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INVESTIGATING THE EFFECTS OF PLASMA ACTUATOR ON THE FLOW CONTROL AROUND NACA2415 AIRFOIL

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Abstract: In this study, the effects of the plasma actuator on flow control at varied Reynolds numbers and attack angles are examined. Plasma actuator is placed on the NACA2415 airfoil at x/C = 0.1. The effect of the actuator to active flow control is examined at Reynolds number between $8x10^3$ and $9x10^4$ in the wind tunnel. The lift force which acted on the airfoil was measured by using a force balance system. The velocity measurements were done by the hot-wire probe, located at the wake region, and the flow around model was visualized by the smoke wire method. When the plasma was active, an increased lift force and a narrowed wake region are observed. The stall angle shifted to the higher attack angle by the effective active flow control at low Reynolds numbers. Prevent of the flow separation was enhanced up to 18° angle of attack and the maximum lift force occurred at the 14° angle of attack which is doubled when the plasma actuator is on.
Keywords: airfoil, flow control, lift force, plasma actuator

PLAZMA AKTÜATÖRÜN NACA2415 AIRFOIL ETRAFINDA AKIŞ KONTROLÜNE ETKİLERİNİN ARAŞTIRILMASI

Özet: Bu çalışmada, değişen Reynolds sayılarında ve hücüm açılarında plazma aktüatörlerin akış kontrolüne etkisi incelenmiştir. Plazma aktüatör NACA2415 airfoil üzerinde x/C=0.1 konumuna yerleştirilmiştir. Aktüatörün aktif akış kontrolüne etkisi Reynolds sayısının $8x10^3$ ile $9x10^4$ aralığında rüzgar tünelinde incelenmiştir. NACA2015 tipi uçak kanat profiline etki eden kaldırma kuvveti, kuvvet balans sistemi kullanılarak ölçülmüştür. Hız ölçümleri, iz bölgesine konumlandırılan kızgın tel probu ile ölçülmüş ve model etrafindaki akış duman tel yöntemi ile görselleştirilmiştir. Plazmanın aktif olduğu durumda, kaldırma katsayısında artış ve iz bölgesinde daralma gözlemlenmiştir. Düşük Reynolds sayılarında etkili aktif akış kontrolü ile akış ayrılması daha yüksek hücüm açılarına kaydırılmıştır. Akış ayrılması önlenmesi 18° hücum açısına kadar artırılmıştır ve 14° de gerçekleşen en yüksek kaldırma kuvveti plazma aktüatörün çalıştırılması ile iki katına çıkmıştır.
Anahtar Kelimler: airfoil, akış kontrolü, kaldırma kuvveti, plazma aktüatör

NOMENCLATURE

Re	Reynolds number
C_L	Lift coefficient
α	Attack angle
f	Frequency
V	Voltage
C	Chord length
x	Location of actuator on airfoil
AR	Aspect ratio
pp	Peak to peak
U_∞	Free stream velocity
U	Local velocity

INTRODUCTION

In many engineering applications, the fluid acting on bodies caused design and control problems. In recent years, optimum design and control have been desired in the aeronautic industry to produce lightweight and compact air vehicles. Many control strategies are developed to control flow around bodies. These methods can be classified as a passive control such as trip wires, geometrical modification, control rod, splitter plates and active control such as synthetic jets, suction or blowing channels, plasma actuators etc (Fırat et al. 2013). In this study, the plasma actuators are investigated because of the promising solutions they provide to the flow control. The plasma actuators convert surrounding air to ionized air and generate a surface plasma which drives the bulk motion of molecules in the plasma region. The bulk motion creates an induced flow on the bodies (Sanlisoy 2013). The advantages of the plasma actuators could be as follows: transfer of electrical energy to the flow without any moving parts and high response time. The flow control characteristics, such as aerodynamic force coefficients, flow separation and the stall angle could be enhanced by plasma actuators at low Reynolds numbers (Akansu and Karakaya 2013; Akansu et al. 2013; Akbıyık et al. 2017). Basically, plasma actuators consist of two electrodes, dielectric material, and a power supply which provides the energy. The plasma actuators can be classified as a DC corona discharge plasma actuators and the dielectric barrier discharge actuators. Preliminary researches were done by using the DC corona discharge which consists of two electrodes located on the geometry and then activated by the power supply. This method has limited use because of glow to spark transition occurrence at high voltages. Roth et al. (2004) designed the dielectric barrier discharge actuator which has electrodes located on the upper and lower surface of dielectric material to prevent this transition.

