THE EFFECT OF PLASMA ACTUATOR UTILIZATION TO THE REDUCTION OF AERODYNAMIC DRAG OF CYLINDER AND BOX MODELS

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ABSTRACT

Aerodynamics drag reduction has an advantage in terms of conversion and conservation energy. Many technologies have been developed in order to reduce the aerodynamics drag, one of them is plasma actuator. Plasma actuator as an alternative kind of active flow control is very promising and powerful in modifying the flow comprehensively. By using ion particles, plasma actuator becomes the forefront in terms of modify a flow and becomes a reliable solution in order to overcome the problems which arise in other types of active control such as installation problems, excessive moving parts which are difficult to control and others. Plasma actuator consists of two sheets of copper electrodes separated by a dielectric material made of acrylic. The final output of the plasma actuators is the ion wind which generated from the movement phenomenon of the air flow around the actuator and was the result of the ionization process in the air so that the air molecules was induced and became unstable. This paper presented two test models, a cylinder which the actuator was placed at the point of separation and a box with two plasma actuators placed at the leading edge and trailing edge to test the ability of plasma to reduce aerodynamic drag effect. The experimental results showed that the plasma actuator with a cylinder model with the 90 degree position can produce aerodynamic drag reduction by 20% while for a box model with a flow rate of 2 [m/s] generated 14.16% reduction of aerodynamic drag.

INTRODUCTION

The advancement in the aeronautical industries in the last decade had been escalating quickly, which can be seen as more and more vehicles have more complicated aerodynamic designs, more complex maneuver capabilities, more aggressive and powerful. This was boosted by the issue of the use of efficient and effective fuel. These things arised because more people are being more aware in the issue of conversion and conservation energy. In its application, using engineered flow, both internal and external gives a lot of advantages especially in the field of conserving fuel significantly, because it directly effects the dominant and dynamic performance of the changes [1]. Conceptually, modifying a flow involves three main phenomenon, which are the manipulation of flow from laminar to turbulent, separation and turbulent [2, 3].

Flow control is basically classified in two methods, which are active control and passive control [2, 3]. In passive flow control, the work domain is located in turbulent flows regime only, because the modified flow is not being given of any energy intervention at all, therefore the movement of the flow is only effected by geometrical factor. Passive control equipment also has its limits, one of which is its construction and the methods of manufacturing such devices. The contribution of passive flow control devices proved to only reduce the drag effect on a body of about 10% [4]. This is considered to be very low, especially in the application of reducing fuel consumption of vehicles.

On the other hand, the performance of active control devices is better than passive control devices. This is because the work domain of active control devices is not only on turbulent flows, but also in transitional zones from laminar to turbulent and also on flow where the separation takes place. Active control is considered to be more efficient because it can causes a direct intervention in the flow interaction, thus creating a controllable flow. Until today, active control have been developed by creating promis-

NOMENCLATURE

A	[m^2]	Wetted Area
C_d	[-]	Drag Coefficient
C_p	[-]	Pressure Coefficient
D	[N]	Drag
d_i	[mm]	Inner Diameter
d_o	[mm]	Outer Diameter
l	[mm]	Length
P	[Pa]	Total Pressure
P_o	[Pa]	Static Pressure
t	[mm]	Thickness
T	[s]	Time
U	[m/s]	Free Stream Velocity
V	[kV$_{p-p}$]	Voltage
w	[mm]	Width

Special characters

ρ	[kg/m^3]	Density
θ	[^{0}]	Angle

ing active control devices such as suction, blowing and synthetic jet. Some of these active control devices have shown significant work performance in reducing aerodynamic drag, e.g.: suction and blowing technologies can reduce up to 15.83% and 14.83% respectively [5]. However, in its application, these active control devices still have its weaknesses and troubles. These devices are seldom controllable, which is a direct result of the presence of moving parts, and its complex installation and preparation.

