International Journal of Engineering Innovation & Research
Volume 3, Issue 2, ISSN: 2277 – 5668

Numerical Investigation of Plasma Actuator Induced Aerodynamic Performance

J. Bruce Ralphin Rose
Email: bruceralphin@gmail.com

Prasad. G
Email: prasadjithu@gmail.com

***Abstract* – The research of gas discharge at atmospheric pressure has energized the field of plasma-aerodynamics. A numerical investigation of flow control has been done on an actuator setup to determine the effect of Dielectric Barrier Discharge (DBDs) actuator to modify the characteristics of a flow. The DBD is also used to examine its ability to prevent the flow separation. The present study is focused on the enhancement of the performance by using a thin plasma actuator to suppress flow separation occurring around the leading-edge. Methods which use small devices that need additional energy for modifying the flow are called active flow control methods. Active flow control methods have the advantage of possibility for power adjustments and operational costs. From this attitude, the use of plasma actuators for flow control is an attractive alternative to promote the boundary layer profile modification. A detailed computational study based on the parameters that evaluate the performance of plasma actuator is performed. It includes various actuator positions and the mode of actuation. A body force is assigned as a source term which energizes the flow. The results prove that plasma actuators can provide significant improvement in aerodynamic performance for the flow conditions assumed in this investigation.**

***Keywords* – Flow Separation, Dielectric Barrier Discharge, Active Flow Control, Boundary Layer Profile Modification.**

***Nomenclature* – $\overline{E}$ - Electric Field (N/C), P - Pressure (Pa), V-Velocity (M/S), ε_0 - Permittivity, ϕ - Potential (V), λ_d - Debye Length (M), ρ - Fluid Density (Kg/M^3), μ - Dynamic Viscosity (N S/M^2), α -Angle Of Attack.**

I. INTRODUCTION

Plasma actuators possess valuable properties that are leading to an increase in significance regarding these devices. This article is a quantitative investigation regarding the applications of plasma actuators in the airplane components. In particular, Plasma actuators are able to control the flow around objects such as turbines and airfoils. A plasma actuator consists of two electrodes separated by a dielectric material. Alternating Current (AC) is supplied to the electrodes that results in ionizing of the surrounding gas (air), thus producing plasma. This plasma is subjected to an induced electric field by the input voltage results in a body force on the surrounding air. [1], [3] It is the body force that enables control of the flow around the object, thus preventing separation and stall of an airfoil section for an instance. A plasma actuator respond quickly without moving parts and these advantages have been guided to a vast increase of research in the field of Aerospace. [2] The body force is produced in a manner such that a velocity component parallel to the airfoil is induced and it energies the flow. The preferable design of the body force vector can be achieved by arranging the electrodes in a certain manner as shown in Figure (2). [3] Such an induced velocity component will increase the momentum of the transitory air much like the commonly used applications like slotted flap.

This article is focused on plasma actuators constructed to keep the laminar flow around an airfoil by means of increasing the momentum flux of the air. Efficient flow control systems are capable to achieve drag reduction and help to reduce the stall effect on airfoils. The methods of flow control usually involve the use of mechanical flaps, suction and blowing techniques, piezoelectric actuators, synthetic jets, as well as MEMS devices. Recently, the introduction of plasma actuators has demonstrated to be an effective method to achieve flow control at reduced cost and weight

In a conventional flap shown in Fig (1) the flow around is separated (for a given angle of attack) when reaching the flap, thus creating a turbulent wake downstream the wing section. Such a wake flow will result in flow separation that encourages a decrease of lift and increase in drag occurs. In the slotted flap, gap between the flap and airfoil guides the fresh air into the turbulent region, as a result separation is delayed and a decrease in lift. [4] A plasma actuator is designed to apply the same principle; in addition, increasing the stall angle and even re-attaching the flow to an airfoil section. [3] However, Plasma actuators have many advantages over other flow control devices.

