L at baseline post-stall angles of attack (reaching +60% at 15^o) and good C_D reduction for higher voltage values (reaching a reduction of -37% at 15^o) showing C_D to be more sensitive to frequency. Similar advantageous findings have been reported elsewhere.[8,9]

Interesting new designs of plasma actuators have been developed and tested recently in order to increase the actuation authority on the flow. Roy et al.[10–12] designed serpentine shaped actuators and tested them in quiescent flow, also comparing different serpentine shapes with the straight actuator case. The results were also validated by simulations and showed a remarkable increment in the introduction of vortical structures, due to their peculiar $pinch - spread$ effect. A complex three-dimensional corkscrew structure is produced and a noticeable plume expands from the pinch section of the actuator at an angle ranging from 38^o to 43^o.

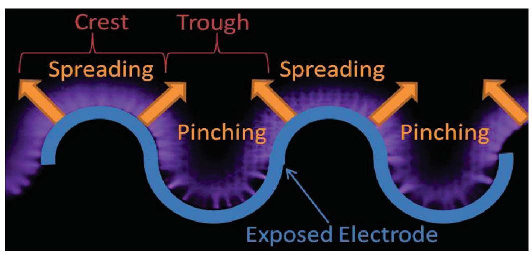


Figure 1. Pinch-spread effect given by serpentine plasma actuator.[13]

The purpose of this experimental campaign is to apply the aforementioned serpentine plasma actuator to a backwards facing step model in a low-speed wind tunnel and examine the three-dimensional influence the plasma induced jet has on the shear layer characteristics.

II. Experimental Setup

A. Wind Tunnel

Experiments are conducted in an open-return wind tunnel with a total working section of 5.5m in length, cross section of 0.9m × 0.9m, and maximum operating speed of 20m/s with a nominal free stream turbulence of 0.5%. Corss-wire measurements were conducted at a specific measurement lcoation with a free stream velocity of 15m/s to determine the boundary layer height at this location. A backwards facing step was then introduced at this location, 3.5m from the tunnel entrance, equal to the boundary layer height (h) of 65mm.

B. Particle Image Velocimetry

The PIV system used for the experiments uses a pulsed Nd:YAG laser (Litron Lasers, model Nano L PIV). It is a double oscillator laser system, providing a laser beam at a wavelength of 532nm. The system is composed of a power supply, the laser box, and an adjustable laser arm. The movable arm allows the laser beam to be positioned in the preferred location within the wind tunnel. At the end of the laser arm, a cylindrical lens is mounted, expanding the laser into a thin sheet of approximately 1mm thick. The camera used to capture the consecutive images is a Lavision ImagerProX 2M CCD camera. It uses a KAI-2001 interline-CCD sensor sized 1600 × 1200 pixels (each being a square of side 7.4 μm) with a dynamic range of 14 bits. A total of 400 image pairs were collected for each test case. The recorded image pairs are initially divided into 32×32 pixel interrogation windows and then processed with a cross correlation algorithm using the DaVis 7.2 software, the interrogation windows are then refined to 16×16 pixel squares.

For the actuator in quiescent conditions, a Δt of 430μs was selected, where as for the actuator with free stream flow the Δt was reduced to 31μs. The time intervals were calculated by the software depending on the camera resolution, the image field of view, and an allowable particle displacement of 5 pixels. To create tracer particles a TSI six-jet atomiser model 9307-6 was used. The seeder is capable of creating particles with a diameter of approximately 1 microns.[14]