Aerodynamic drag has a direct correlation with fuel consumption. The drag force contributes to a resisting force, which is in the opposite direction to the direction of flow, thus creating a negative effect on the model. Aerodynamic drag itself is classified into two categories, namely pressure drag and friction drag [6]. Pressure drag is the difference from the total pressure in the upstream region of the model to the total pressure in the downstream region. In this particular case, the cylinder model is chosen because the change of flow in a cylinder model can be controlled conveniently. Whereas, friction drag is the sum of the forces in the same direction of the flow.

The research aims in investigating the effect of the performance of plasma actuators as a newly alternative active control devices for aerodynamic drag effects by using a cylinder model to investigate pressure drag and a box model to investigate friction drag. By using plasma actuators, it gives a better option of using active control devices which is easy to install and more flexible due to the absence of moving parts.

PLASMA ACTUATORS

A plasma actuator is used to induce flow by sucking up the flow in its upstream region and blowing it by adding energy, which comes from the formation of ion winds or electrical winds, in the downstream region. Ion winds are caused by the release of electrons in a potential difference from an electrode, which acts as a power source, to another electrode which acts as the ground [7]. The suction phenomenon in the upstream region is the result of the release of electrons into free air, which then causes the molecules of air to be unstable. Whereas the blowing phenomenon in the downstream region is the result of an ionization process exactly between the two electrodes which forms a filament of unstable free air molecules and is trapped due to the presence of electric arc, which is usually called electric plasma. The more air molecules induced, the more effects which caused a change in properties in the region around the actuator. Figure 1 is given to illustrate the working principle of a plasma actuator.

This research uses plasma actuator with two thin copper sheets (thickness = 0.5 [mm]) as electrodes. One of the electrodes is connected to a power supply of 11 [kV_{p-p}] and the other is connected to the ground. These electrodes are separated with an acrylic dielectric material of 3 [mm] thickness. The dielectric material is used as an isolator from the electrical field effect which is caused by the electric arc along the electrode. The region of the electrode which is connected to the power supply is called the upstream region, and the region connected to the ground is called the downstream region. The maximum region of plasma formation is 3-5[mm] from the source of the electrodes.

In the formation of electric plasma, some devices such as oscilloscope, function generator, amplifier, multimeter and high voltage transformer is needed. Oscilloscope acts in monitoring and measuring the electricity supply, both the voltage, current, frequency and the form of the wave. Function generator works as the source of frequency and creates wave forms such as sinusoidal, square or triangle wave forms. Amplifier is responsible in maintaining the stability of the current which is being supplied to the transformer and is able to maintain the electrical load needed. High voltage transformer acts to create a high voltage energy supply of 11 [kV_{p-p}] with a ratio of 1:137.5. Whereas the multimeter is used to measure the amount of electricity supplied to the transformer and amplifier. Figure 2 is presented to better understand the principle of the system and devices in this research.