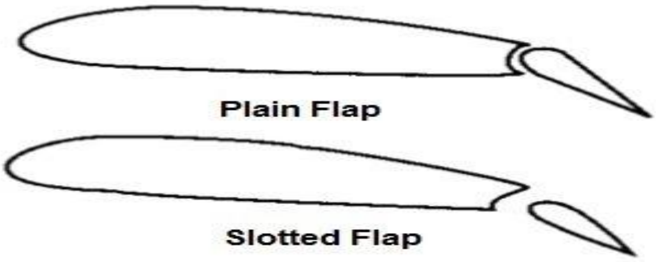

Fig.1. Schematic comparison between Airfoil Section of a conventional flap and a slotted flap

A. Plasma Actuator

The Single Dielectric Barrier Discharge (SDBD) plasma actuator [2] is shown in Fig (2). It is a relatively simple device consisting of a pair of electrodes separated by a dielectric material, typically arranged in the asymmetric configuration as displayed in Fig (2).

When an AC voltage is applied across the electrodes, and the frequency is large enough; the air ionizes in the region with the largest electric potential.

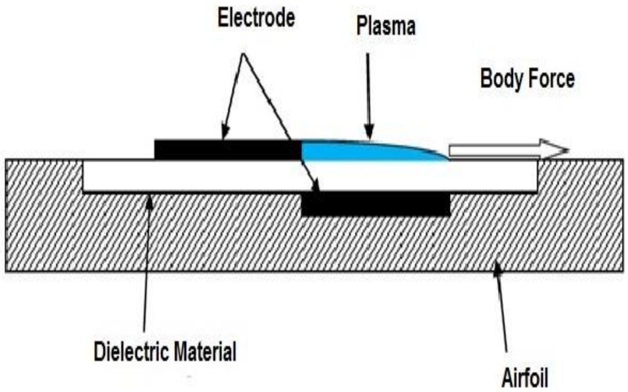

Fig.2. Single Dielectric Barrier Discharge (DBD) Plasma Actuator

This region is located above the embedded electrode and beginning near the edge of the outer electrode. The ionized air produces a body force on the ambient air in the presence of an electric field gradient [3], directed away from the exposed electrode, (i.e.,) parallel to the dielectric material. In order to ionize the air using the plasma actuator, a large voltage has to be applied between the electrodes, (typically between 10 and 20 kV), operating with an input frequency of 1-10 kHz [5]. Because of the large frequencies, plasma actuators can be regarded as “quasi-steady” devices, as these frequencies are typically well above the fluid response frequency. [4] In experiments conducted by Corke et al. [3] [4] the electrodes were made of a copper foil tape, while the dielectric material was made of a kapton film. Dielectric materials can be used such as Macor, Teflon or even glass. The difference between the materials is their breakdown voltages and ductility. The ductility leads to the integration of the actuator, as those dielectrics with low ductility such as Macor cannot be easily integrated on curved surfaces. [3]

Plasma Actuator is used for Transition Delay [10]; from designers point of view it has no moving parts, making them solid-state devices. It is very simple in design than the mechanical devices with moving parts. In a typical aerodynamic implementation point, one of the electrodes is exposed to the atmospheric air, while the other is embedded in the skin of an aircraft wing, completely covered by the dielectric material. Since it is an active control device, it can be used as needed, and not in constant. But the passive vortex generators are used as uncontrolled devices exist all the time. One of the greatest advantages is that, when properly integrated, plasma actuators have almost no effect on the flow when in the off position as the exposed electrode is less than 0.1 mm in thickness.

In contrast, the disadvantages of plasma actuators is that because of the large voltage requirements necessary to drive plasma actuators, large, heavy amplifiers are typically required for adequate voltage supply. In the case of an unmanned aerial vehicle, a large amplifier cannot be carried, or the costs in weight and increased vehicle size outweigh the gain in performance. Further research is required in the area of amplifier design and performance to eliminate this problem. Also, significant research is still required in the techniques of proper integration of plasma actuators into aerospace vehicles such that they cause minimal adverse flow disturbance.

