

Experimental Study of the Flow Field around a Circular Cylinder Using Plasma Actuators

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ABSTRACT

In this paper different configurations of plasma actuator for controlling the flow around a circular cylinder made of Quartz were experimentally investigated. Three thin plasma actuator electrodes were flush-mounted on the surface of the cylinder and were connected to a DC high voltage power supply for generation of electrical discharge. Different configurations of plasma actuator were used for this study and pressure distribution experiments showed that the existence of the plasma decreases the pressure coefficient of the cylinder and the variation of the pressure coefficient can change the behavior of the lift and drag coefficient of the cylinder for all configurations. According to the pressure distribution data, two configurations of the plasma actuators made the best influence on the aerodynamic performance and also on the drag reduction.

Keywords Plasma actuator, Generalized glow regime, Quartz, DC high voltage power supply, Flow control, Wind tunnel, Pressure coefficient, Drag coefficient, Aerodynamic performance parameter.

1. INTRODUCTION

In order to control the aerodynamic characteristics of a moving body, the flow field around that should be controlled properly so that the separation phenomenon postponed or delayed significantly because the separation phenomenon will increase the drag coefficient and also the instability of the flow field. So it can be realized that flow control is one of the main principles of aerospace engineering especially the aerodynamics major which can bring important improvements for the future studies. Generally there are two types of flow controlling methods namely as passive and active flow control methods. Today the passive flow control methods are not paid too much attention for controlling the flow because at high Reynolds numbers, they would significantly increase the drag coefficient. Unlike with the passive flow control methods, the active flow control methods have been used widely during the recent decades (Roth et al. 2004; Sosa and Artana 2006; Leger et al. 2001; Sosa et al. 2007). The main goal of the active methods is to control the separated flow on the body surface applying different kind of methods such as surface suction and blowing, oscillations of the body, synthetic jets and etc. In active flow control methods, the energy as an input to the system can be in the forms of heat, laser, plasma, acoustic energy and etc whereas for passive flow control methods, there is no need of energy in the input

of the system. The input energy of the system of the active flow control methods can be turned on and off as needed therefore active flow control methods are more flexible in contrast to the passive ones.

One of the most beneficial instruments for active controlling the flow field around moving bodies in the recent years is *plasma actuators*. During the recent years, plasma actuators have been paid too much attention for this purpose (Boeuf and Pitchford 2005; Font and Morgan 2005; Visbal et al. 2006). They consist of two or more electrodes which are separated by a dielectric material such as plastic, Quartz, nylon, Teflon, kapton and etc. When the electrodes are connected to a positive and negative polarities of a DC or an AC high voltage power supply, positive ions and negative ions (electrons) would be generated at anode and cathode respectively. As the voltage difference between the electrodes increases, electrical field would become more intensive and eventually Columbian force would be generated. This force causes the positive ions attract to the negative ones and vice versa and while they are migrating, they would collide to neutral particles and exchange their momentum with them. Therefore it can be claimed that the principle of plasma actuators is based on momentum transferring. As a matter of fact, an ionized fluid flow comprises of positive and negative ions (electrons) is produced which is directed from anode to cathode because the mass of

the electrons is negligible in contrast to the positive ions. This ionized flow is called ionic wind (plasma) and produces a tangential wall jet at close vicinity of the moving bodies which affects the flow structure around the moving bodies. Plasma actuators have many advantages such as simplicity, reliability, no moving part, low cost and weight, quick response time, easily installation and etc. On the other hand, the main disadvantage of plasma actuators is the generation of Ozone gas during their operation which is harmful for human's health.

Since plasma actuators have considerable advantages, they have been successfully used in a variety of different flow control applications including exciting boundary layer instabilities on a sharp cone at Mach 3.5 (Matis 2004), lift augmentation on a wing section (Patel *et al.* 2006), low pressure turbine blade separation control (List *et al.* 2003), turbine tip clearance flow control (Van Ness *et al.* 2006), bluff body control (Thomas *et al.* 2006), drag reduction (Wilkinson 2003), unsteady vortex generation (Visbal and Gaitonde 2006) and airfoil leading edge separation control (Post and Corke 2006). The main concentration of this paper is to control the flow field around a circular cylinder, so some of the experimental researches will be briefly reviewed.

Artana *et al.* (2003) controlled the near wake region around a circular cylinder by using plasma actuators for Reynolds numbers from 2300 up to 58000. The plasma actuator for this purpose consisted of a wire electrode (copper wire) and a planar electrode (an Aluminum foil) which were located at stagnation point and $\theta=180^\circ$ respectively. They concluded that plasma actuators modified the size of the mean recirculation region and produced an increase in the shear stresses of the layers bounding the contour of this region. In addition to control the near wake region, they calculated the pressure distribution around the circular cylinder at $Re = 21600$ and 57600 when the plasma actuator was on and off. The pressure distribution results showed that the plasma actuators play no important role in separation point and they decrease the pressure coefficient more as Reynolds number increases.