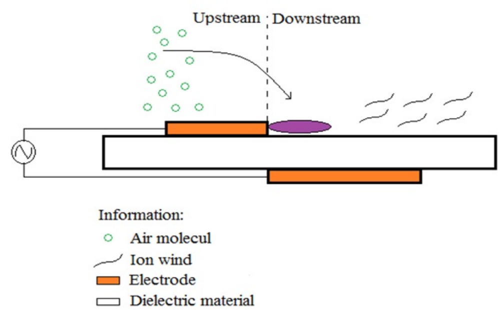


Figure 1. Plasma actuator mechanism

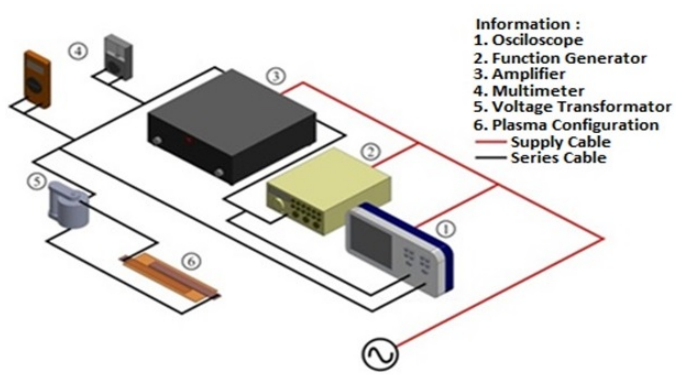


Figure 2. Plasma actuator devices schematic

The formation of plasma follows the principle of Townsend, where the failure of an isolation causes the electricity to flow perfectly and using the dielectric as a barrier from the electromagnetic field. The result of an electrical isolation failure is the presence of small electrical arcs along the electrode which forms simultaneously and uniformly. Therefore, the choice of the dielectric material affects the success of the process highly.

AERODYNAMIC DRAG

In its application, aerodynamic drag is commonly effected by the appearance of adverse pressure gradient, which is the starting point of separation. As explained before, aerodynamic drag is classified into pressure drag and friction drag, where the total of both drag is the total of the drag forces acting on the body. However, theoretically, one of those drag can represents the basis of drag formation, if the model is dominant in one of the drag forces.

Theoretically in an inviscid flow, the pattern of the flow started changing to a separated flow in the 90^o angle of a cylinder model. Whereas in a flow where it is initially a laminar or turbulent flow, in an angle less than 90^o, the flow has started changing into a separated flow. Therefore the placement of the actuator in the 90^o angle is considered to be a good place, where the flow started changing into separated flow and is expected to be modified to cancel the separation.

The same principle is also applied to the box model. However, with its characteristics which is more dominant in destructing the flow and the low pressure region located in the downstream region, the actuator is placed in two different locations, which are in the leading edge to maintain the flow from being destructed by the bluff body shape and in the trailing edge to increase the energy of the flow to avoid the occurrence of a separation in the downstream region. The assumption of placing the actuator in the trailing edge is that the vortex produced will be smaller or broken down, thus the pressure in the separation region is not very low.

Drag is commonly expressed in a non-dimensional unit, which is usually used in the comparison of prototypes. This non-dimensional unit of drag is called the Drag Coefficient Cd, with the expression as follows [6]:

$$C_d = \frac{D}{1/2\rho U^2 A} \tag{1}$$

Whereas for the calculation of the pressure distribution which is commonly used in cylinder models, a non-dimensional unit is also used which is called the Pressure Coefficient with the expression as follows [6]:

$$C_p = \frac{P - P_0}{1/2\rho U^2} \tag{2}$$

EXPERIMENTAL SETUP

For this research, an acrylic hollow cylinder with an outer diameter (do) of 99 [mm] and inner diameter (di) of 93 [mm] and a total length of 400 [mm] was used. The plasma actuator is placed exactly on top of the cylinder, with the orientation of the flow from left to right and the plasma actuator on the 90^o angle on the axis of the cylinder. To give a better understanding, Figure 3 is given as follows:

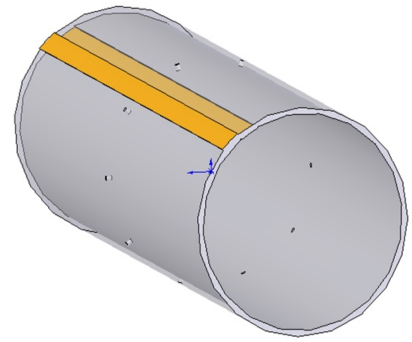


Figure 3. Cylinder model with plasma actuator

In this cylinder model, measurements are conducted to obtain the pressure distribution around the surface of the cylinder. Therefore, 10 holes of 3[mm] diameter were drilled to the cylinder. All of the holes are connected to pressure tapping and then connected to a manometer to examine the pressure difference of each points, as given in Figure 4:

