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COMPUTATIONAL ANALYSIS OF NACA 23012 AIRFOIL WITH PLASMA ACTUATOR

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ABSTRACT

Flow separation is undesirable phenomenon where the boundary layer separates from the surface, causing wake which affects performance by increasing drag and reducing lift. There are passive method to control the flow separation but active methods of plasma actuation using plasma actuators are highly effective and responsive. In this paper, flow separation effectiveness by using plasma actuator on NACA 23012 airfoil at 0^o, 2^0, 4^0, 6^0, 8^0, 10^0 angles of attack was studied computationally. Ansys fluent 2019R2 Academic version with Spalart-Allmaras turbulence model at 1m/s inlet velocity was chosen for the analysis which yield approximately 6.8e04 Reynolds number. User-Defined Function (UDF) in ".c" format was used for simulation of plasma actuation. There was significant reduction in drag coefficient (cd) and increase in lift coefficient (cl) at every angle of attack with plasma actuation turned ON for flow control. On insight, there was 46.2% reduction in drag coefficient and 45.8%increase in lift coefficient especially at 10^0 angle of attack. This proves the effectiveness of plasma actuators on flow separation control and promising increase in performance of wings.

Keywords: Plasma Actuator, Flow Separation, Plasma, Airfoil, Angle of Attack, Ansys Fluent.

I. INTRODUCTION

The pursuit for increasing the performance of aircraft has led to many great innovations. Every factor of the aircraft part and its function is considered and many new innovations are emerging. When considering the issue of flow separation over the wing, Scientists went through lots of methods like vortex generators, flow vanes, leading edge slats etc. and there's always room for new innovations and plasma actuators come under such categories of active flow separation control methods. This section contains briefly introduction of plasma actuators and their applications.

Plasma Actuators

Plasma actuators, also known as DBD (Dielectric Barrier Discharge) plasma actuators are devices that use plasma to actuate (to put into motion) the flow where fluid dynamics is involved. As the name suggests, plasma is the hot ionized air and plasma actuators generate wall bounded jets by ionizing the surrounding air without any moving parts. They have dielectric material between two asymmetric electrodes. When a high voltage AC signal is passed through the electrodes, low-temperature plasma is formed between those pairs of asymmetric electrodes and air molecules that get ionized and accelerate from primary to secondary electrode like a jet stream. The thrust by the actuator increases with increase in voltage in quiescent air. The dielectric surface temperature also plays an important role in its efficacy. Based on environmental conditions, its temperature can be varied for optimum performance. Increase in dielectric surface temperature increases the performance of the actuator but at a cost of little more energy consumption. It is generally between 10 and 20kV AC voltage with input frequency of 1-10 kHz. One electrode is exposed to air as fixed on the surface and other is implanted in the surface and exposed electrodes show no effect on the flow as its thickness is less than 0.1mm.

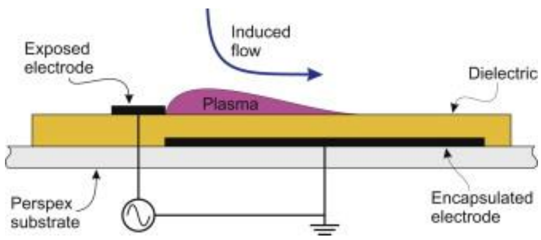

Figure 1: Single Dielectric Barrier Discharge Plasma Actuator

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Plasma Actuators Applications

Plasma actuators are helpful in various other applications other than laminar flow separation control over airfoil. Huang et al.[7] showed they can be used in flow separation control over low pressure turbine blades at low Reynolds number in gas turbine. Benard et al.[9] demonstrated their use to improve free shear layer mixing at nozzle exit. They are also used as devices for noise cancellation. Thomas et al.[10] used plasma actuators to study the flow separation control over particular cylinders which are used in aircrafts landing gear and this helped in reducing noise generated by the structure due to separation.