McLaughlin *et al.* (2004) applied Dielectric Barrier Discharge (DBD) plasma actuator to a circular cylinder at a Reynolds number of 7400 to control the cylinder wake vortex. Preliminary data indicated that plasma actuators are effective in controlling vortex shedding frequency and in achieving spanwise coherent shedding. They also could alter the vortex shedding frequency within forcing amplitude/frequency bands at lower Reynolds numbers. Flow visualization test showed that the actuators have played significant role in affecting the flow separation and the wake behavior.

McMullin and Snyder (2007) numerically studied the wakes control downstream of a cylinder. They applied a moving wall boundary condition to conduct simulations of the circular cylinder wake flow control at $Re = 8000$. Large Eddy Simulation (LES) was able to predict the "lock-in" behavior and the spanwise coherence of the wake was quantified using a statistical correlation. A frequency analysis at a monitoring point in the wake

showed the weak frequency peaks at harmonics of the forcing frequency. These peaks apparently were caused by additional small vortices induced by the instantaneous start/stop of the actuators. Finally they concluded that the amplitude of the lift and drag oscillations is significantly increased by the actuators but that the mean drag may increase or decrease depending on the forcing frequency.

Thomas *et al.* (2008) used several plasma actuators on a circular cylinder in order to decrease noise and Karman shedding at Reynolds number of 3.3×10^4 . They performed steady and unsteady actuation for this goal and concluded that by either steady or unsteady actuation, Karman shedding is totally eliminated, turbulence levels in the wake significantly decrease and near-field sound pressure levels associated with shedding are reduced by 13.3 dB.

Sosa *et al.* (2009) reduced the drag coefficient of a circular cylinder up to 25 % by means of several electrode plasma actuators. They concluded that the DBD actuator, for a fixed value of the power coefficient adds a higher momentum to the flow and consequently produces a higher drag reduction than the DBD actuator with the same power coefficient.

In this paper, we are going to extend our previous study (Tabatabaeian *et al.* 2012). The prominent differences between the current study and the previous one (Tabatabaeian *et al.* 2012) are the *material of the model* and also the *configuration of the plasma actuators*. For this study, we have used three electrodes (Aluminum foils) for producing electrical discharge on the surface of the cylinder which is made of Quartz. Pressure distribution experiments were carried out for each configuration at Reynolds of 68000 ($u = 37$ m/s) when the plasma actuator was on and off and the lift and drag coefficients of the cylinder were calculated according to the pressure distribution results.

It is important to mention that no study has been done on Quartz cylinder by previous researchers up to now probably due to difficulties of arranging pressure tapping holes on the Quartz model.

2. EXPERIMENTAL SETUP

2.1 Wind Tunnel

All the experiments of this study have been done in an open loop low speed wind tunnel of rectangular cross section (0.3×0.3 m²) and 60 cm in length that enables testing at flow velocities up to 40 m/s. The turbulence intensity of this wind tunnel is approximately 1%.

2.2 Model

A hollow cylinder with a 3 mm thick wall which is made of Quartz has been used for this study. The dimensions of the model are 300 mm in length and 32 mm in external diameter. Three electrodes have been used for producing electrical discharge. The electrodes are flush mounted on the surface of the Quartz cylinder and consist of three planar electrodes (Aluminum foil) with 200 mm in length and 3 mm in width. The thickness of the Aluminum foils is 50 μ m and the gap

between electrodes is 31 mm. It is important to mention that the concentration of electrical charges is at sharp points like the corners of our planar electrode. In order to avoid this problem, the corners of the Aluminum foil were rounded completely. Fig. 1a shows the schematic of configuration 1 used for this study. As it is clear, for configuration 1, the angular position of electrodes A and B with respect to the horizon is 60 degrees and the electrode C locates at $\theta = 180^\circ$. The other configurations were attained by rotating the cylinder in counterclockwise direction by 30° , 60° , 90° , 120° , 150° and 180° . The schematic of configurations 2 to 7 has been showed in Fig. 1b.

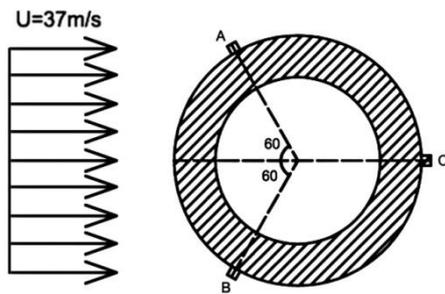


Fig. 1a. Schematic of configuration 1.