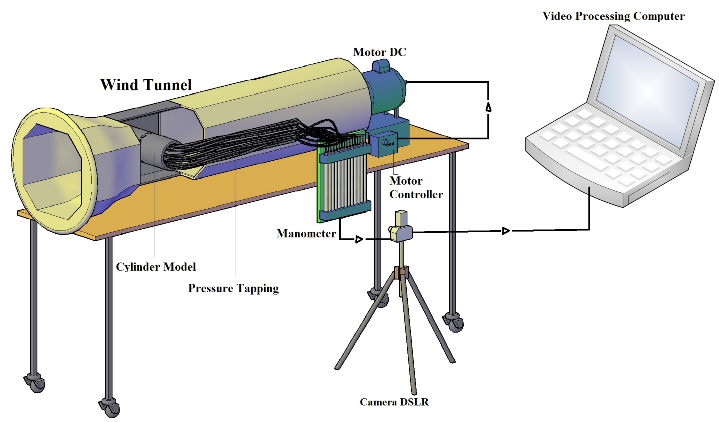


Figure 4. Data logging schematics

Like the cylinder model, the box model is also made of acrylic which also acts as the dielectric material. Two actuators are placed on the box model, on the leading edge and the trailing edge respectively as illustrated in Figure 5.

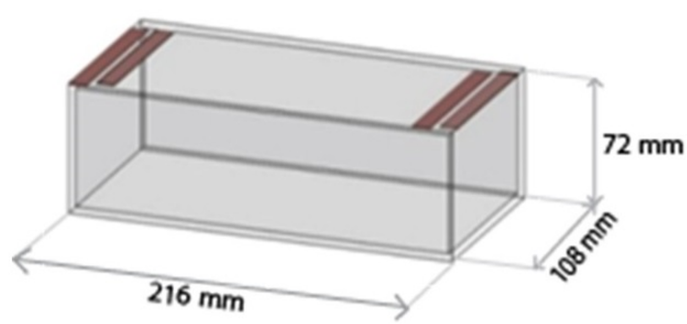


Figure 5. Box model with plasma actuator

The measurements done for the box model focuses to obtain the amount of drag forces. Therefore load cells are placed to measure the forces in the axis direction. Figure 6 is given to a better understanding in the experimental process.

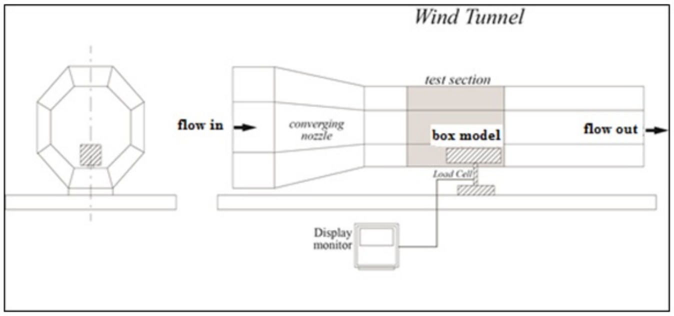


Figure 6. Data logging schematics for the box model

These experiments are conducted inside a type Armfield C2-00 wind tunnel, which has a maximum flow velocity of 19.44 [m/s]. The same width of the actuator for each model is used, which is 10 [mm], and the length of the actuator which follows the dimension of each model. All measurements are statistically tested, with an error limit of less than 5%. This is done to ensure the validity of each measurement.

RESULTS AND DISCUSSION

The area study in this research is laminar to turbulent transition and turbulence regime, because there have many advantages in the boundary layer. Small Reynolds number in the working of Plasma Actuator is used as initial limitation in the scope of this study.