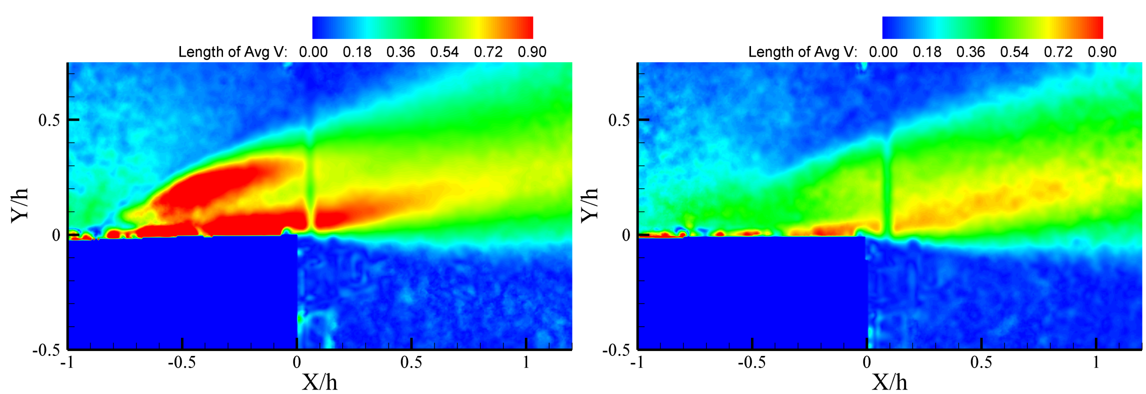
C. Plasma System

High voltage is generated using a Voltcraft 3610 power supply connected to a circuit board which can output a variety of signals. A shielded connector block by National Instruments is used to connect the circuit board to a computer, using a PCI-6713 analog output card. LabView is used to control the driving frequency, modulation frequency, duty cycle, phase, and signal shape of the system, which has a maximum output of 30kHz at 0 to 100% DC. The final output is connected to a Minipulse 6 trasformer, capable of 30kHz output at voltages up to 40kV$_{p-p}$ (peak-to-peak voltage). The voltage and frequency of the output signal are measured with a high voltage probe LeCroy PPE 20kV, while a current probe in the transformer is used to measure current. The experiments with the serpentine actuator were performed at 16kV$_{p-p}$.

III. Results

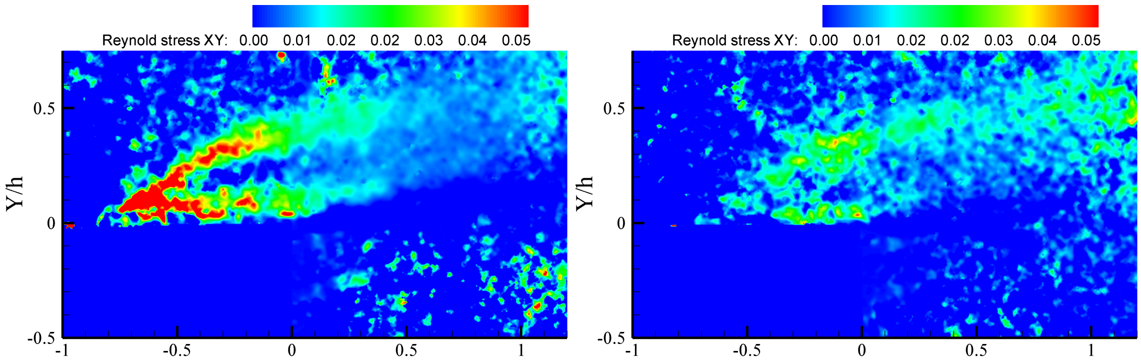
Figure 2(a) and (b) show the time averaged velocity contours corresponding to the PIV laser sheet placed along the pinch and spread regions of the actuator, respectively. The actuator in this figure is placed on the step, however there is no free stream flow. It is clear that at the pinch location, the induced flow has a stronger upwards component compared to the spread region. This is because at this location, the induced jet from opposite sides collide head-on and the interaction leads to an upward motion of the flow.

The turbulence Reynolds stress, Re_{xy} is an important dynamic quantity affecting the mean flow since it is responsible for a major part of the momentum transfer due to turbulent fluctuations. The Reynolds stress is not only an indicator of the r.m.s. velocities but also related to vorticity which is has strong influence on mixing, making it a suitable parameter to analyse. The calculated Reynolds stresses are provided in Figure 3 for the quiescent actuator along the pinch and spread locations. In Figure 3(a) two dominant areas of high Re_{xy} are identifiable, the first is tangential to the step and the other region is pointing away from the step upwards on at an approximately 40^o angle.