Table 1. The studied topics in the literature.

Research team	Studied topics	Required properties
Zito et al. (2012), Thomas et al. (2009), Ryan and Subrata (2012)	Dielectric materials	-high dielectric strength, -low dielectric constant (quartz-like materials) -increased thickness of dielectric material -flexible to mount on curved bodies, thin and nonfragile
Debien et al. (2012), Erfani et al. (2015), Thomas et al. (2009)	Electrode geometry	The embedded electrode should be sufficiently wide to obtain optimum body forces. There are a variety of exposed electrode geometry in the literature which has been investigated.
Thomas et al. (2009), Roth et al. (2004)	Multi actuator arrays	the body forces increase with the number of actuators. the enhancements are not proportional to the number of actuators. Paraelectric and peristaltic actuation mechanisms are introduced to enhance body forces.
Benard and Moreau (2010), Little and Samimy (2010), Guler et al. (2018)	Signal modulation	Duty cycles, burst modulation, and amplitude modulation signals were used in the literature.
Roth et al. (2004), Song et al. (2012)	Plasma discharge mechanism	Corona discharge, dielectric barrier discharge, nanosecond pulse discharge.
Abdollahzadeh et al. (2018), Feng et al. (2012), Taleghani et al. (2012), Meng et al. (2018)	The effect of plasma applicator on the flow control	The effects of plasma applicator on the lift coefficient, the drag coefficient and stall angle delaying are examined.
Jolibois et al. (2008), Sosa and Artana (2006)	Plasma actuator position	Optimum position is near separation edge.
Feng et al. (2012)	Wake region characteristics	The effects of the plasma applicator on the wake region of airfoils are drifted to downward and the recirculation region narrowed and shortened

The studies in the literature are carried out in the stationary medium to investigate the generated flow with the plasma actuator (wall jet velocity) or in controlled flow field to examine the effect of plasma actuator on the flow control. There are electrical parameters which are effective in the plasma actuator characteristics whereas there are flow control parameters which are affected by the electrical properties of the plasma actuator. The effective parameters are the voltage, frequency, plasma power, dielectric material properties, electrode design while the flow control parameters such as the plasma-induced velocity, velocity distribution, pressure distribution, velocity profile in the wake region, the lift coefficient and the drag coefficient are effected parameters by the plasma actuator. The challenges of the plasma applicators can be listed in Table 1.

Although there are many studies on the flow control with the plasma actuator, the limitations of the plasma actuators are not given comprehensively. In this study, limitations of the flow control with the plasma actuator are examined. While the plasma actuators are effective at very low Reynolds numbers (up to $5x10^4$ Re), it becomes insufficient at low Reynolds numbers (higher than $5x10^4$ Re). The enhancement of the lift coefficient and the wake region narrowing and shifting to downward are given at varied angles of attack.

EXPERIMENTAL SETUP

In this study, the plasma actuator was driven by a custom-made power supplier. It consists of a signal generator, Mosfet Audio Amplifier to amplify the signal, and coils to raise the output voltage to the desired level. The obtained signal in each step was measured by Tektronix P6015A high voltage probe and Fluke 80i-110s AC/DC current probe and acquired by NI PCIe-7841R model data acquisition card and monitored using Tektronix TDS2012B oscilloscope and Labview interface.

The open low-speed wind tunnel with a square test section of 570 mm × 570 mm ×1000mm which had lower than 1 % turbulence intensity was used to perform the experiments at Nigde University. It had free stream velocity range of 0-15 m/s and the exhaust of the wind tunnel connected to the open atmosphere to provide safe laboratory conditions. The model in wind tunnel has swept up to 20° angle of attack and the maximum blockage ratio has stayed below 0.1 and it is usually chosen between 0.01 and 0.1 with 0.05 being typical (Barlow et al. 1999). The plasma actuator is placed on NACA2415 airfoil geometry which has 150 mm chord length and 510 mm span length between the end-plates. Two end plates of 280 mm in diameter were used to provide two-dimensional flow around the model.