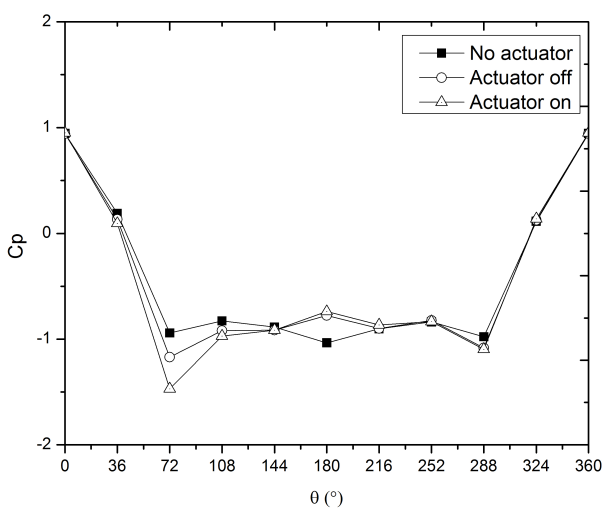


Figure 7. Measurement results of pressure distribution

In the cylinder model, some measurements variations are made, which are the measurements of the pressure distribution without the actuator, with the actuator and when the actuator is activated. All of those measurements are conducted in a 9 [m/s] free stream flow or in a Re = 60,000 flow regime. The results of these measurements are shown in Figure 7.

The measurement with the presence of the actuator is done because it is predicted that even with just the presence of the actuator in the 90^0 angle, the pattern of the flow can change and directly effects the pressure distribution in the surface of the cylinder, where a little fluctuation is observed in the $36 \leq \theta \geq 288$ region. This phenomenon is predicted because the presence of the actuator also directly acts as a passive control device with a riblet or groove method on older passive control devices, which is able to alter the flow due to change in surface contour.

Whereas when the actuator is activated, the change in pressure distribution can be seen most significantly in the range of $36 < \theta > 108$, and for the angle above 108^o, a similar dominant trend can be seen even though with the activation of the actuator, a better pressure coefficient is obtained than without the actuator.

The location where the actuator is placed proved to give a significant effect on the pressure distribution, where it shows a more negative pressure and this directly proportional with the increase in flow velocity on the surface of the cylinder. Increasing the negative pressure in the pressure distribution gives an advantage in the reduction of aerodynamic drag especially in cylinder models, as shown in Figure 8. Plasma actuator is able to reduce drag up to more than 20%, whereas the presence of the plasma actuator itself (without being turned on) gives a passive reduction effect of 16% as compared to the initial cylinder condition. The placement of these actuators are intended to maintain the streamline of the flow to not be completely destroyed in the upstream region and to reduce the effect of vortex shedding, which usually takes place in the trailing edges of bluff bodies. The measurement result of the drag forces in the box model can be seen in Figure 9.

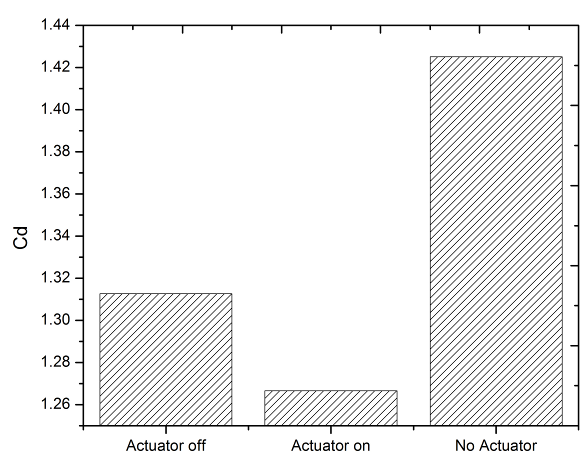


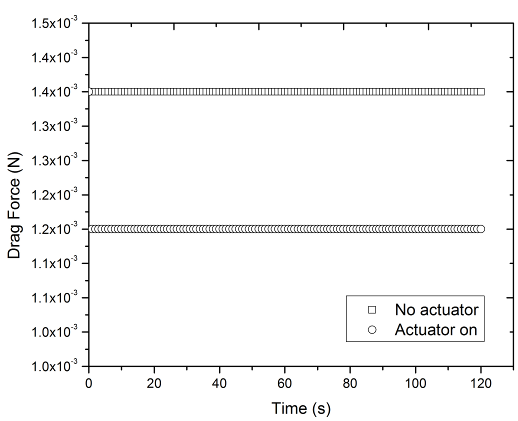
Figure 8. The comparison of the drag coefficient in each configuration for cylindrical model

Some measurements variations are also made in the box model, which are with a free stream velocity of 2 [m/s], 5 [m/s], 7.5 [m/s] and 10 [m/s], which varied from Re = 20,000 to Re = 150,000. Two plasma actuators are used in this model, in the leading edge and the trailing edge respectively. The placement of these actuators are intended to maintain the streamline of the flow to not be completely destroyed in the upstream region and to reduce the effect of vortex shedding, which usually takes place in the trailing edges of bluff bodies.