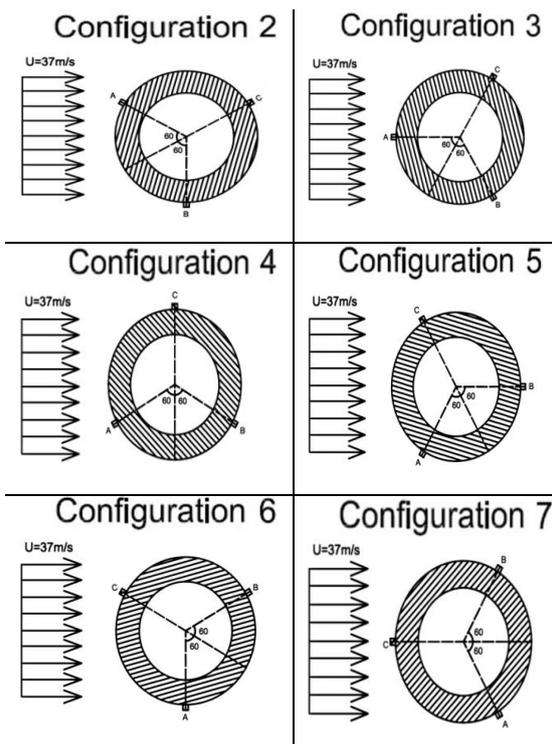


Fig. 1b. Schematic of the model and configurations of plasma actuator.

2.3 DC High Voltage Power Supply

In order to apply a voltage difference high enough to sustain a stable electrical discharge, a DC high voltage power supply (50 kV, 20 mA) has been used. The electrodes A and B were connected to the positive polarity and the electrode C was grounded. By increasing the voltage difference between these

electrodes, we can reach to the *generalized glow regime*. The characteristics of this regime will be mentioned later. A $2.5\text{ M}\Omega$ resistor has been used in order to increase the security of the high voltage power supply system against electrical arcs because they are carrying high electrical currents and can damage the power supply system easily if preliminary cautions are not be considered.

2.4 Pressure Measurement

In order to measure the pressure distribution around the circular cylinder, 18 pressure tapping holes have been mounted on the cylinder and were connected to a pressure transducer system. The pressure tapping holes were mounted in two rows and the diameter of these pressure tapping holes was 1.5 mm.

3. RESULTS AND DISCUSSION

3.1 Generalized Glow Regime

When the plasma actuator was on, all of the experiments were carried out at generalized glow regime. The pattern of this regime shown in Fig. 2 obtained by darkening the Lab. This regime was characterized by a homogeneous luminescence (plasma) covering the cylinder surface. The plasma occupied uniformly the space between electrodes A to C and B to the C and made the cylinder look like it supported a thin film of ionized air (plasma). The direction of the plasma is from A to C and B to C. The corona discharge was homogeneous, showed a little bit noise and the current remained stable over a long period of time. For all configurations of plasma actuator, the generalized glow regime established at a specific electrical current and voltage difference range.

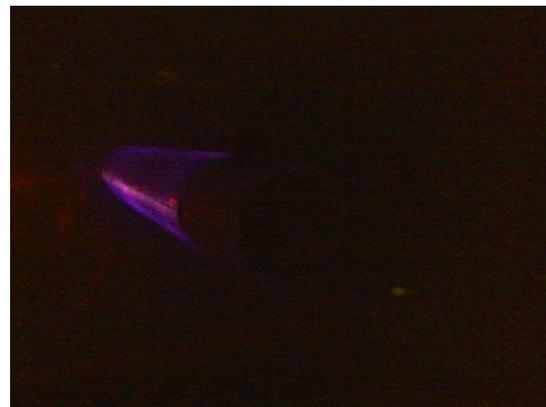


Fig. 2. Generalized Glow Regime (Side view).

Table 1 shows the mean voltage differences and electrical currents for all configurations that the generalized glow regime was produced. It is important to note that the “**angle of rotation**” phrase (if indicated in any table or diagram) relates to the counterclockwise rotation of the configuration 1. For example if angle of rotation equals 30° , it describes configuration 2 or if angle of rotation equals 60° , it describes configuration 3 and so on for the rest. Eventually, angle of rotation of 180° , represents configuration 7.

Table1 Mean voltage differences and electrical currents in generalized glow regime for all configurations.