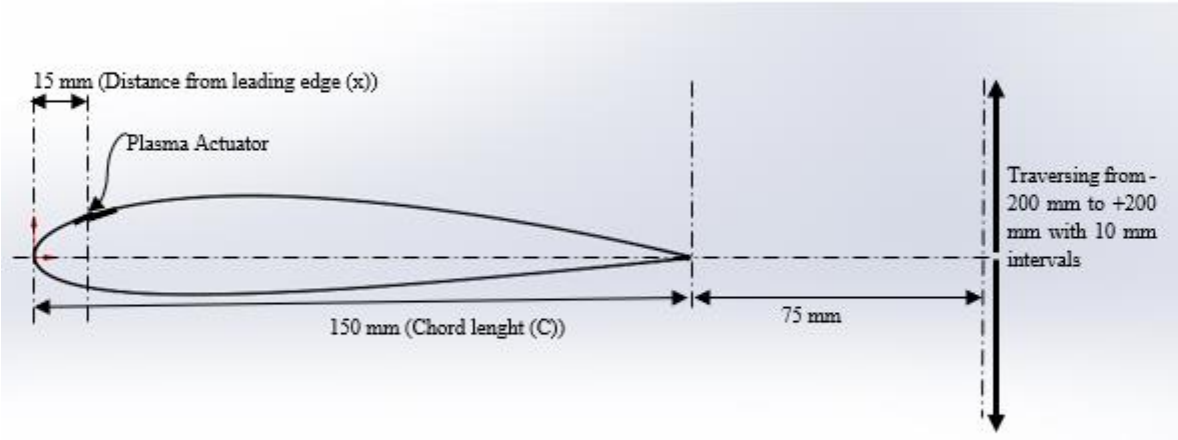

Figure 1. Details of the geometry and the hot wire traversing measurement location