II. LITERATURE SURVEY

Since many years, lots of research has been going on in the field of plasma actuators for flow separation control effectiveness. Many researchers made their contributions and paved the path to modern innovative implementations. Blasius et al. [8] derived analytical solution for laminar boundary layer over a flat plate. Ozturk et al. [13] presented the flow over a flat plate at Reynolds number 750 to 9600 and they investigated flow structure over flat plate. New types of plasma actuator models for flow control in multiple directions were introduced by Wang et al. [4-5]. Suzen et al. [12] made a model on Maxwell's equations stating body force produced by plasma actuator is function of charge density and strength of electric field produced by actuator. Thomas et al. [11] compared performance of NACA 0012 with steady and unsteady plasma actuators. Biao Wei et al. [6] used a microsecond pulsed surface DBD actuator to study the flow control on a high-lift wing. Corke et al. [2] made his contributions to modelling and applications of single DBD plasma for enhanced aerodynamics. Followed by many researchers who contributed their part in studying the flow control effectiveness using plasma actuators and every study shows that there was significant leap in performance of the surface with use of plasma actuator as compared to without plasma actuator. This made rise in research on aerodynamic applications of plasma actuators across the globe and extensive studies are made by many universities and leading industrial manufacturers which boosted the popularity for plasma actuators for flow separation control and shows a promising future for the innovation.

Scope and Objective

In this study, objective is to investigate flow separation control over NACA 23012 with plasma actuators at a Reynolds number of $7{\times}10^4$ computationally. Ansys Fluent is used for CFD analysis and effectiveness of flow control is evaluated at various angles of attack. The results achieved are compared between flow control without plasma actuators and with plasma actuators on NACA 23012 airfoil and their performance parameters are evaluated. As NACA 23012 airfoil is mostly used in high altitude aircrafts and unmanned vehicles, the Reynolds number of 10^5 was chosen for the computational analysis. Coefficient of lift and coefficient drag values are calculated at 0°, 2°, 4°, 6°, 8°, 10° to get an insight of the variations of the coefficients with and without use of plasma actuators and relative difference between them. This study helps in easy understanding of the usefulness of plasma actuators and helps in concentrating more in this field of research and help yield better results though they are already better in terms of their performance. By studying the effect of plasma actuators at these angles of attack, we get a clear understanding on how things change and impact the performance of airfoil at every degree change in angle of attack.

CFD Plasma Actuator Model

A simple steady plasma actuator model is used for the study and it is developed with the use of user defined function (UDF) for the Ansys Fluent. UDF file contains C-code file which has to be compiled before CFD analysis in Ansys. Visual studio compatible with Ansys version need to be installed for the code to be working or compiled. The code makes the declaration of cell coordinate, declaration of plasma, x-coordinate and y-coordinate. It deals with the strength of plasma source, position, solving and effect. It needs to be defined as a rectangle source in momentum to simply the code. The code was written by Lee Ming Wei, School of Aerospace Engineering in University Sains Malaysia.

Surface model

Surface used in the analysis is NACA 23012 airfoil which has design lift coefficient of 0.3, camber position of 15% of chord with normal camber line and maximum thickness is 12% of chord length.

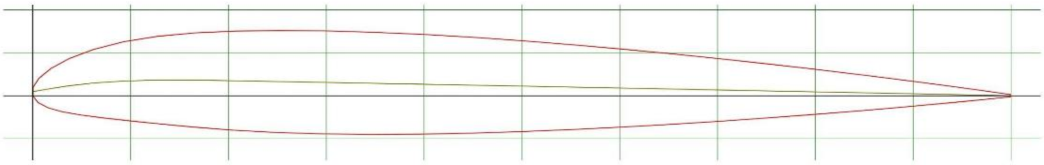

Figure 2: NACA 23012 Airfoil

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \bar{V}) = 0 \quad (1)$$

$$\rho\frac{D\bar{V}}{Dt} = -\nabla P + \mu\nabla^2\bar{V} \quad (2)$$

The analysis is done is Ansys Fluent 2019 R2 Academic version and conservation equations for mass and momentum are solved numerically by the flow solver.

Here $\bar{v}$ is velocity field, ρ is fluid density, P is pressure and μ is dynamic viscosity. Ansys Fluent allows incorporating plasma actuators with UDF and allows changes to the equations based on UDF. The details on mesh used for analysis and boundary conditions in Ansys Fluent are provided in further sections.

