

Numerical Analysis of Flow Separation Control of an Airfoil by Plasma Actuator

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ABSTRACT

Plasma actuators operating under atmospheric conditions show great promise for flow control due to their unique physical characteristics, such as the body force generated by a strong electric field. This study numerically examines the effect of low-powered plasma actuation on the aerodynamic performance of a NACA 2412 airfoil. Utilizing the Shyy plasma actuation model, the study simulates its effects through defined functions. The analysis investigates the lift and drag coefficients at various angles of attack, with a freestream velocity of 14.5 m/s. Without plasma actuation, the airfoil experiences common aerodynamic challenges, such as flow separation near the trailing edge, which reduces efficiency. However, plasma actuation accelerates the airflow over the upper surface, delaying flow separation and decreasing drag. This results in smoother airflow and increased lift, particularly at higher angles of attack. The use of plasma actuation achieved approximately a 21% increase in the lift coefficient. Overall, plasma actuators enhance airflow control, reduce drag, and boost lift, improving the airfoil's aerodynamic performance. This improvement is supported by pressure contour analysis, which demonstrates a more favorable pressure distribution with plasma actuation.

Keywords: Plasma Actuator, Shyy Model, Airfoil, Flow Control.



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1. Introduction

Flow control is an evolving and critical field, particularly in industries like aerospace and automotive. It can be classified into two main categories: passive and active. Passive flow control devices are fixed and operate without energy input, while active devices require an actuator and thus consume energy. The primary functions of flow control devices vary, including increasing lift, reducing drag, and minimizing noise, with a primary goal of preventing flow separation—often referred to as flow separation control. Achieving higher lift, for example, necessitates addressing flow separation.

In most cases, flow control involves influencing the boundary layer's transition from laminar to turbulent and preventing flow detachment. Modern aircraft incorporate various flow control mechanisms, such as adjustable guide vanes in gas turbines and high-lift devices like flaps and leading-edge slats. However, these devices share a common drawback: they rely on complex moving components, resulting in high development and manufacturing costs, wear, and demanding maintenance.

To address these challenges, researchers are developing plasma actuators for flow control. Plasma actuators introduce momentum to the flow without any moving parts, effectively delaying or preventing flow separation. They can function alone or alongside other flow control devices to improve performance. Pioneering research in the late 1990s and early 2000s laid the foundation for the use of plasma actuators in aerospace applications, and ongoing research continues to advance this technology for various aerodynamic purposes. [1]

Numerical Simulation of Plasma Actuators has become an increasingly prominent area of research. The primary challenge in simulating plasma actuators lies in accurately representing their behavior, their impact on the surrounding

flow field, and the distribution of the plasma region. As research in this field continues to expand, various numerical models have been developed to address these challenges.

One approach, exemplified by Suzen et al. [2], involves modeling the body force generated by the plasma actuator using Maxwell's equations, which relate it to the charge density and the electric field's strength produced by the actuator. In the same study, the distribution of the plasma over the embedded electrode was modeled using a half-Gaussian distribution, which was based on prior experimental findings. This model is regarded as high fidelity since it aligns with the physical principles governing the actuator's performance.

On the other hand, Aholt and Finaish [3] adopted a simpler approach by incorporating a body force source term into the Navier-Stokes equations, even though it does not directly correspond to the physical representation of the actuator's behavior (i.e., the solution of Maxwell Equations). Nevertheless, this straightforward model effectively demonstrated the practicality of plasma actuators in active flow control. In this paper this later method with some alteration was used.

Plasma actuators on 2D airfoils pose challenges in ANSYS simulations due to complex plasma physics, which is often simplified with User-Defined Functions (UDFs), limiting accuracy. Current research predominantly focuses on laminar flows and low Reynolds numbers, leaving gaps in understanding turbulent flow applications.[4] Additionally, limited experimental validation restricts practical scalability and integration into real-world systems. These gaps highlight the need for advanced plasma dynamics modeling, better validation with experimental data, and exploration of high-

Reynolds-number or turbulent flow scenarios to enhance simulation accuracy and applicability [5].