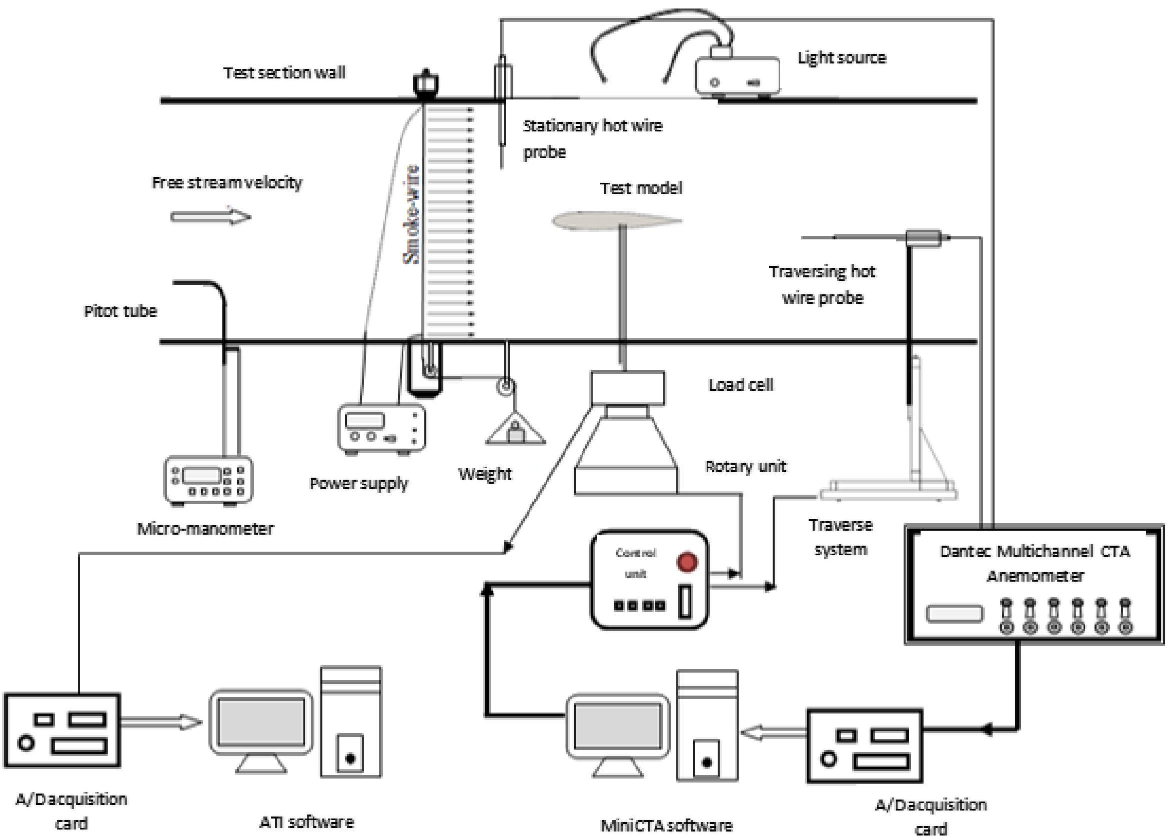

Figure 2. Presentation of the measurement systems

The plasma actuator was located on NACA2415 airfoil at x/C = 0.1 as shown in Figure 1. In this configuration, the exposed and grounded electrodes have 5 mm, 12 mm width respectively. It consists of 495 mm grounded and exposed electrodes in length and 3 layers of Kapton dielectric tape between them.

Effect of plasma actuators to flow around airfoil observed by measuring the velocity in the wake region, measuring the aerodynamic forces act on the model and visualizing the flow around the model. The measurement system configuration is given in Figure 2. In the force measurement method, the ATI model load cell measures the 6 components of force, was used to measure the lift component. The attack angle is controlled by the computer-aided rotary unit which connected to load cell. The measurements were conducted at a sampling frequency of 200 Hz and 3000 samples were collected by the data acquisition card. Also, each measurement repeated 2 times to eliminate measurement errors. Then, the lift force acts on the airfoil, projection area of the airfoil, free stream velocity and air density in test section of wind tunnel were measured to calculate the lift coefficient.

The velocity in the wake region of the model and free stream velocity were measured by a hot-wire anemometer. In this method, Dantec 55P11 model probe located at a point which is 210 mm far from the model test section in horizontal direction is used to measure the free-stream velocity. The same probe is also used to measure the velocity in the wake region by locating it downstream of the NACA2415 airfoil model. It was controlled by a traverse mechanism to scan the velocity profile in the wake region. The velocity measurements were taken 75 mm downstream of the airfoil and along the distance ranging from -200 mm to 200 mm with 10 mm intervals as shown in Figure 1. In each interval, 16,384 samples were collected with a sampling frequency of 2 kHz.

Smoke-wire system was used to generate smoke in the wind tunnel test section. It consists of a wire connected to a power supply, light generator, and a camera. To generate the smoke, paraffin injected to the wire which flows through the wire and just small portion of it stay on the wire and when the power supply turned on, the wire heated up and evaporated the paraffin. The top plane of the test section was illuminated by KRUSS OPTRANIC cold light generator to visualize the flow around the airfoil and Fujifilm HS20EXR camera was used to capture the flow visualizations.

RESULTS AND DISCUSSIONS

The NACA2415 airfoil model was compared with the other studies to validate the geometry. In Figure 3, the attack angle versus lift coefficient around the Reynolds number $6x10^4$ of compared with the study of Micheal et al. (1996).

In Figure 4, Mueller (2002) expresses the effect of Reynolds numbers to the lift coefficient for Reynolds numbers in the range of 10^4<Re<10^7 for airfoil models. The flow structure and the lift coefficient change with the Reynolds number. Especially, at the low Reynolds number, the lift coefficient gradient increases by the change of Reynolds number. Similar results are observed for NACA2415 airfoil at 10° angle of attack when it is compared with the range of smooth airfoils.

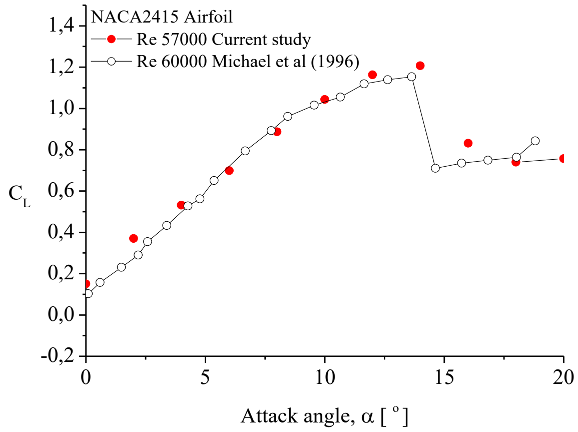

Figure 3. Lift coefficient versus angle of attack for NACA 2415 airfoil

This transition region corresponds to the effective plasma actuation velocities. Plasma actuator generates induced flow on the surface with approximately 2.5 m/s velocity at 8 kV peak to peak voltage and 3.6 kHz frequency in still air. This induced velocity reattaches the separated flow from the airfoil at low Reynolds numbers up to $5x10^4$ which corresponds to 6.5 m/s free stream velocity. Because, the induced velocity has the required momentum to reattach the flow on the surface at low Reynolds number.