III. METHODOLOGY

Analysis is performed on NACA 23012 airfoil with chord length 1000mm (equals to 1m) at a velocity of 1m/s. Domain around the airfoil was constructed semi-circular with 20000mm (20m) radius at leading edge with center at $1/4^{th}$ of the chord and other dimensions of domain are as shown in fig 3.1 (airfoil was very tiny compared to domain). Plasma source is defined at 2% of chord and the value of plasma source is 5. We use Ansys Fluent firstly to analyze the airfoil without plasma actuator and thereby analysis is done on airfoil with plasma actuator and results of coefficient of lift and drag are compared in both the cases to interpret the effectiveness of flow separation control while plasma actuator is used. This helps us comprehend the usefulness of plasma actuators in aerodynamic applications.

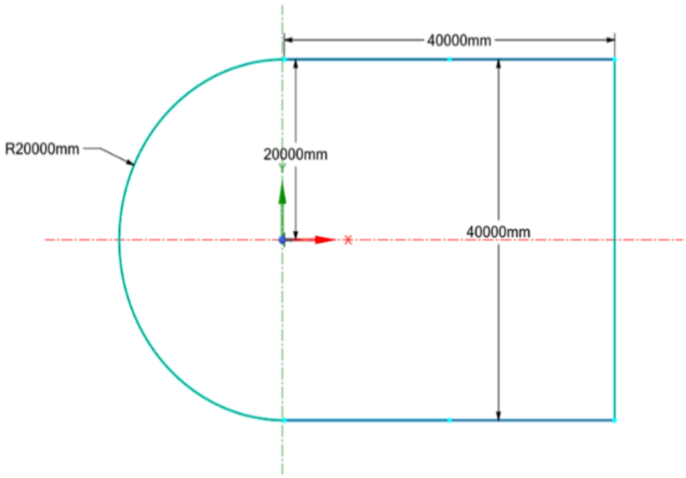

Figure 3: Domain Dimensions (note that airfoil is very tiny in the huge domain)

Boundary Conditions and Mesh

The computational grid has three main boundaries. The left side (leading edge side), top and bottom edges are velocity inlets while the right side of the grid is pressure outlet as it is an outflow boundary. These boundaries are suitable for low speed and incompressible flow. The other boundary is airfoil surface and it is a no-slip wall boundary. Triangular mesh is used with 45000 node cells for analysis due to its simple construction and precise results. This gird size was 20 chord lengths from $1/4^{th}$ of chord for velocity inlet and 40 chord lengths from $1/4^{th}$ of chord for pressure outlet. The figures of boundary conditions and mesh are included below (note that airfoil is very tiny in the huge domain).

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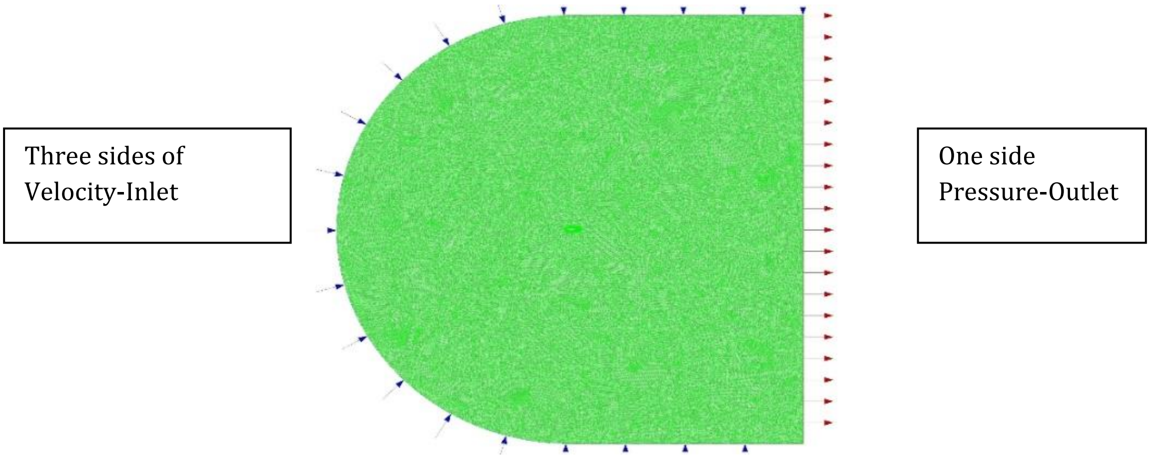


