An Approach to Suppress Flow Separation by Plasma Vortex Generator as a Combined Active and Passive Control Mechanism

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Abstract. Flow control is an important issue in fluid mechanics and aerodynamics as separated flow introduce undesirable impact on overall system performance. Several active and passive techniques have been used to control the flow when necessary. But in passive control techniques, the actuator has to be fixed on the surface so that it can create vortices along streamline to enhance the mixing in the separated region to delay or suppress separation. Among passive flow control system vortex generators (VGs) are generally used but it control the flow with the cost of drag increase. It would be advantageous by combining both active and passive flow techniques together. In this regard plasma actuator (PA, active flow control device) and VGs are combined together with a view to not only suppress the separation but also minimizing the drag that could arise by using conventional passive control techniques. The combination flow control device is named as Plasma Vortex Generator (PVG) which proves its effectiveness to control separation as conventional VGs do but without any drag penalty.

1. Introduction

Due to the separation of flow from the wall, the control of separation is necessary to ensure the performances of various practical devices. As a result, flow control has great practical importance and becomes the rapidly growing field in fluid mechanics which has several engineering benefits but not limited to turbulence management, separation delay or suppression, drag reduction, lift enhancement, fuel economy, mixing improvement, noise control, environmental compliance and so on. Both active and passive flow control techniques are used to control the flow, although all of them have some limitation. Among various passive control devices, vortex generator (VG) is most effective which introduced by Taylor [1] in the late 1940s. These VG are simply a series of thin plates of various shapes (rectangular vanes [2], doublets & wishbone [3], trapezoid vanes & delta vanes [4-8], triangular vanes [9], cylinder [10]) that are placed normal to the surface with an angle along flow direction. Due to this angle of incidence incoming air creates vortices which adds momentum to the wall surface thus mixing is enhanced. This enhancement suppress or delay the separation. The conventional vane-type VG has a height of the order of the boundary layer thickness, and has a penalty of drag increase as they are with certain angle along flow direction. This penalty is critical for shorter flow separation control situation. In order to minimize the drag penalty, smaller VGs submerged in the boundary layer have been developed and investigated [11]. To overcome these limitation, a novel approach has been taken to combine both active and passive flow control techniques together. Among various active flow control
methods plasma actuator (PA) are prominent due to its simplicity and quick response capability which is consistent of an exposed electrode and an embedded electrode, separated by a dielectric material. A set of configurations of PAs have been investigated both experimentally and numerically to figure out the optimum configuration to make the so called PVG. Among tested three configurations as shown in Figure 1, the leading edge type of PA has been modified to construct the PVG as this one gives maximum induced flow which is 1.81 m/s [12]. The device is named as plasma vortex generator (PVG) which combines both plasma actuator and conventional vortex generator together. These PVGs are placed normal to the surface but without any angle of incidence along the flow direction. The plasma induced flow from the vane tip to the hub produces a pair of stream-wise counter-rotating vortices downstream.

The angle of the PVG (β) is zero against a main flow, and thus the drag penalty is expected to be low if the plasma is switched off. The basic difference of vortices formation between conventional VGs and PVGs is shown in Figure 2.

2. Experimental setup and simulation
The experiment is carried out in an open type wind tunnel of Tokyo Metropolitan University (TMU), Tokyo, Japan with a free stream velocity of 4 m/s. Flow separation is created in a 20° slope of diffuser section of the wind tunnel. All measurements have been conducted along B. Details of measurements and dimension (not to scale) shown in Figure 3.
The streamwise lengths of straight section is 0.63 m and the diffuser section is 1.4m. The cross section of the entrance was 0.2 m by 0.2 m. A tripping wire of 2 mm diameter was fixed at x = 50 mm in the straight entrance section to develop a turbulent boundary layer. To confirm the development of turbulent boundary layer velocity profile measured in some stream-wise locations and compare with 1/7th law [13]. Dimensions of VGs' have been characterized from Lin [2]. As the comparison has been made between PVG and VG on separation, hence same configurations have been considered for both except the angle of incidence (Figure 2) which is shown in Table 1.