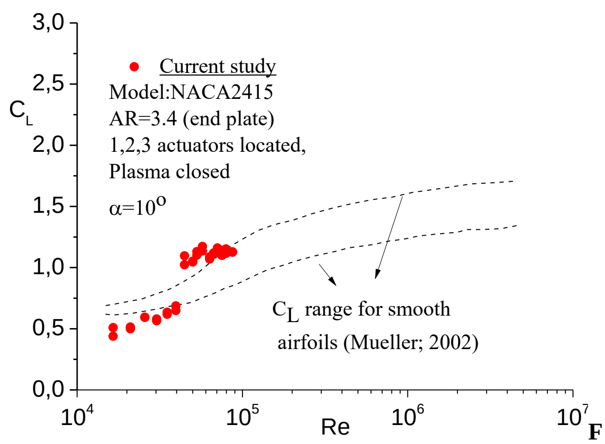

Figure 4. Lift coefficient range of airfoils at low Reynolds numbers

However, the momentum which is generated from the induced velocity of plasma actuator becomes insufficient in higher Reynolds numbers and flow separation occurs. As a result, the flow separation can not be prevented and the plasma actuator becomes insufficient in the flow control at high Reynolds numbers (Re>5x10[5]). In case of separation of flow from the upper surface of the airfoil, the lift coefficient stays lower.

The change of lift coefficient depends on the Reynolds numbers shown in Figure 5 in the case of active and passive plasma actuators. While the lift coefficient enhanced for the value of $5x10^4$ Re, the effect of plasma actuator becomes inadequate for the higher Reynolds numbers in the current experimental conditions. At very low Reynolds numbers, a high rate of increment of the lift coefficient is observed. It is because of the high ratio of plasma-induced velocity to free-stream velocity at very low Reynolds number. By increasing the Reynolds number, free stream velocity becomes dominant in the total velocity. The total velocity consists of the plasma induced velocity which was 2.5 m/s in still air for the given operating condition of plasma actuator and the free stream velocity which corresponds to 6.5 m/s for $5x10^4$ Re. The plasma actuator was effective till $5x10^4$ Re.

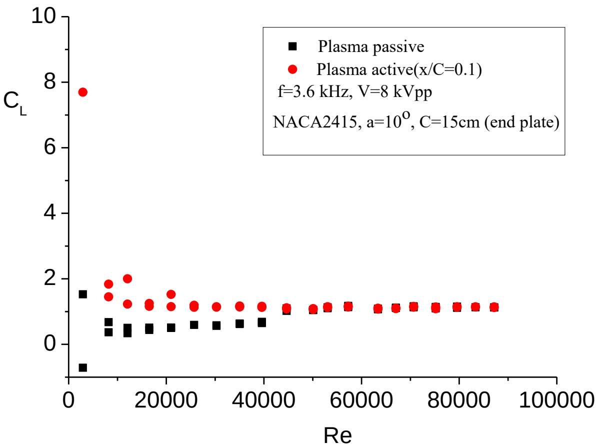

Figure 5. Lift coefficients versus Reynolds numbers in the cases of active and passive plasma actuators

The lift coefficient's dependency on the angle of attack when the plasma actuator is passive at different Reynolds numbers are given in Figure 6. Lift coefficient curves for Re 57200, 75000 and 87000 overlapped. It indicates that the flow structures are approximately the same. On the other hand, lift coefficient curves diverge at very lower Reynolds numbers which indicates the change of flow structure. This could be explained by the stall effect. While the stall effect is uncertain at very low Reynolds numbers, it becomes clear with an increase of the Reynolds number.

Figure 7 presents the lift coefficient's dependency on the angle of attack when the plasma is active and passive. When the plasma actuator is passive, the lift coefficient increased up to 0.6, by increasing the angle of attack up to 6°. By using the plasma actuator, the lift coefficient enhanced to 1.45. The maximum lift coefficient occurs at 14° angle of attack. When the angle of attack increased further, the plasma actuator becomes insufficient to force the flow reattach to the airfoil surface. The flow boundary layer breaks of the airfoil surface to cause flow separation and the stall effect is observed.