II. MATHEMATICAL MODEL

There have been numerous attempts to model the body force accurately; however, no model is truly consistent with the experiments done because of the complicated chemistry of the surrounding air. Hence, the force (per unit volume of plasma) can be estimated with the vector quantity

$$F_B = \left(-\frac{\varepsilon_0}{\lambda_D^2}\phi \right)\overline{E} \qquad (1)$$

Where, ε_0 is the permittivity, ‘ϕ’ is the potential, λ_d the Debye radius, and $\overline{E}$ is the electric field. The Computational Fluid Dynamics (CFD) code is used in this analysis for computing the solution of Reynolds-Averaged Navier-Stokes (RANS) [13] equations in the ANSYS 14.5 solver. Eq. (2) and (3) are the conservation equations for mass and momentum, respectively.

$$\frac{D\rho}{Dt}+\rho(\nabla.\overline{V})=0 \qquad (2)$$

$$\rho\frac{D\overline{V}}{Dt}=-\nabla P+\mu\nabla^2\overline{V} \qquad (3)$$

Here, ‘V’ is the velocity field, ‘ρ’ is the fluid density, ‘P’ is the pressure and ‘μ’ is the dynamic viscosity. The selection of FLUENT solver was made because of the various required solutions. It includes the ease of incorporating a model to represent the plasma actuators with an aid of a user defined function (UDF). [9][14] UDFs are written in C -program allow for additions and/or alterations to the flow solver and governing equations by compiling subroutines and linking them to FLUENT. Some features of FLUENT have made it an obvious choice to create a numerical model for ion flow control. Through the creation of UDFs, it is possible to make additions to the governing flow equations. By adding a source term to the momentum equation, the user can simulate the addition of a body force such as the electrostatic force associated with ion flow control. The solutions for this study are obtained using the pressure based, segregated solver. Second order spatial discretization was applied for pressure and momentum, as well as the selected turbulence model. For pressure-velocity coupling, the SIMPLE method has been used.

III. COMPUTATIONAL SET UP

CFD analysis is used to determine the flow separation characteristics, because it provides the required features of the velocity and pressure fields throughout the analysis. NACA 64-212 airfoil is considered for the current analysis in the view of application. By examining the velocity field, it would be possible to identify the regions where the flow separates and the direction. By examining the pressure field, it is possible to identify regions where flow reversal is likely to occur. The advantage of plasma actuator modeling in CFD facilitates the prediction of flows over different configurations and flow properties of interest in aerospace purposes.

IV. EXPERIMENTAL ANALYSIS

The aerodynamic forces variation over the wing model NACA 64-212 is calculated at various Angles of Attack (AoA) by a standard Low Speed Subsonic Wind Tunnel (LSWT) of test section 30cm*30cm. Wind tunnel is a device used to measure the aerodynamic force such as lift, drag, lateral forces, yaw, roll, and pitching moments at various AoA. The computed pressure variations on the manometers allow one to produce common curves such as lift coefficient versus AoA. The results are presented in the figure (6) and compared with the CFD solutions. The Speed of LSWT is customized according to the requirements of flow velocity. Flow control experiments with single DBD plasma actuators are used to control flow separation and unsteady vortex shedding from a circular cylinder in a cross-flow. Smoke flow visualization is carried out in a cylinder with and without plasma actuator to identify the effects. [12]

A. Grid Generation and Boundary Conditions

The computational Grid generated around the airfoil with plasma actuator is shown in Figure (3). The numerical simulation process is employed for determining the accurate solution and plays an important role towards pressure contours. The Fluent-paired mesh generating software, Gambit, was used to create the computational domain. It was important to maintain a fine mesh resolution near the boundary layer region of the external flow in order to resolve the turbulent and transitional characteristics. Boundary Conditions are highlighted in Figure (4). The inlet flow velocity is assumed as 50m/s.