Configuration	Angle of rotation (deg)	Mean voltage difference (kV)	Mean electrical current (mA)
1	0	22.3	0.6
2	30	22.1	0.45
3	60	22.25	0.5
4	90	22	0.45
5	120	21.6	0.57
6	150	21.3	0.7
7	180	21.3	0.7

The values of the mean voltage differences and electrical currents in table 1, show that for configurations 4 to 7, lower voltage difference and higher electrical current are needed to sustain the generalized glow regime because for configurations 4 to 7, more volume of plasma will be encountered with the momentum of the free stream velocity in comparison with configurations 1 to 3 so the ions will move faster than configurations 1 to 3. Therefore the electrical current for configurations 4 to 7 increases because the electrical current is due to the movement of the ions. On the other hand it is obvious that the total electrical power of DC high voltage power supply is constant. Consequently when electrical current increases, the amount of voltage difference must be decreased so that the electrical power remains constant. That is why for configurations 4 to 7, higher electrical current and lower voltage difference is needed to establish generalized glow regime. Fig. 3 and Fig. 4 show the behavior of the mean voltage difference and electrical current of generalized glow regime for all configurations of plasma actuator.

If the value of the voltage difference exceeds than the value of the voltage difference in which the generalized glow regime has been established, then electrical arcs will be appeared that are very dangerous and may damage the DC high voltage power supply system. So we must be careful not to enter the electrical arc regimes during increasing the voltage difference. Fig.5 shows the electrical arc regime.

3.2 Effect of the Plasma on the Pressure Distribution of the Cylinder

In this section, we are going to present the effect of the plasma on the pressure distribution of the cylinder at $Re = 68000$ ($u = 37$ m/s) for all configurations of the plasma actuator. In other words, the main aim of this section is to compare the pressure distribution of the cylinder in plasma on and off conditions. It is important to note that all the experiments in plasma on condition for all configurations of the plasma actuator have been carried out in generalized glow regime which was completely discussed. Fig.6 shows the pressure distribution of the cylinder for configurations 1 to 7 in plasma on and off conditions. The “angle” phrase in horizontal axis of all diagrams of Fig. 6 relates to the angular position of the

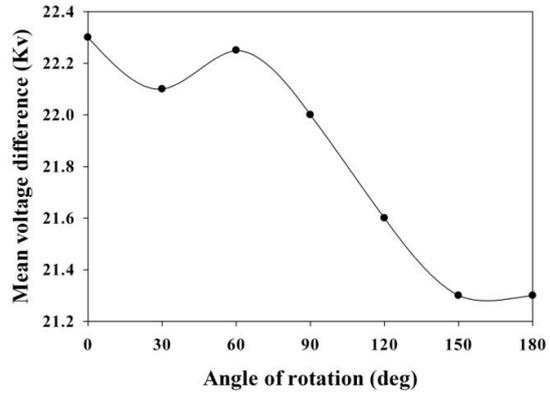


Fig. 3. The behavior of the mean voltage difference for all configurations of plasma actuator.

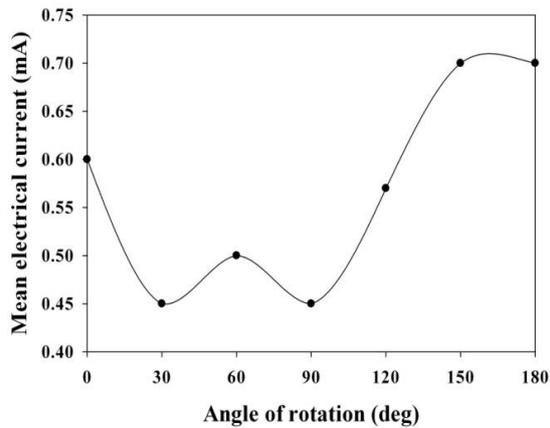


Fig. 4. The behavior of the mean electrical current for all configurations of plasma actuator.

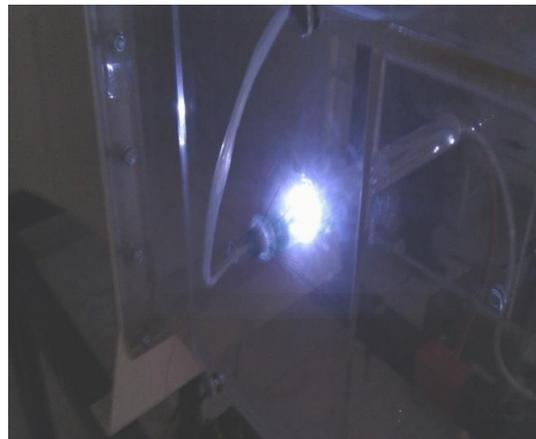


Fig.5. Electrical arc regime.

pressure tapping holes of the cylinder according to the horizon.