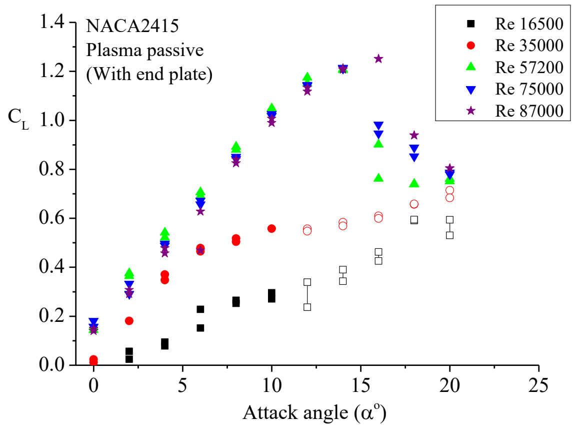

Figure 6. Lift coefficient versus angle of attack at different Reynolds numbers

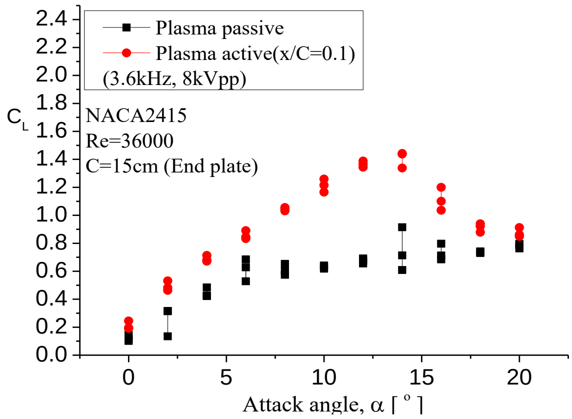

Figure 7. Effects of the plasma actuator on the lift coefficient under variation of angle of attack

The applied voltage, frequency, and the signal type have an influence on the performance of the plasma actuator. Especially, higher applied voltage increases the induced flow which enhances the flow control. The lift coefficient versus Reynolds number is plotted in Figure 8 for the different applied voltages.

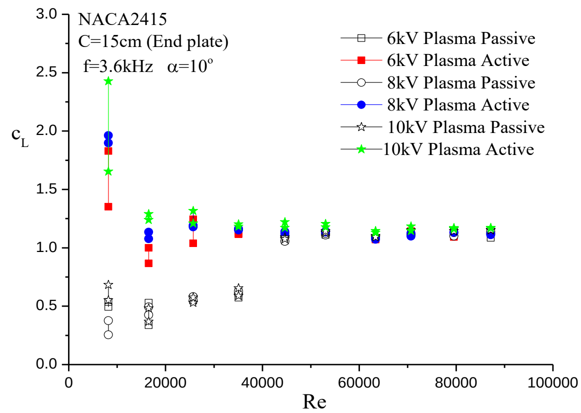

Figure 8. Effect of the plasma actuation voltage to the lift coefficient at different Reynolds number when the angle of attack is 10°