(a) Pinch (b) Spread

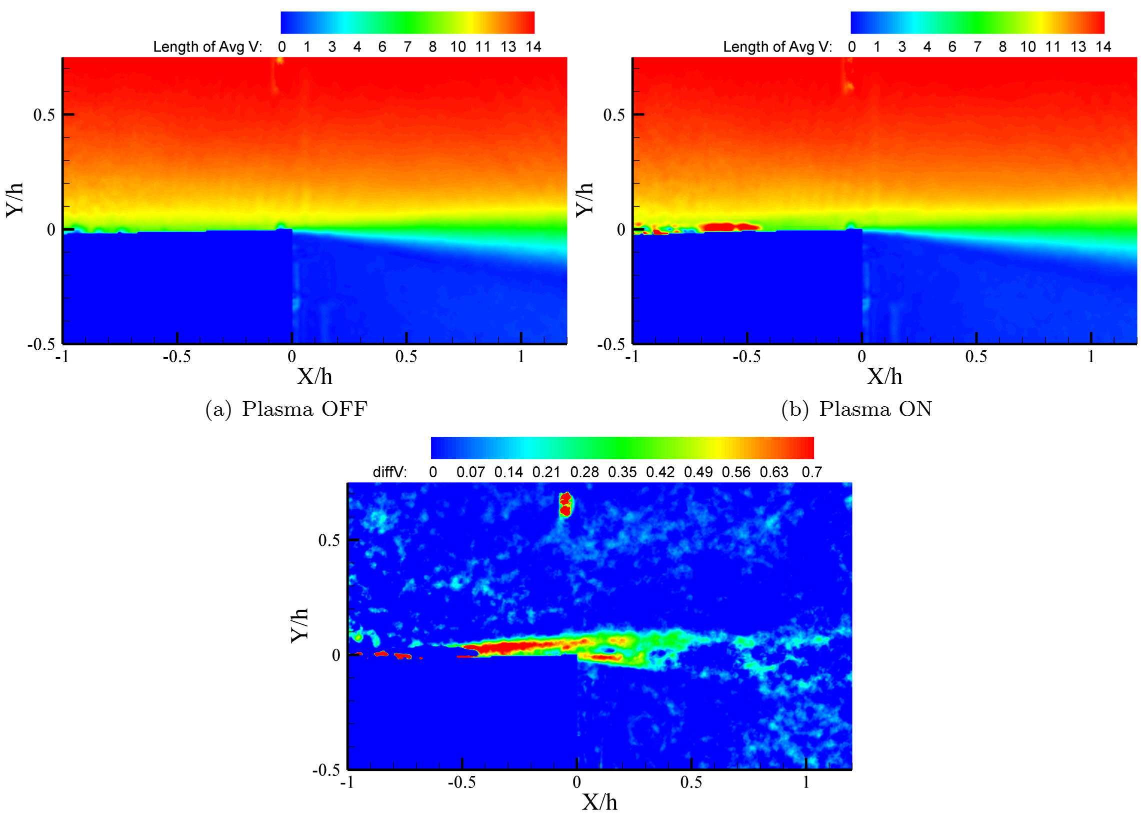
Figure 2. Velocity contour along the pinch and spread under quiescent conditions (units m/s).