According to Fig. 6a, it is clear that as soon as the flow separates (about 80° and 280°);existence of the ionized flow (plasma) decreases the pressure coefficient of the cylinder especially from 80° up to 120° and 240° up to 280°. For this configuration, the separation points of the cylinder are located inside the plasma region and the momentum of the plasma forces the separated flows to

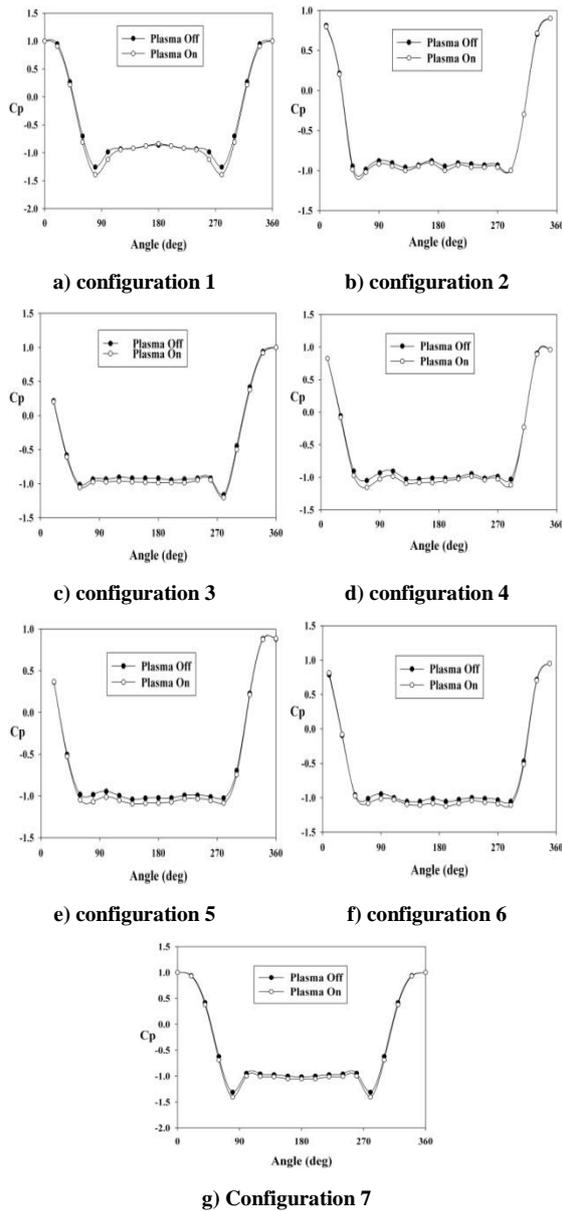


Fig. 6. Effect of plasma on pressure distribution of the cylinder for configurations 1 to 7.

develop more to downstream of the cylinder in contrast to the plasma off condition. This phenomenon significantly decreases the pressure coefficient of the cylinder from 80° up to 120° and 240° up to 280° and reduction of the pressure coefficient causes more suction in this range of angles. For this configuration, the pressure distribution of the cylinder is symmetric and the plasma plays no important role in changing the separation points because the separation occurs at 80° and 280° either the plasma actuator being on or off. This feature is compatible with the symmetrical distribution of the actuators.

Fig.6b shows the pressure distribution of the cylinder for configuration 2 in plasma on and off conditions. For this case, the plasma plays no important role in changing the pressure coefficient of the cylinder before the separated region. But after separation of the flow, existence of the plasma has considerably decreased the

pressure coefficient of the cylinder especially from 70° up to 270° . The reduction of the pressure coefficient causes more suction at downstream of the cylinder mainly from 70° up to 270° because for this configuration, the separation point of the upper surface is located inside the plasma region and the momentum of the plasma will force the separated flow from the upper surface to develop more to downstream of the cylinder compared to plasma off condition and this causes more suction. On the other hand, the separation point of the lower surface is not located inside the plasma region but existence of the plasma which is directed from B to C generates suction and pull the separated flow to develop more to downstream of the cylinder. That is why when the plasma actuator become active, more suction will be occurred especially from 70° to 270° compared with plasma off condition. In this configuration, the plasma has no affection on the separation points because the flow separates at the same points either the plasma actuator being on or off.

Fig.6c shows the pressure distribution of the cylinder for configuration 3 in plasma on and off conditions. For this case, the effect of the plasma on reduction of the pressure coefficient of the cylinder is negligible but as flow separates, the plasma significantly reduces the pressure coefficient of the cylinder from 60° up to 280° . This reduction causes more suction at this range of angles in contrast to the plasma off condition because for this configuration similar to the previous one, the separation point of the upper surface is located inside the plasma region and the momentum of the plasma will force the separated flow from the upper surface to develop more to downstream of the cylinder in contrast to the plasma off condition and this causes more suction. On the other hand, the separation point of the lower surface is not located inside the plasma region but existence of the plasma which is directed from B to C generates suction and pull the separated flow to develop more to downstream of the cylinder. That is why when the plasma actuator become active, more suction will be occurred especially from 70° to 270° compared with plasma off condition. For this configuration, similar to previous cases the separation points are the same either the plasma actuator being on or off. So the plasma has played no important role in changing the separation points.