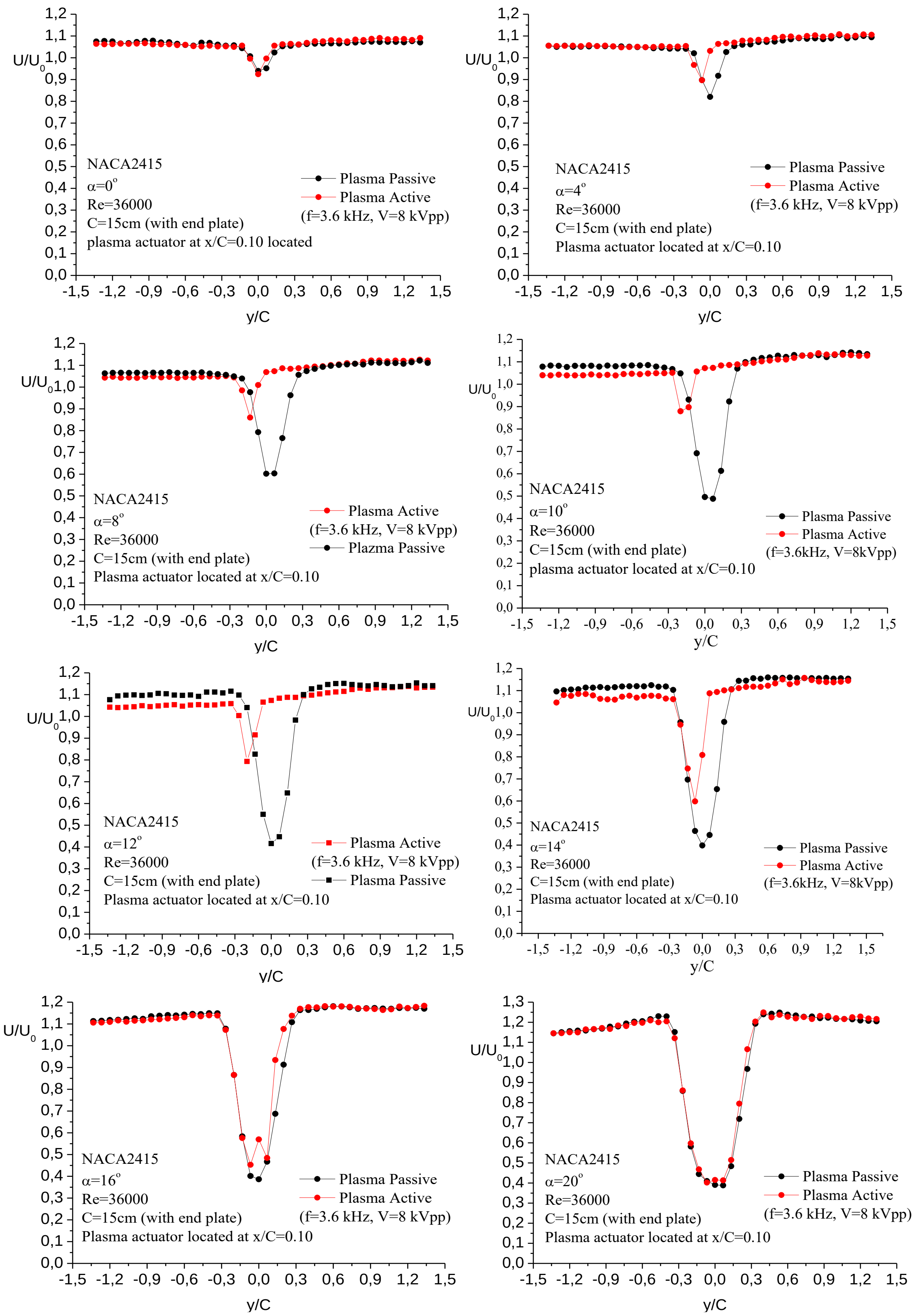

Figure 9. Effect of plasma actuator on the dimensionless velocity over wake region downstream of NACA2415 airfoil at a varied angle of attack

The plasma actuator enhances the lift coefficient up to 5x10^4 Re for all voltage values, after that the plasma actuator becomes inadequate for higher Reynolds numbers. When the plasma-induced flow is sufficiently high, the lift coefficient enhancement occurs. However, the free-stream velocity is quite bigger than the induced flow at a higher Reynolds number. That is why the plasma actuators become insufficient to control the flow separation around the model at higher Reynolds numbers.

Figure 9 represents the effect of the plasma actuator on the velocity distribution over the wake region at varied angles of attack. According to the Figure 9, the wake region is enlarged by increasing the angle of attack. By using the plasma actuator, the wake region is narrowed essentially. Also, the effect of the plasma actuator on the flow attachment is clearly seen up to 14° angle of attack. The wake region is shifted further downstream because of the flow attachment at the upper surface of the model. When the angle of attack exceeds 14°, the plasma-induced flow becomes insufficient to control the flow separation and hence the wake region is not affected by the plasma actuator.

Figure 10 shows the flow structure around NACA2415 airfoil when the angle of attack and the Reynolds number were 10° and 36000 respectively. It is clearly seen from Figure 10, the applied voltage changes the induced velocity by the plasma actuator. Changes in the induced velocity attach the flow to the wall. While the plasma actuator is passive, the flow is separated and a wide rage of wake occurs. By applying 5 kV voltage to the plasma actuator, the flow separation was prevented partially. Because the plasma-induced flow was insufficient to upgrade the momentum of fluid elements moving in the close vicinity of wing surface to keep attaching the flow on the airfoil totally. By applying 6 kV of voltage, the flow kept on moving close to the airfoil surface. The increase of voltage causes an increment in the induced flow. When the Reynolds number or the angle of attack increases, a higher voltage levels are needed to obtain the flow attachment as shown in Figure 11. However, the power supply or the dielectric material constraints to apply higher voltages.