2. Methodology

Computational Domain and Boundary Conditions:

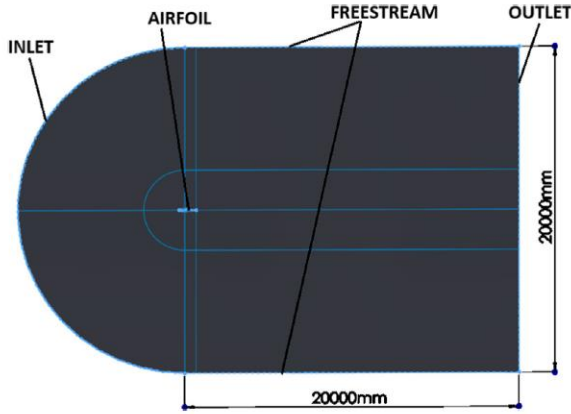


Fig.1 Computational Domain with Dimensions

The geometry of the domain and NACA 2412 airfoil coordinates is created in ANSYS Design Modeler software. Airfoil coordinates is obtained from Airfoil Tools database [6]. The chord length was selected as 1m. A C-H shaped flow domain is created in which the airfoil is situated in the middle. In the flow domain, both inlet boundary is located 10c away from the leading edge of the airfoil and outlet boundary is located 20c away from the trailing edge of the airfoil. The bottom and top boundary is located 10c away from the mid-section of the airfoil.

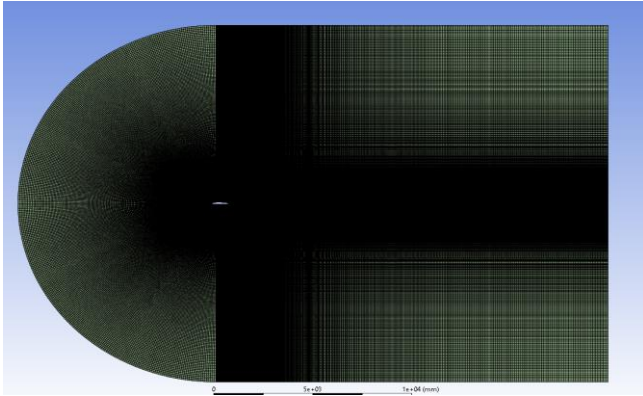


Fig.2 Mesh of the entire Domain

The computational domain and the mesh near the surface of the airfoil are shown in Figure. The mesh is C-H typed grids computational domain of 999460 cells. The mesh is mapped face and the first layer thickness near the airfoil blade is 1.5×10^{-6} m to guarantee that y^+ is less than 1. The turbulence model used in ANSYS fluent is Spalart Allmaras according to the recommendation of previous studies. [7] The solver used is coupled solver; all the spatial discretization parameters are in second-order upwind dispersed mode for the accuracy of the results. The turbulence intensities at velocity inlet and pressure outlet are 1% and 5% respectively. The inlet air velocity is set to be 14.6 m/s; air density = 1.225 kg/m³, air viscosity = 1.789 4e-05 kg/m. s, The Angle of Attack (AOA) of the airfoil is varied from 0° to 18°.

Plasma Actuator Equations:

The plasma actuator consists of two electrodes: one is exposed and the other is covered. It produces non-thermal plasma by ionized air above the covered electrode when high voltage and high frequency alternating current is applied.

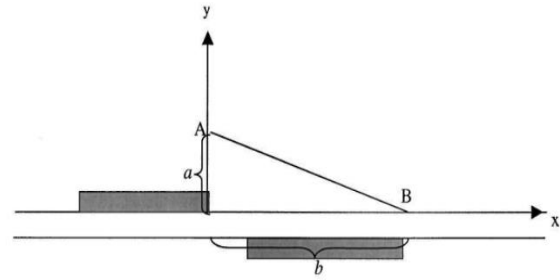


Fig.3 The Plasma Boundary using approximation

As a result, the surrounding molecules collide with the ionized particles and momentum exchanges. This produces a downward body force due to an electric field which causes the particles near the boundary layer to accelerate creating a structure similar to wall jet. Thus, it enhances the ability of the coolant near the boundary layer to stick to the wall. This model is brought up by Shyy which assumes a tri-angular electric field over the exposed electrode. [8] The Shyy model is also known as the linearized model as the electric field strength is considered to vary linearly, as it moves away from the electrode. The variation of the field E can be written as,

$$E(x, y) = |E| = E_0 - K_1x - K_2y \quad (1)$$

$$E_0 = \frac{V}{d} \quad (2)$$

The K_1 and K_2 can be found using:

$$K_1 = \frac{E_0 - E_b}{b} \quad \text{and} \quad K_2 = \frac{E_0 - E_b}{a} \quad (3)$$

Then, the components of the electric field can be found from,

$$E_x = \frac{EK_2}{\sqrt{K_1^2 + K_2^2}} \quad \text{and} \quad E_y = \frac{EK_1}{\sqrt{K_1^2 + K_2^2}} \quad (4)$$

Thus, body force components will be,

$$f_x = E_x \rho_c e_c \quad \text{and} \quad f_y = E_y \rho_c e_c \quad (5)$$

These forces act only in the region where the plasma is present, this is indicated by the delta function,

$$\begin{aligned} \delta &= 0 \quad \text{when } E < E_b \\ \delta &= 1 \quad \text{when } E \geq E_b \end{aligned} \quad (6)$$

here, E_b is the breakdown voltage.