**Table 1. Dimension of VG and PVG**

| Parameters              | Dimensions (mm) |
|-------------------------|-----------------|
| Height, h               | 7               |
| Length, l               | 28              |
| Spanwise spacing, d     | 64              |
| Distance from separation, ΔxVG | 70             |

Three sets of experiments, namely (1) no actuator (2) with PVG and (3) VG, have been conducted to evaluate the performance of PVG on flow control by comparing it with conventional VGs. Flow profiles have been visualized by using hot-wire anemometer with also smoke sheet, smoke wire visualization as the hot wire sensor used in this research has the ability to give only the magnitude of velocity not the direction. The velocity profiles obtained from hot-wire have been overlapped with the smoke visualization to ensure the near wall reverse flow. The separation phenomena for case (i) has been investigated numerically by using commercial CFD to confirm the experimental result. k-ε (RNG) with enhance wall treatment has been implement in simulation. The flow domain is shown in Figure 4 and corresponding boundary conditions has been shown in Table 2.
Table 2. Boundary conditions and solver setup

| Parameters                  | Case (1)                      |
|-----------------------------|-------------------------------|
| Model                       | k-ε (RNG) with enhance wall treatment |
| Inlet B.C.                  | Velocity inlet (4m/s)         |
| Outlet B.C.                 | Pressure outlet               |
| Bottom Wall B.C.            | No slip wall                  |
| Solution Method             | Pressure velocity coupling    |
| Pressure                    | Second order                  |
| Momentum                    | Second order upwind           |
| Turbulent KE                | Second order upwind           |
| Turbulent Dissipation Rate  | Second order upwind           |

3. Results and discussions

Flow separation have been observed by passing a sheet of smoke in the wind tunnel and flow is separated at x=640 mm i.e. 10 mm downstream from the location B3. Flow separation has been shown in Figure 5 and 6 by smoke sheet and smoke wire visualization respectively.

As hot-wire probe only give the magnitude of local velocity, hence the profile obtained from time averaged velocity by the hot-wire probe is overlapped with smoke wire data and simulated results in Figure 7 in which experimental velocity profiles showed good agreement with the numerical results. Momentum addition by both PVG and VG suppress the separation further downstream as shown Figure 8 by smoke sheet visualizations. Velocity profiles obtained by hot-wire probe and smoke wire by using VG and PVG have been overlapped together to ensure the repeatability of the experiment and a good agreement have been found which is shown in Figure 9. As PVG is controllable by switching OFF and ON as per flow situation and it is found that at switching OFF condition of PVG provides the same velocity profile that is obtained without actuator case. That’s mean, in switching OFF condition it doesn’t affect the normal flow structure. On the other hand the VG is always attached to surface with an angle of incident along flow direction. In case of no controlled case (when it not necessary to control the flow), it appends a drag due to its angle of incident which is undesirable. The velocity profiles of PVG switching OFF and no actuator case are almost identical which proves that no drag penalty has
been occurred which is shown in Figure 10 at location B4.

Figure 7. Velocity profiles obtained from smoke wire, hot-wire and numerical results for case-1.

Figure 8. Separation suppression by VG (top) and PVG (bottom).

Figure 9. Velocity profiles by VG and PVG.

Figure 10. Impact of PVG in switching OFF condition on uncontrolled flow.

4. Conclusion
From the above discussion and pictorial representations, it is revealed that the new concept of flow control by plasma vortex generator is very promising as its effectiveness to suppress the separation in a turbulent boundary layer flow as like as conventional vortex generator. Moreover, it can be controlled as per requirement and in switching OFF condition, PVG doesn’t have any impact on the flow, hence
the drag penalty is minimized that is a common phenomenon in uncontrolled flow situation if VG is used.

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