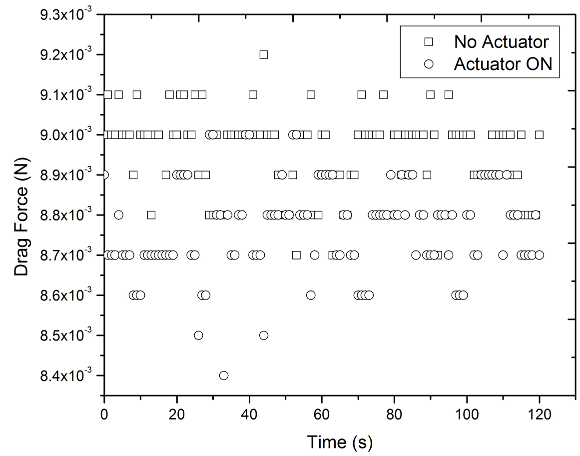
The measurement result of the drag forces in the box model can be seen in Figure 8. It can be seen that in Figure 9 (a), a significant reduction in drag force for the box model and the data obtained shows a constant and steady values. This is predicted because in the 2 m/s variation, the pattern of the flow did not change much and was in the laminar flow regime. Whereas for (b), (c) and (d), the flow pattern is more dominant in the turbulent regime, which causes the measurement to be more oscillating, but in general shows a reduction pattern of the drag forces, although not very significant.

Theoretically, the change in drag forces causes a change in the drag coefficient as shown in Figure 10, where in low velocity flow; the actuator can reduce the drag forces best. However, for a high velocity flow, the drag coefficient of the model did not change much from its initial drag coefficient. In other words, the actuator did not perform well in reducing the amount of the drag forces.

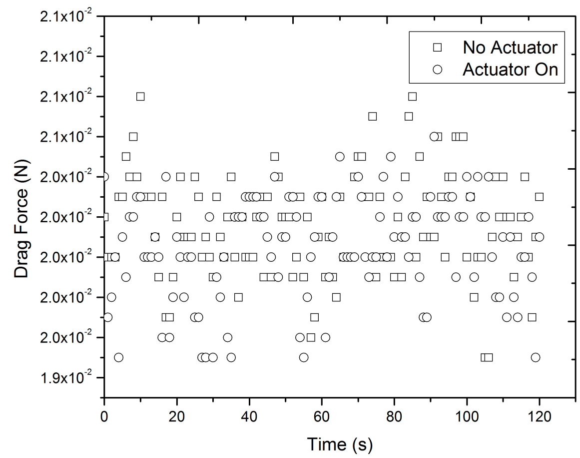
The ability of the plasma actuator in reducing the aerodynamic drag forces has its limits. This is directly proportional to the velocity of the free stream flow, which makes it difficult for the actuator to induce flows as shown in Figure 11, where the free stream velocity is more than 7.5 [m/s]. Plasma actuator is considered to work well for a laminar flow for a box model, with a drag reduction of 14% for a 2 [m/s] free stream flow. This is predicted to be the effect of the large box geometry, which causes the plasma to have little effects on the model. By seeing the pattern of the obtained results, it can be predicted that the effect of a Plasma Actuator will be more effective in a lower Reynolds number.