The effective force acting on the neutral particles is given by,

$$f_{effx} = \alpha f_x \delta \quad \text{and} \quad f_{effy} = \alpha f_y \delta \quad (7)$$

α is a factor which is used to consider the collision efficiency among the electrons and neutral particles.

Now the plasma actuator is designed with named expression equations in fluent. Eq 1 to Eq 7 is used to create named expressions which work like defined functions in this case. The edge this has over the UDF system is its simplicity of nature and it doesn't require codes to run. It is in setup drop down.

Equations are modified so that the electric field work on the airfoil surface and create the triangular delta zone which is the area inside which the electric field is active and the body force is generated by the plasma actuator Shown below.

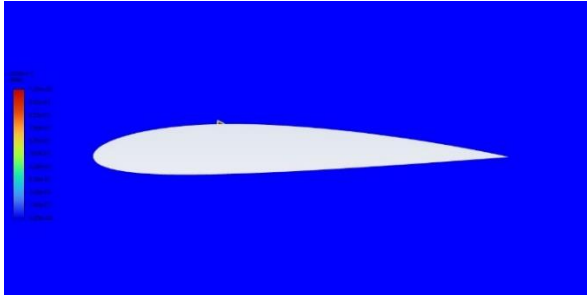


Fig.4 Delta Zone

Now the named expressions create the F_x and F_y force components which are added via the cell-zone conditions as a source term into the continuity equation. This creates the effect of plasma on the airfoil surface at 0.3 chord length. [9]

Validation

Here the current study is compared with John E et al [10]. We can notice that there is significant change in co-efficient of lift in higher angles of attack but at lower angles the values are near identical. The cause of this variation is due to the difference in meshing method.

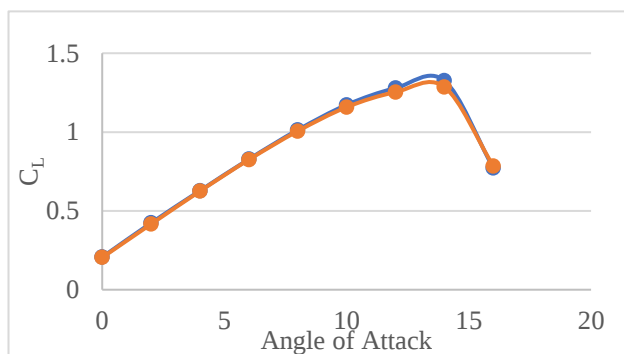


Fig.5 Validation of Airfoils Performance without plasma actuator.

3. Result & Discussion

In figure 6 the effectiveness of the plasma actuator is observed by once enabling it and without it. The variation of Co-efficient of Lift is seen in the study over the Range of AOA 0° - 18° . It is observed that difference of co-efficient of lift increased over the range and near the stall angle there is a significant difference that suggests that at higher angles of attack the performance of the actuator is better. Observing the Graph, it can also be said that the plasma actuators effect was linear at beginning then it increases rapidly. As we can see a steep climb of the line near the higher angles of attack.