Fig.6d shows the pressure distribution of the cylinder for configuration 4 in plasma on and off conditions. It can be realized from Fig.6d that before separation region, the plasma has no effect on reduction of the pressure coefficient of the cylinder but soon after the separation points, existence of the plasma considerably decreases the pressure coefficient of the cylinder from 70° up to 290° and this causes more suction at this range of angles. It is clear that reduction of the pressure coefficient from 70° up to 180° is more in comparison with that of from 200° up to 290° because for this configuration, the separation point on the upper surface is located inside the plasma zone but the separation point on the lower surface is not inside the plasma zone. For this case, the momentum of the plasma forces the separated flow from the upper surface of the cylinder to develop more to downstream of the cylinder and this phenomenon decreases the pressure coefficient more

and causes more suction especially from 70° up to 180°. But the separated flow from the lower surface of the cylinder will not encounter with the momentum of the plasma and existence of the plasma which is directed from B to C have less effect in pulling the separated flow from the lower surface to downstream of the cylinder in contrast to the configuration 2 and 3 because for this configuration, the distance between the lower separation point and the plasma region which is directed from B to C is more compared to configurations 2 and 3 so it will be developed less to downstream of the cylinder compared to the separated flow from the upper surface. Therefore the pressure coefficient will be decreased less and less suction will be occurred from 200° up to 290° in contrast to that of from 70° up to 180°. For this configuration, the separation points are the same either the plasma actuator being on or off. Fig. 6e shows the pressure distribution of the cylinder for configuration 5 in plasma on and off conditions. Fig. 6e shows that for this configuration like the previous configurations, the influence of the plasma is after the separation phenomenon. For this configuration, like configuration 4, the separation point of the upper surface is inside the plasma region whereas the separation point of the lower surface is not inside the plasma region. The existence of the plasma from A to C and also the momentum of the free stream velocity cause the separated boundary layer of the upper surface of the cylinder to develop to downstream of the cylinder more compared to the separated boundary layer of the lower surface of the cylinder. This causes the reduction of the pressure coefficient from 80° to 200° become more in contrast to that of 200° to 300°. For this configuration, the directions of the free stream velocity and the plasma flow which is from B to C, are opposite to each other and this phenomenon causes flow interaction so that more suction will be occurred in contrast to plasma off condition. It is important to mention that for this configuration like the previous ones, the existence of the plasma has no affection in the separation points because the separation occurs at the same points either the plasma actuator being on or off.

Fig.6f shows the pressure distribution of the cylinder for configuration 6 in plasma off and plasma on conditions.

It is obvious that before separation points, the plasma has no influence on reduction of the pressure coefficient of the cylinder but as separation occurs, existence of the plasma significantly decreases the pressure coefficient especially from 70° up to 290°. For this case, the two separation points are located inside the plasma region and the directions of the plasma and the free stream velocity are opposite to each other. When the plasma actuator becomes active, the free stream will encounter with the ionized flow(plasma) and a flow interaction will be occurred. This phenomenon decreases the pressure coefficient especially from 70° up to 290° comparing with the plasma off condition. Therefore more suction will be happened. It is important to note that for this configuration like the previous ones, the separation points of the cylinder are the same.

Fig.6g shows the pressure distribution of the cylinder for configuration 7 in plasma off and plasma on

conditions. No significant change could be observed before the separation point. As soon as the flow separates (about 80° and 280°), the existence of the ionized flow (plasma) would decreased the pressure coefficient especially from 80° up to 280°. For this configuration similar to configuration 6, the two separation points are located inside the plasma region and the directions of the plasma and the free stream velocity are opposite to each other. When the plasma actuator becomes active, similar to the previous configuration, the free stream will encounter with the ionized flow (plasma) from the opposite direction and flow interaction will be occurred. This phenomenon will considerably decrease the pressure coefficient of the cylinder from 80° up to 280° compared with the plasma off condition so more suction will be occurred. It is important to note that for this configuration like the previous ones, the plasma has not played an important role in changing the separation points.

3.3. Effect of the Plasma on the Lift and Drag Coefficients of the Cylinder

Fig.7 shows the behavior of the drag coefficient of the cylinder for all configurations of plasma actuator in both plasma on and off conditions.

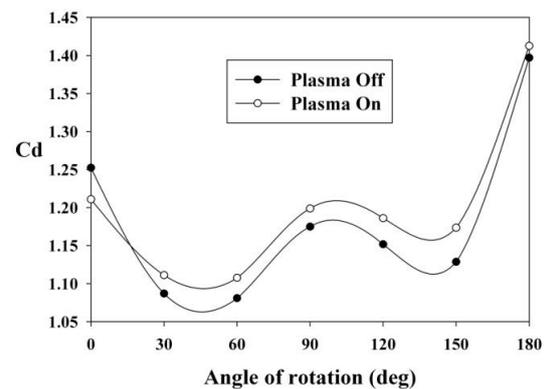


Fig. 7. Drag coefficient of the cylinder for all configurations of plasma actuator in both plasma on and off conditions.