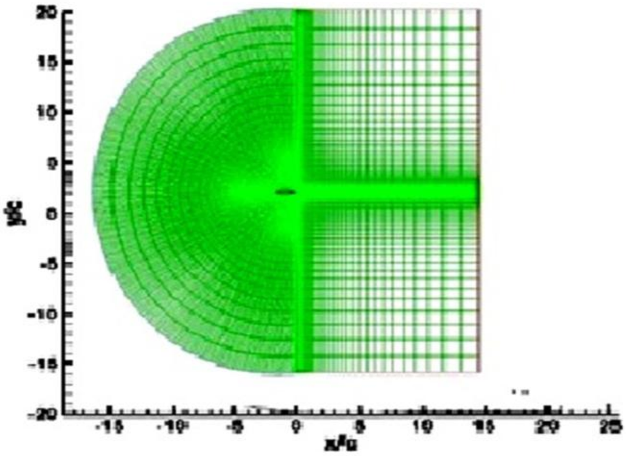

Fig.3. Computational Grid around Airfoil

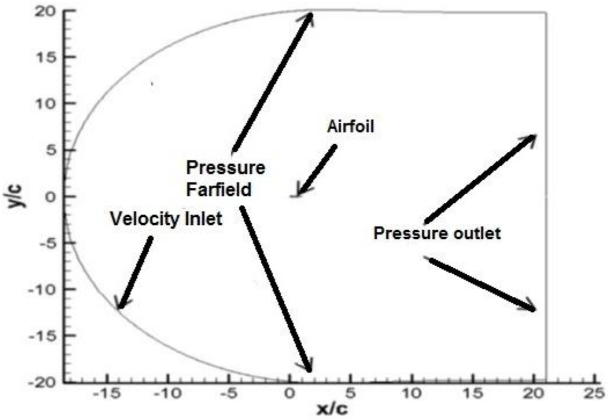

Fig.4. Boundary Conditions around the Airfoil

V. RESULTS AND DISCUSSION

The Dynamic Pressure Variation with Chord wise positions for a range of AOA is illustrated from Fig (5) – (8) from the CFD solutions. The Graphical representation shows the Dynamic Pressure variation against AoA which is an important parameter in quantifying the lift and drag forces. As the AoA increases, the dynamic pressure variation is shown and the Stalling AoA is computed.

The dynamic pressure increases severely in proportion to the change in AoA particularly on the upper surface of the airfoil. The presence of DBD plasma actuator is included through the UDF and it makes significant acceleration to the nearby active fluid. In particular Fig (7) and (8), highlights the essential outcome of the plasma actuator in this investigation by a rapid increment in dynamic pressure near the mid-chord location. Figure (9) shows the velocity vector at 14^o AoA. The flow is separated after 50% of chord at 14^o AoA which is the Stalling Angle. Above which the lift is instantly decreased and drag is increased due to the separated flow region.