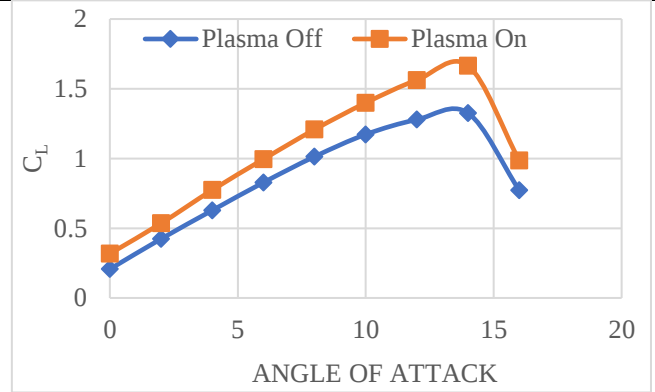


Fig.6 Difference of C_L with and without Plasma

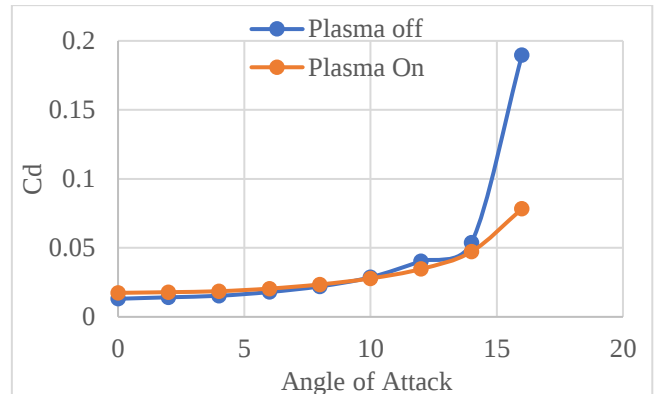


Fig.7 Difference of C_d with and without Plasma

There isn't much difference made on drag co-efficient by the plasma at lower angles of attack we can see from figure 7 but it is noticeable that at high angle of attack specially near the stall angles the co-efficient of drag increases drastically for the airfoil without the plasma actuators effects but with the plasma actuators effects the rapid increase in stall angle is neutralized and the curve is much less steep than the one without the plasmas effect.

The observation of the velocity, pressure and turbulent viscosity contours at 4° and 12° angles of attack with and without the plasma actuators effect are presented in figure 8-13. In figure 8,9 the velocity contours are present for four- and twelve-degrees angle of attack, (where the bottom image in all cases indicate that the plasma actuator is active and the top one is where the effect is turned off.) the contour map shows the boundary layers thin non-moving zone as the blue outline also the blue point at the leading edge and trailing edge are the stagnation points. In fig 8,9 second images it is visible that from chord length 0.3 and upper surface of the airfoil the velocity increases. Also, from figure 10,11 at the same location the pressure is drops evident through the light coloration of the upper surface. These drop in pressure and increase of velocity is the effect of the plasma actuator in work. Because of the increase in velocity the fluid molecules stay attached to the upper surface of the airfoil for longer via inertia and pressure in the process controlling the flow nature. The turbulent viscosity contours in figure 12,13 provides a look into the flow nature as for lower AOA the flow nature isn't affected much but for higher angles the flow separation is much more controlled. So, it is evident that plasma actuator can be used as a flow control device.

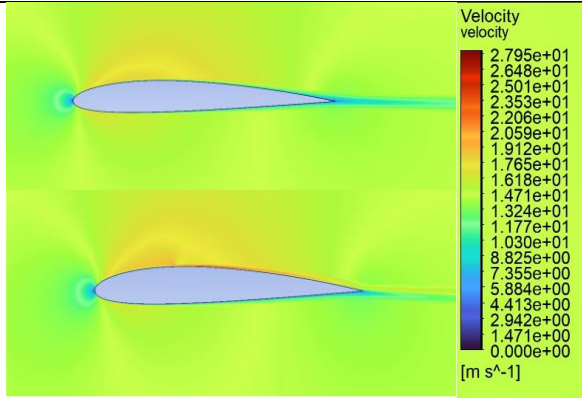


Fig. 8 Velocity contour at 4° angles of attack without and with the plasma actuators

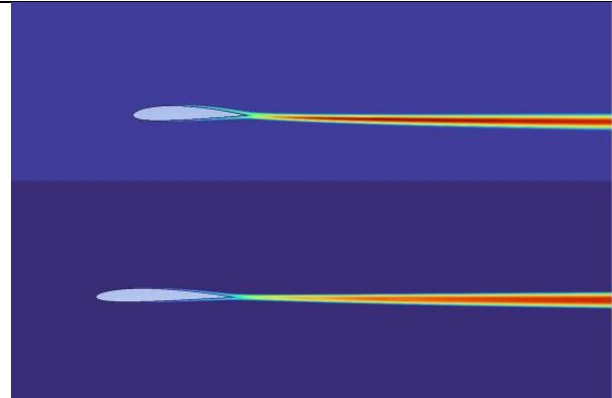


Fig. 12 Turbulent Viscosity contour at 4-degree angle of attack without and with the plasma actuators