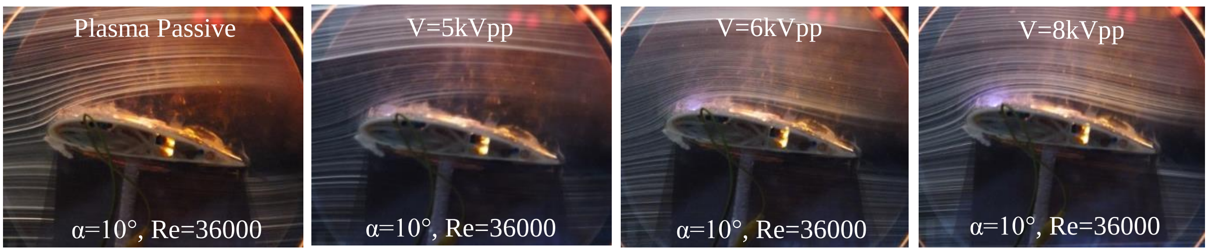

Figure 10: Effect of the applied voltage of the plasma actuator to the flow structure around NACA2415 airfoil

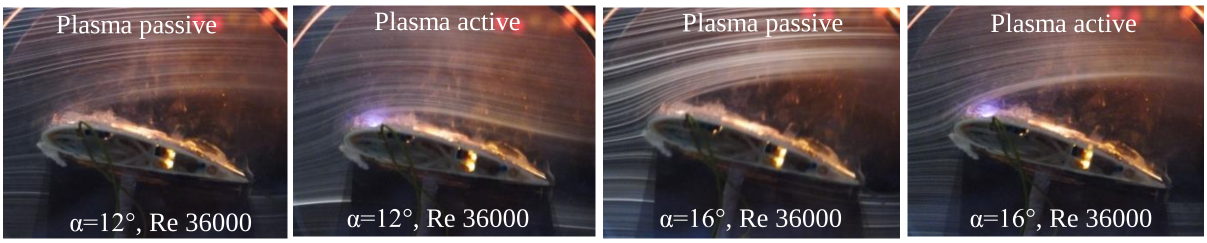

Figure 11: Effect of the angle of attack in passive and active cases of plasma actuator at 8 kV_{pp} voltage and 3.6 kHz frequency to the flow structure around NACA2415 airfoil

Table 2. The uncertainties of the measured and calculated parameters.

Measured Parameter	**Uncertainty (%)**
Atmospheric pressure	1.1
Ambient temperature	0.67
Chord length	0.66
Span length	0.19
Air viscosity	0.51
Pressure transducer	9.6
Air density	1.2
Projected area	0.68
Hot wire anemometer	5.44
Lift force	5.5
Calculated Parameter	**Uncertainty (%)**
Reynolds number	5.6
Lift coefficient	12.26

The uncertainty of the measured and calculated parameters are calculated according to methodology defined by (Coleman and Steele 2009). The uncertainties of the measured and calculated parameters are given in Table 2.

CONCLUSION

In this study, limitations of the flow control with a plasma actuator are examined. While the plasma actuators are effective at very low Reynolds numbers (up to $5x10^4$ Re), it becomes insufficient at low Reynolds numbers (higher than $5x10^4$ Re). The plasma actuator was able to increase the lift coefficient for the range of Reynolds number varied from 0 to $5x10^4$. At very low Reynolds numbers, a high rate of increment of lift coefficients was observed because of the high ratio between plasma-induced flow and free-stream velocity. A rate of increase in the applied voltage caused higher induced velocity. At very low Reynolds numbers, the induced flow could manipulate the flow structure and enhanced the lift coefficient. When the plasma actuator is passive, the lift coefficient increased to its value of 0.6 by increasing the angle of attack up to 6°. When the plasma actuator is activated, the value of lift coefficient was 1.45 at 14° angle of attack. Also, the stall effect shifted to the higher angle of attack. The wake region was narrowed by the plasma actuators up to 14° angle of attack. In addition, the wake was shifted further downstream because of the flow attachment at the upper surface of the model.

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