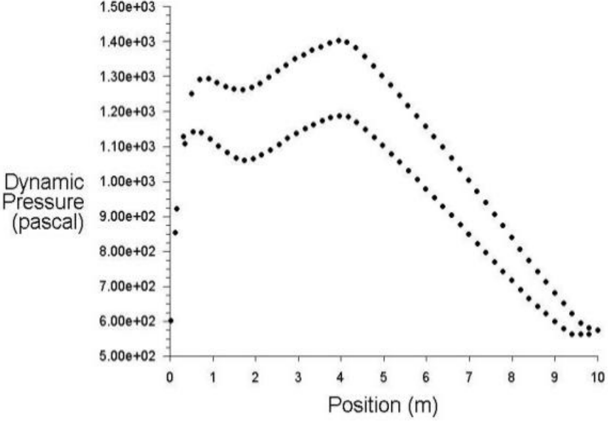

Fig.5. Dynamic Pressure Vs Chordwise positions for 0o AoA

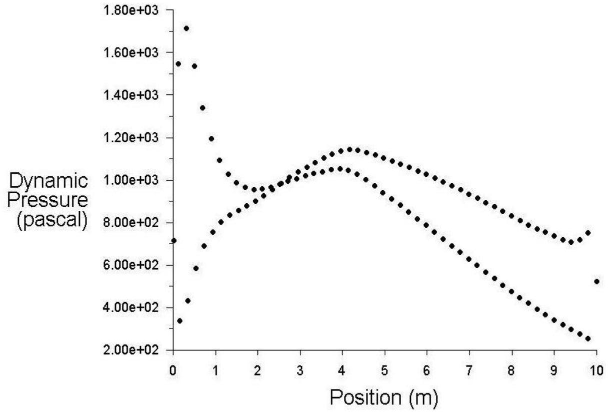

Fig.6. Dynamic Pressure Vs Chordwise positions for 5o AoA

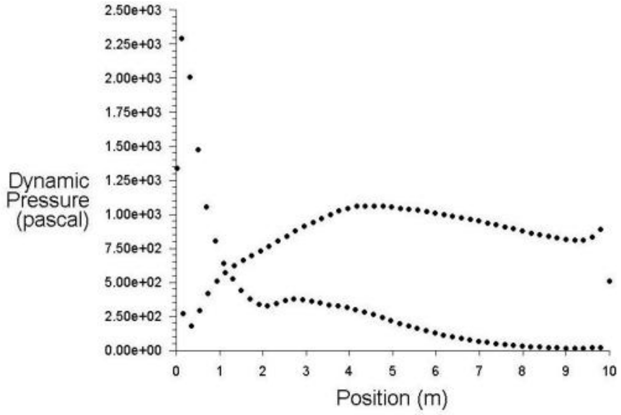

Fig.7. Dynamic Pressure Vs Chordwise positions for 10o AoA

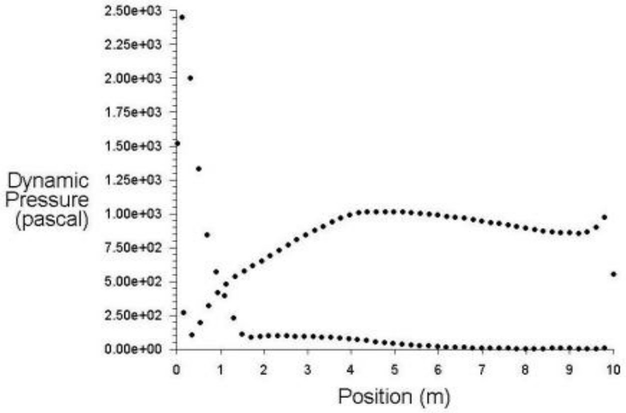

Fig.8. Dynamic Pressure Vs Chordwise positions for 14o AoA

The graph between coefficient of lift and AoA is shown in Figure (10). The Stalling angle is measured to be 14^{o} for the selected NACA airfoil. Here the Experiment Data of the Airfoil and numerical Results are displayed for the low Reynolds number (Re). When Compared to experimental results numerical results with Plasma actuator shows greater significance. These results are similar to theoretical data. [15] The Plasma actuators delaying the stall angle to few degrees by modifying the local flow field velocity over a range of Mach numbers.

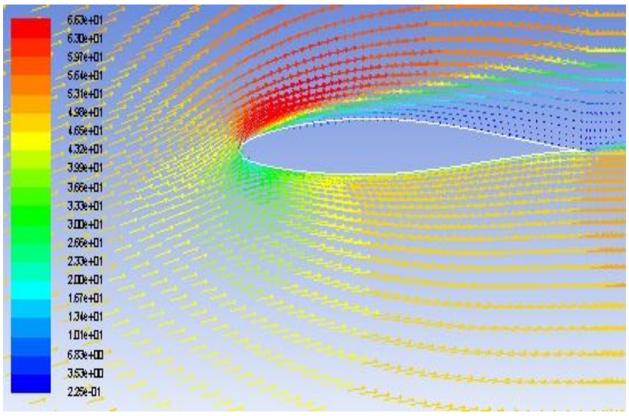

Fig.9. Velocity vector contour at 14o AoA (Stalled)

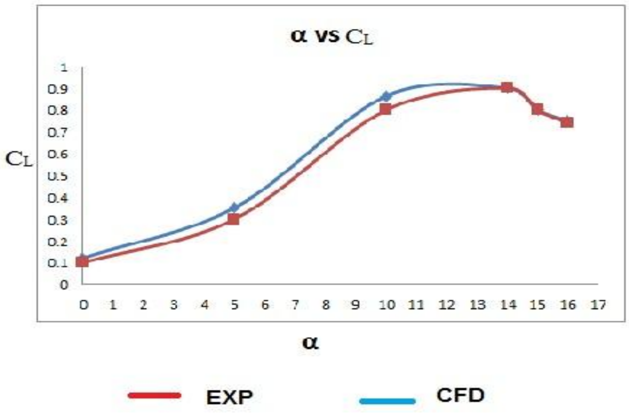

Fig.10. Coefficient of Lift Vs AoA

VI. CONCLUSIONS

The primary objective of this research is to investigate and demonstrate the effectiveness of aerodynamic plasma actuators as a means of active flow control over airfoils for a range of AoA. The important conclusion is the dependence on actuator location relative to the separation region as drawn from these results. A fully functional and effective plasma actuator would enhance the fixed properties of a given airfoil section otherwise. If separation control can be achieved, it comes at a great cost in terms of required power. The optimum location for an actuator would be just upstream of the separation location. With a properly tailored body force parts like ailerons, flaps, and other lift inducing (moving) parts of an airplane could be completely replaced in future.