Figure 4: Computational Grid Boundaries

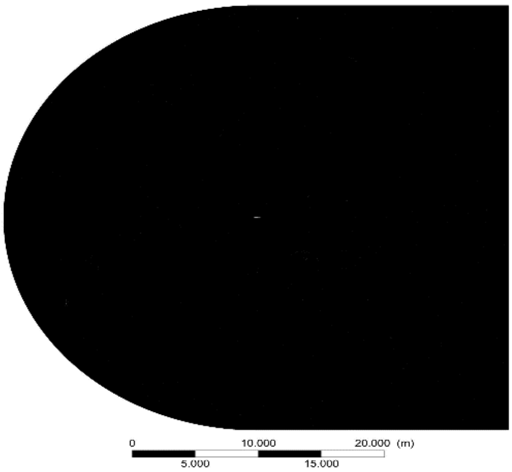


Figure 5: Full Grid View

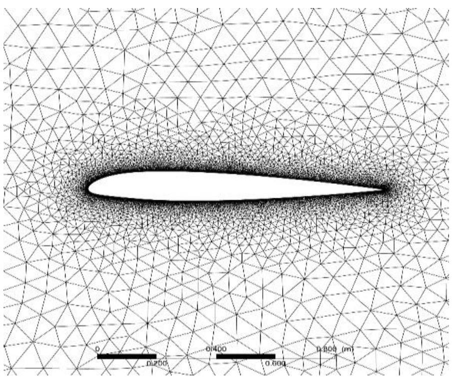


Figure 6: Computational Grid View

Simulation Process

The generated mesh file with boundary conditions is now ready for analysis setup. The fluid is air and it's properties are set to default. Launch Fluent from setup (on Fluent Launcher select 2D with double precision) and few options need to be validated which are numbered below.

1. After meshing, open the fluent setup from the workbench.
2. Under 'Models' choose the Viscous Model to be Spalart-Allmaras (1eqn).
3. Select 'Magnitude and Direction' for velocity specification method for boundary conditions at inlet and velocity magnitude to be 1m/s.
4. Set Absolute Criteria in Residual Monitors to 1e-06 which is 0.000001.

5. Now for plasma actuator setup, go for 'compiled' in User-Defined Functions and add the ".c" source file, build the 'libudf' library and load to continue.
6. Now set the user-defined memory and node memory locations as 1.
7. Setup the 'Source Terms' in cell zone conditions. Edit the X Momentum sources to 1 and select the UDF plasma source::libudf.
8. Now hybrid initialize and calculate with required iterations. Print the force reports after the end of calculation.
9. Now enter CFD Post to interpret and analyze the results.