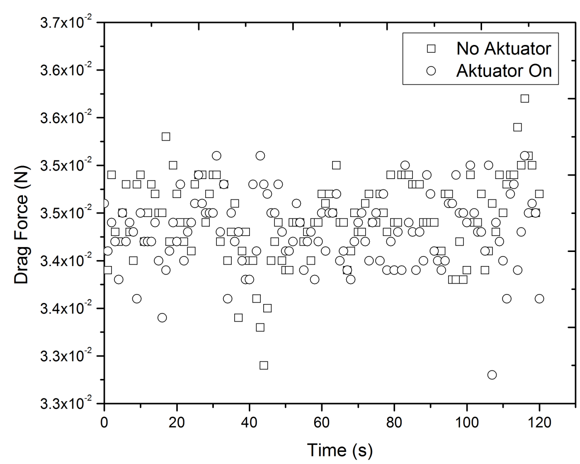
(a)



(b)



(c)



(d)

Figure 9. Measurement results for the box model in a (a) 2 [m/s], (b) 5 [m/s], (c) 7.5 [m/s], (d) 10 [m/s] velocity.

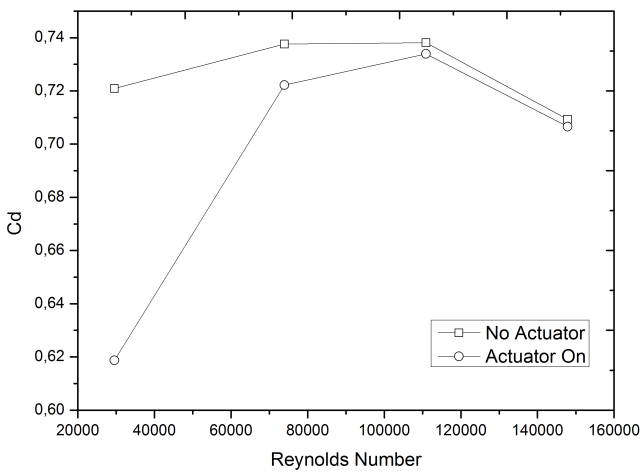


Figure 10. Drag coefficient against Reynolds Number

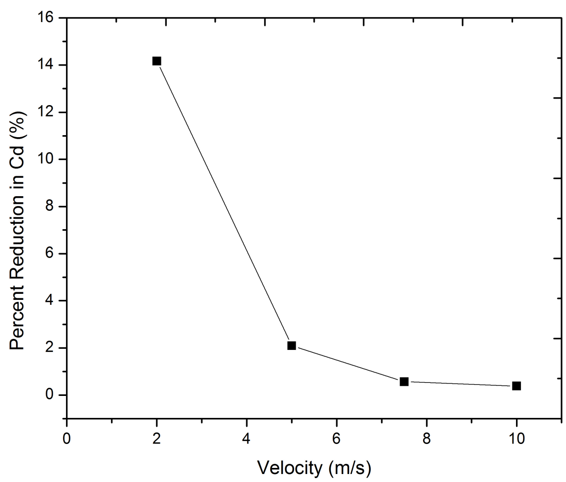


Figure 11. Percentage of reduction of aerodynamic drag

CONCLUSION

The use of a plasma actuator as one of the alternative active control devices is investigated in this research experimentally and shows a positive result in reducing aerodynamic drag. For a cylinder model, the plasma actuator is placed in the separation region and is known to reduce the drag by 20% in a 9 [m/s] free stream flow (Re = 60,000), whereas for the box model, two actuators are placed in the leading and trailing edge of the model and is known to reduce the drag up to 14% in a 2 [m/s] free stream flow (Re = 20,000 to Re = 150,000). In this case, plasma actuators can control the flow by inducing the flow and giving energy that can alter the pattern of the flow to be once again fully developed, which is considered very advantageous. It is true that a Plasma Actuator works best to reduce drag in a friction drag type, as its characteristic to directly intervene the flow. But as it can be seen from the result, Plasma Actuator also able to reduce the form drag type by the shown percentage, even in as such blunt shape as box model where the form drag type is clearly the dominant one.

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