According to Fig.7, existence of the plasma has increased the drag coefficient of the cylinder for all configurations of the plasma actuator except for configuration 1. The enhancement of the drag coefficient for configurations 2 to 4 is because of the development of the separated flows toward downstream of the cylinder and consequently the generation of suction. For configurations 5, 6 and 7, the directions of the free stream velocity and the ionized flow (plasma) is opposite to each other and this case causes flow interaction to occur. For configuration 1, as the plasma actuator activated, the drag coefficient of the cylinder decreased up to 3.2% because existence of the plasma produces more suction at downstream of the cylinder especially from 80° up to 120° and 240° up to 280°(see Fig.6a). In this range of angles, suction appears that decreases the size of the near-wake region and also the drag coefficient. This phenomenon was reported by Thomas *et al.* (2008) and Sosa *et al.* (2009). They produced the plasma approximately in this range of

angles (from 80° up to 120° and 240° up to 280°). Thomas et al. (2008) performed flow visualization test

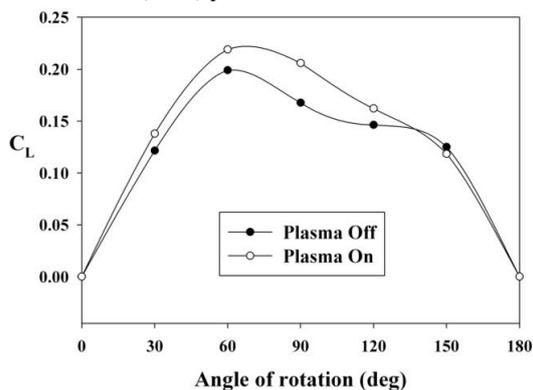


Fig. 8. Lift coefficient of the cylinder for all configurations of plasma actuator in both plasma on and off conditions.

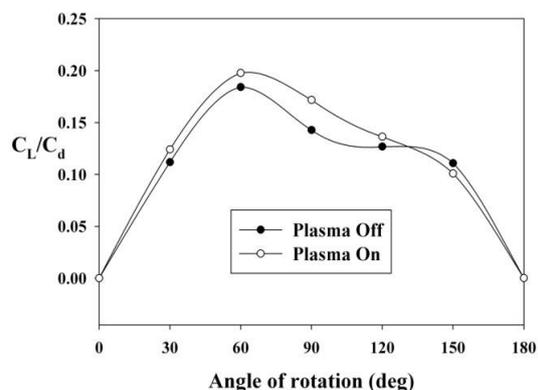


Fig. 9. Aerodynamics performance parameter for all configurations of plasma actuator in both plasma on and off conditions.

and the results showed that the plasma is able to decrease the size of the near-wake region. Furthermore Sosa et al. (2009) decreased the drag coefficient of a cylinder up to 25% at $Re = 8300$. The main difference between present study with that of Thomas et al. (2008) and Sosa et al. (2009) is the application of the category of the plasma actuator because they applied DBD (Dielectric Barrier Discharge) whereas, here we applied PSD (Plasma Sheet Device) for generation of the plasma. Therefore reduction of the near-wake region causes the drag coefficient to be decreased for configuration 1.

As we know, the main goal of aerodynamics is to reduce the drag coefficient in order to improve the aerodynamic performance of the moving bodies. If we want to compare the aerodynamic performance of the model for configurations 1 to 7, it is clear that for configuration 1, the plasma has played an important role in modification of the flow structure around the cylinder. Since existence of the plasma has decreased the drag coefficient of the cylinder, so configuration 1 is suitable for aerodynamic applications. But for the other configurations, the plasma has increased the drag coefficient of the cylinder and these configurations are not good for aerodynamic applications. Therefore for

this study, configuration 1 is the best among the other ones.

Fig.8 shows the behavior of the lift coefficient of the cylinder for all configurations of plasma actuator in both plasma on and off conditions. As it was mentioned previously, the pressure distribution of the cylinder for configurations 1 and 7 were symmetric either the plasma actuator being on or off so the lift coefficient of the cylinder is zero for these two configurations but for the other configurations due to the asymmetry in the flow field, we have lift coefficient for both plasma off and on conditions.