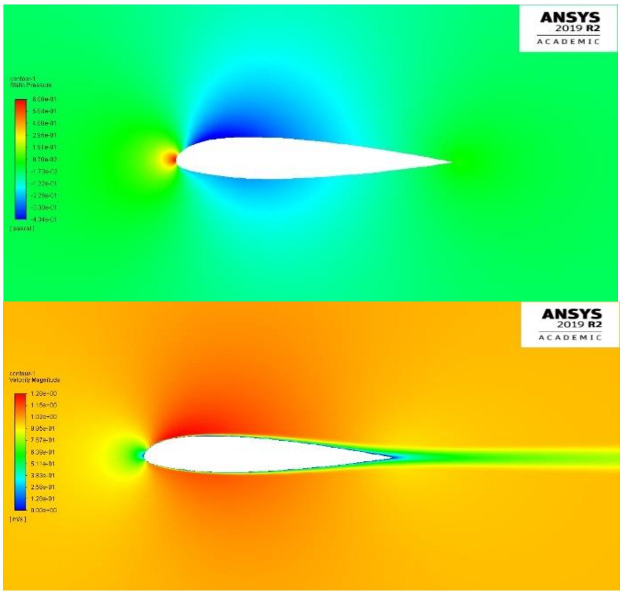
IV. RESULT AND DISCUSSION

The numerical results after computation are tabulated below and this give the clear understanding on the effectiveness of plasma actuator on flow separation control. The below table contains values for vectors, coefficient of drag and coefficient of lift which are analyzed at various angles of attack. Comparison and discussion of results at each angle of attack is included in this section.

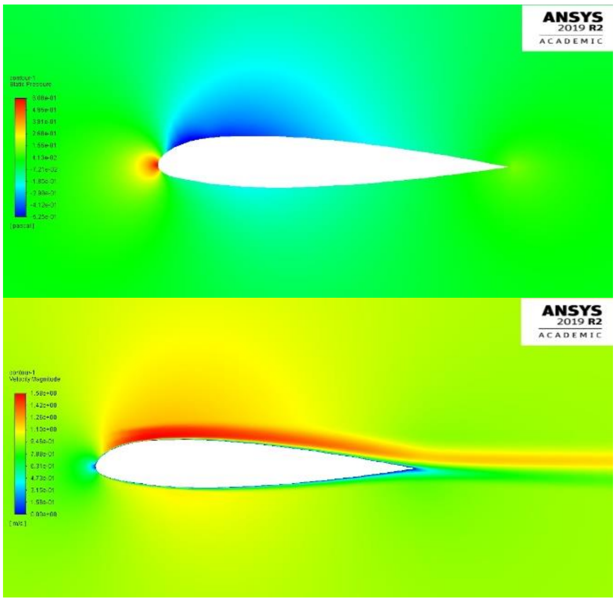
Table 1: Numerical result after computation

	Vector						Data			
	V		cd		cl		Without Plasma		With Plasma	
AOA	x	y	x	y	x	y	cd	cl	cd	cl
0	1	0	1	0	0	1	0.02443	0.11310	0.02206	0.26531
2	0.999391	0.034899	0.999391	0.034899	-0.0349	0.999391	0.02553	0.30307	0.02016	0.48994
4	0.997564	0.069756	0.997564	0.069756	-0.06976	0.997564	0.02813	0.48319	0.01963	0.71223
6	0.994522	0.104528	0.994522	0.104528	-0.10453	0.994522	0.03245	0.65314	0.02053	0.92687
8	0.990268	0.139173	0.990268	0.139173	-0.13917	0.990268	0.03941	0.79713	0.02293	1.12972
10	0.984808	0.173648	0.984808	0.173648	-0.17365	0.984808	0.05141	0.89969	0.02765	1.31233

0° Angle of Attack



Above and below are velocity and pressure contours respectively at 0° angle of attack without plasma actuator.



Above and below are velocity and pressure contours respectively at 0° angle of attack with plasma actuator.