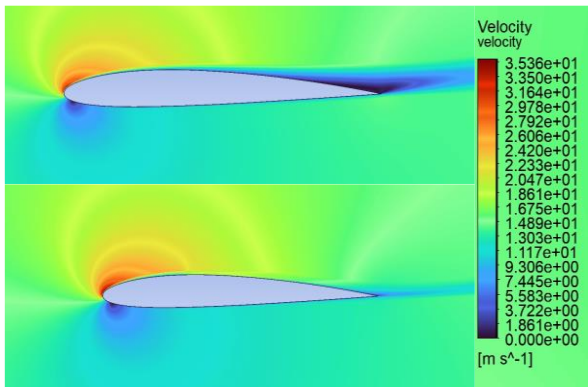


Fig. 9 Velocity contour at 12° angles of attack without and with the plasma actuators

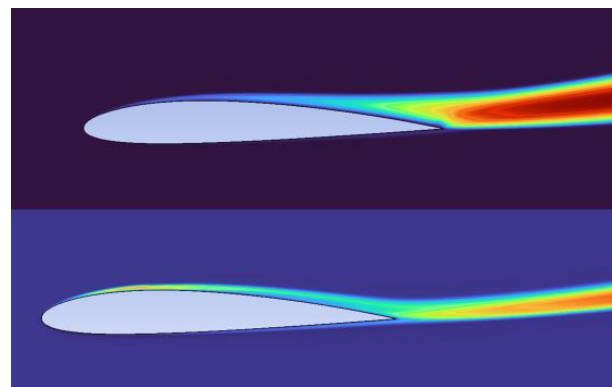


Fig. 13 Turbulent Viscosity contour at 12-degree angles of attack without and with the plasma actuators

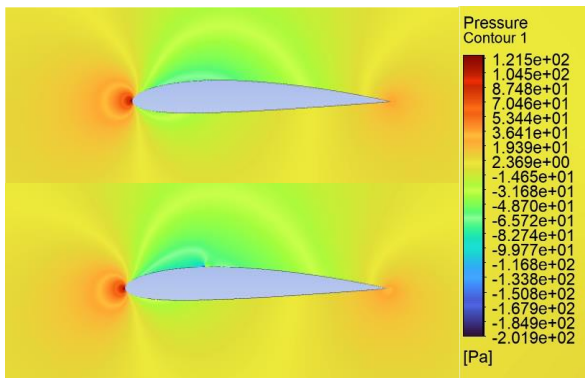


Fig. 10 Pressure contour at 4° angles of attack without and with the plasma actuators

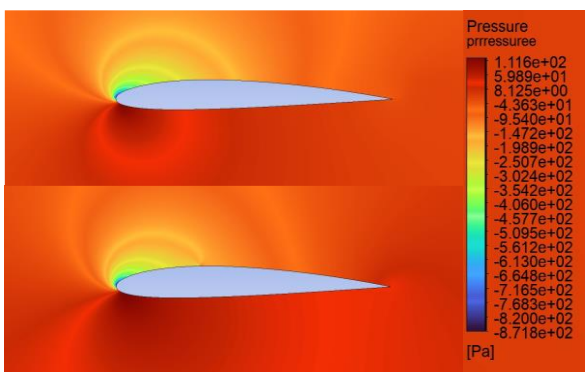


Fig. 11 Pressure contour at 12° angles of attack without and with the plasma actuators

4. Conclusion

The current paper has emphasized on finding the effect of plasma actuator on flow separation control on an airfoil for a range of angles of attack at a low Reynolds number. Since the use of plasma actuator was yielded impressive results, it can be assumed that implication of plasma actuator on upper surface of an airfoil will yield positive results. It concludes to.

- Plasma actuation accelerates airflow over the airfoil's upper surface, delaying flow separation, reducing drag, and improving lift-to-drag ratio.
- Plasma actuators reduce flow separation and shift stagnation points, enhancing aerodynamic efficiency at higher angles of attack.
- The contour analysis reveals smoother airflow, a low-pressure zone at the upper surface, and optimized pressure distribution, showcasing the role of plasma actuation in improving airfoil performance.
- Optimal performance range is higher angles of attack.
- Around 21% improved performance for the same Airfoil.
- Obtained results indicate that plasma actuators can be a viable method to control flow actively.

Further study is needed for calculating efficiency of the process acknowledging producing the plasma with high voltage current. Also, the interaction of the plasma at different environment of the atmosphere example rainy foggy cloudy weather effects. Perfecting the plasma physics is also a direction of study needed more exploration.

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