(a) Pinch (b) Spread

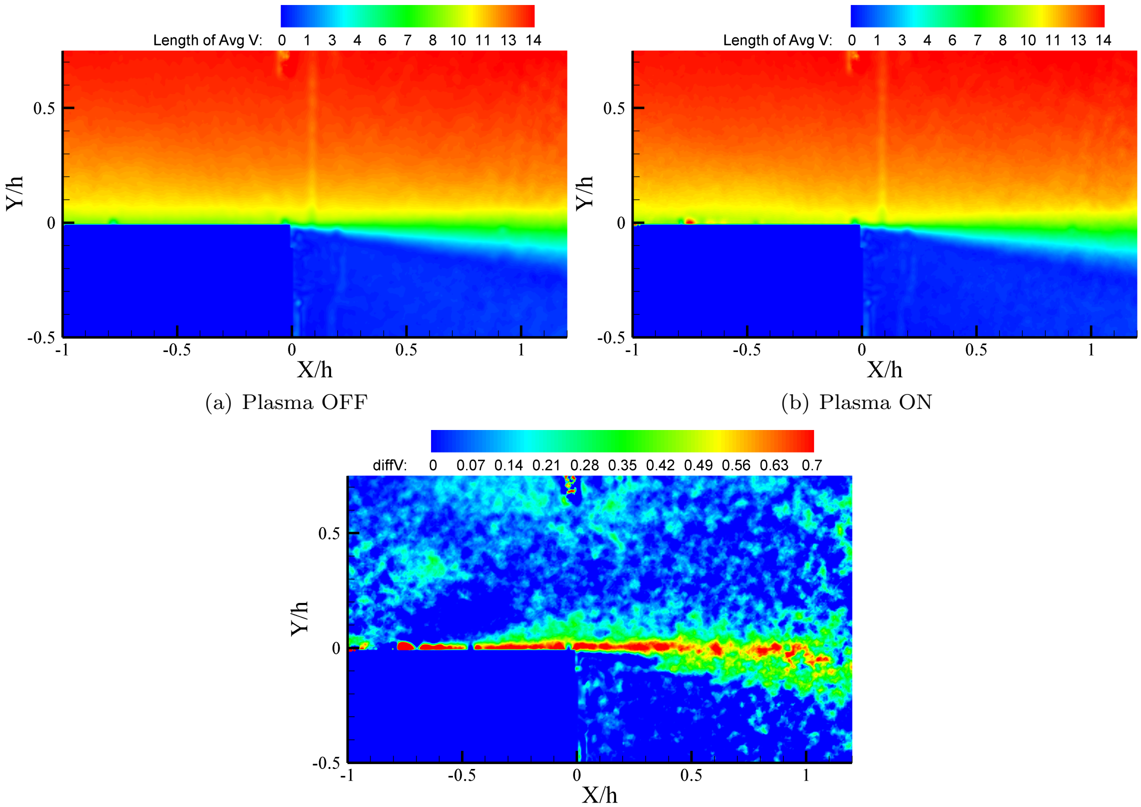
Figure 3. Reynolds stress contour along the pinch and spread under quiescent conditions (units Kg/ms^2).

Figure 4 displays the time averaged velocity contours during the operation of the wind tunnel with the plasma actuator off, actuator on, and also the difference in velocity between the two off and on cases in Figure 4(c). Here, the flow is left to right and the laser sheet is illuminating the pinch portion of the actuator. The same results are presented for when the laser sheet is positioned over the spread portion of the actuator in Figure 5. Examining the velocity contours in Figure 4(a) & (b) and Figure 5(a) & (b), it is difficult to identify the influence of the plasma actuator. Examining the difference between the actuator off and on cases, it is evident that the pinch portion of the actuator has a greater influence upstream of the step leading edge (Figure 4(c)), whilst the spread portion influence more the separated shear layer downstream.



(c) Difference

Figure 4. Average velocity contour for pinch location (units m/s).



(a) Plasma OFF (b) Plasma ON

(c) Difference

Figure 5. Average velocity contour for spread location (units m/s).

At the pinch location, see Figure 4(c), an upwards vectored jet is produced, forcing the incoming flow away from the wall, which explains the strong influence upstream of the step leading edge. The three-dimensional nature of the serpentine induced jet leads to the generation of streamwise vortices. According to Riherd and Roy[15] these vortices can lead to the generation of boundary layer streaks, a type of transient instability mechanism capable of achieving large energy growth over finite time scales, which are initiated by streamwise vorticity. It is suggested by the authors that these streaks can be used to provide a means of flow control or to induce transition from laminar to turbulent flow.

IV. Conclusion

The present investigation examines the application of a three-dimensional serpentine plasma actuator, as an active flow control device, to manipulate the flow over a backwards facing step. The serpentine actuator is characterised by two regions, namely the pinch, and the spread. At the pinch location, the induced jet from opposing sides collide and an strong upwards jet is created. At the spread location, because there is no canceling effect of the induced jet from opposite sides of the actuator, a greater streamwise influence is achieved.

Further studies are underway to understand in greater detail the infleuence of such three-dimensional actuators on the flow properties, such as the flow reattachment downstream of the step as well as the vortical structures inside the recirculation bubble.

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