According to Fig. 8, existence of the plasma has considerably increased the lift coefficient of the cylinder for configuration 4 in contrast to the other configurations because for configuration 4 the separation point of the upper surface of the cylinder locates inside the plasma region whereas the separation point of the lower surface has not been located inside the plasma zone. Therefore the momentum of the plasma will force the separated flow of the upper surface to develop more to downstream of the cylinder and this phenomenon will decrease the pressure coefficient of the upper surface of the cylinder more in contrast to the lower surface. The separation point of the lower surface is not inside the plasma region and also existence of the plasma which is directed from B to C is not able to pull the separated flow to downstream of the cylinder properly so reduction of the pressure coefficient of the lower surface is less than the upper one and these conditions will increase significantly the lift coefficient of the cylinder for configuration 4. For configurations 6, the lift coefficient of the cylinder has been decrease due to the flow interaction which was discussed previously. For configurations 2 and 3, the enhancement of the lift coefficient of the cylinder is not that sensible like configuration 4 because for these two configurations, the distance between the separation point of the lower surface and the plasma region (from B to C) is less than that of configuration 4 therefore reduction of the pressure coefficient of the lower surface of the cylinder for configurations 2 and 3 is more than configuration 4. The separation point of the upper surface for configurations 2, 3 and 4 is located inside the plasma region and the pressure coefficient of the upper surface will be decreased due to the development of the separated flow to downstream of the cylinder. So it can be realized that the pressure difference between the lower and upper surface of the cylinder for configuration 4 is more than those of configurations 2 and 3. So existence of the plasma increases the lift coefficient of the cylinder for configuration 4. For configuration 5 similar to configuration 6 because of flow interaction, the enhancement of the lift coefficient of the cylinder is not that sensible as configuration 4.

Fig. 9 shows the aerodynamics performance parameter ($\frac{C_L}{C_d}$) versus the angle of rotation of the cylinder.

It is obvious that the existence of the plasma has significantly increased the aerodynamic performance of the cylinder for configuration 4 comparing with the

other configurations because $\frac{C_L}{C_d}$ has increased considerably due to existence of the plasma. In other words, the plasma has considerably increased the lift and drag coefficient of configuration 4 and also $\frac{C_L}{C_d}$.

Therefore the influence of the plasma for improving the aerodynamic performance for configuration 4 is the best among the other ones.

4. CONCLUSION

In this study we experimentally investigated the effects of various configurations of plasma actuator on the flow structure around a circular cylinder made of Quartz. For this goal, three thin electrodes (Aluminum foils) were flush-mounted on the surface of the cylinder and were connected to a DC high voltage power supply in order to produce electrical discharge. The experiments were performed at $Re = 68000$ ($u = 37$ m/s) for both plasma off and on conditions for all configurations. The pressure distribution results showed that the existence of the plasma decreases the pressure coefficient of the cylinder for all configurations in a certain range of angles due to suction at downstream of the cylinder. Furthermore the pressure distribution results indicated that the plasma plays no important role in changing the separation point for all configurations because the separation occurs at the same points either the plasma actuator being on or off.

Having the pressure distribution of the cylinder, the lift and drag coefficients were calculated for all configurations in both plasma off and on conditions. For configuration 1, the plasma decreased the drag coefficient because of suction that decreases the size of the near-wake region.

For the other configurations, the plasma increased the drag coefficient because of two main reasons namely as:

- 1) The plasma produces more suction at the downstream of the cylinder for configurations 2 to 4.
- 2) The directions of the free stream velocity and the plasma flow are opposite compared to each other and this condition causes more flow interaction to occur for configurations 5 to 7. So the plasma has increased the drag coefficient of the cylinder except for configuration 1, so this configuration is more suitable for aerodynamic applications than the other ones.

The pressure distribution over the cylinder for configurations 1 and 7 were symmetric therefore the lift coefficient of the cylinder for these two configurations is zero either the plasma actuator being on or off. But for the other configurations due to asymmetry of the flow field, the lift coefficient was existed. The existence of the plasma significantly increased the lift coefficient of the cylinder for configuration 4 because the difference between the lower surface pressure of the cylinder and the upper one was maximum compared to configurations 2 and 3. For configurations 2 and 3, the enhancement of the lift coefficient of the cylinder was not sensible as configuration 4. The lift coefficient of

the cylinder for configurations 5 and 6 were decreased due to the flow interaction phenomenon.

The most suitable configuration having the best aerodynamic performance refers to the configuration with the most $\frac{C_L}{C_d}$ parameter. For configuration 4 both lift and drag coefficients of the cylinder have grown larger due to existence of the plasma. So for this configuration, the parameter $\frac{C_L}{C_d}$ is maximum.

For further studies on the cylinder made of Quartz, we recommend to use two thin Aluminum foils so that one of them locates at stagnation point ($\theta = 0^\circ$) of the cylinder and the other one locates in front of the first Aluminum foil ($\theta = 180^\circ$). The Aluminum foil locating at the stagnation point should be connected to the positive polarity and the other one should be grounded. By rotating the cylinder in clockwise or counterclockwise directions, we can study the flow field around the cylinder and also the behavior of the lift and drag coefficients of the cylinder. In order to study the flow field around the cylinder by details, flow visualization and PIV experiments must be performed.

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