ACKNOWLEDGEMENT

Anna university support for the work of the authors is greatly acknowledged. It has provided extensive computing resources and materials for the completion of this project work successfully.

REFERENCES

[1] Suzen, Y. B., Huang, P. G., and Jacob, J. D., “Numerical Simulations of Plasma Based Flow Control Applications”, AIAA-Paper, 35th AIAA Fluid Dynamics Conference and Exhibit, Toronto, Ontario Canada.2005.

[2] Corke, T. C., Post, M. L., and Orlov, D. M., “SDBD plasma enhanced aerodynamics: concepts, optimization and applications”, Computers & Fluid, vol. 43, 2007 pp. 193-217.

[3] Corke, T. C., and Post, M. L., “Overview of Plasma Flow control: Concepts, Optimization and Applications”, AIAA-Paper, 43th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2005.

[4] He, C., Corke, T. C., and Patel, M. P., “Plasma Flaps and Slats: An Application of Weakly Ionized Plasma Actuators”, Journal of Aircraft, vol. 46, no. 3, 2009, , pp. 864-873,.

[5] C. L. Enloe, M. G. McHarg, and T.E. McLaughlin, “Time-correlated force production measurements of the dielectric barrier discharge plasma actuator”, Journal of applied physics 103. 2008.

[6] Enloe, C. L., McLaughlin, T. E., VanDyken, R. D., Kachner, K. D., Jumper, E. J., Corke, T. C., Post, M., and Haddad O., “Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Geometric Effects”, AIAA Journal, vol. 42, no. 3, 2004, pp.595-604.

[7] Shan, H., Jiang, L., Liu, C., Love, M., and Maines, B., “Numerical Study of Passive and Active Flow Separation Control Over a NACA 0012 Airfoil”, Computers & Fluid, vol. 37, 2008, pp. 975-992.

[8] Aholt, J., and Finaish F., “Active Flow Control Strategy of Laminar Separation Bubbles Developed over Subsonic Airfoils at Low Reynolds Numbers”, AIAA-Paper,49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, 2011.

[9] M. Abdollahzadeh, J. Pascoa, P. Oliveira., “Numerical Modeling of Boundary Layer Control Using Dielectric Barrier Discharge”, IV Conference on Fluid and Thermodynamic Energy, 2012.

[10] Marios Kotsonis, Pieter Boon, Leo Veldhuis, “Plasma for Transition Delay”, International Conference on Fluid Control, Russia, 2007.

[11] Chin-Cheng Wang and Subrata Roy, “Energy and force prediction for a nanosecond pulsed dielectric barrier discharge actuator”, Journal of physics, 2012.

[12] Flint O. Thomas, Alexey Kozlov and Thomas C. Corke, “Plasma Actuators for Bluff Body Flow Control”, AIAA, 2010.

[13] Ed Peers, Zhaokai Ma, Xun Huang (2009) “A numerical model of plasma effects in flow control”, Physics Letters A, 2010, pp 1501–1504.

[14] Ira H. Abbott and Albert E. Von Doenhoff, “Theory of Wing section”, Dover Edition, 1958.

AUTHOR’S PROFILE

Prof. Bruce Ralphin Rose. J

is currently working as Assistant Professor of Aeronautical Engineering Department at the Regional Centre of Anna University Tirunelveli, India. He received his B.E (2006) and M.E (2009) degrees in Aeronautical Engineering from Anna University, Chennai, India. He is also pursuing Ph.D. degree in Aeronautical Engineering at the Anna University Chennai, India. His research areas include Aircraft structural optimization, aeroelastic tailoring with advanced composites and metals, and Aircraft design.

G. Prasad

pursuing Master Degree in Aeronautical Engineering from Regional Centre of Anna University, Tirunalveli. He obtained Bachelor Degree in Aeronautical Engineering from Anna University, Chennai, India (2012).His area of interest is Aerodynamics and ComputationalFluid Dynamics. His main focus is on Aerodynamic Boundary layer and flow control problems.