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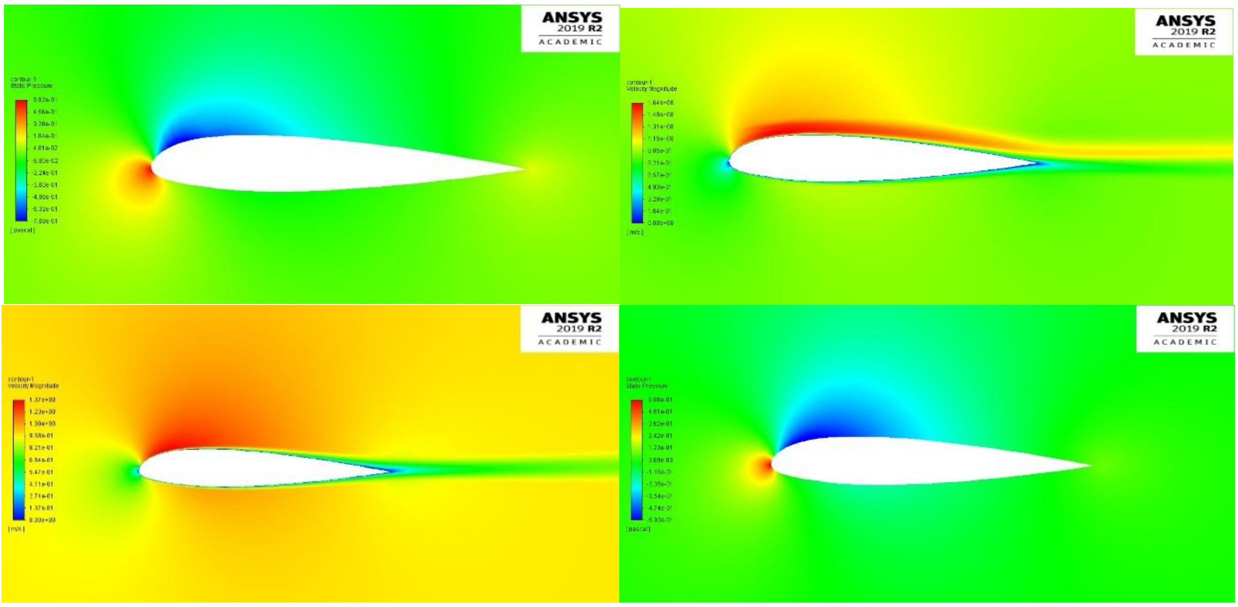
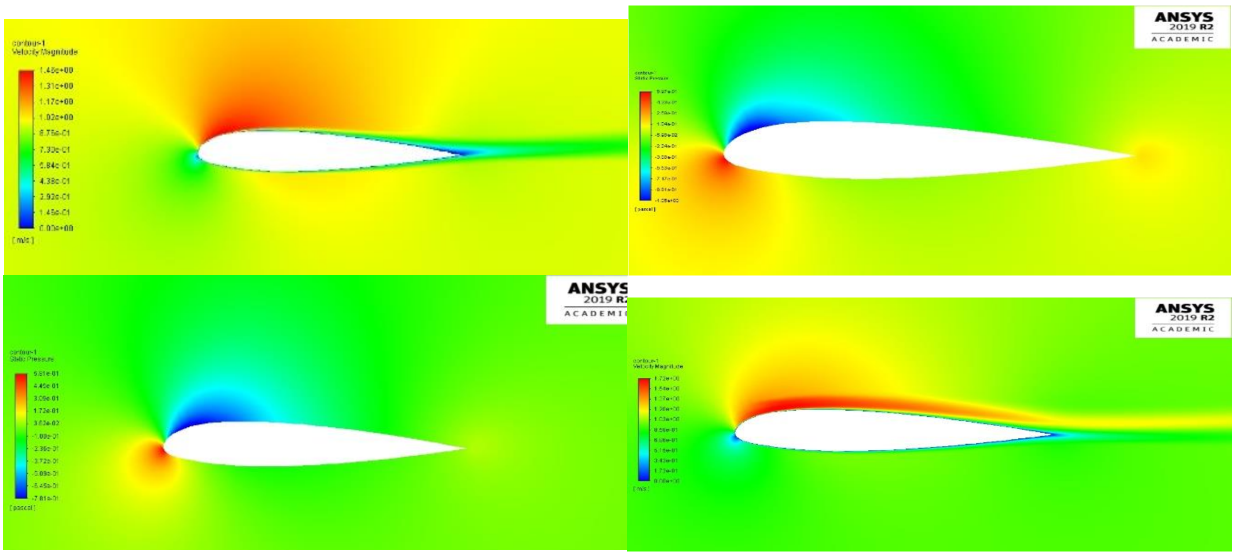
At 0° angle of attack, the coefficient of drag achieved on analysis without the plasma actuator was 0.02443 and coefficient of lift was 0.11310. With the use of plasma actuator, there was significant change and results were cd=0.02206 and cl=0.26531 which was 9.7% reduction in drag coefficient and 134% increase in lift coefficient. Moreover, contours show that there was increase in velocity of flow on upper curve of airfoil due to induced plasma.



Without Plasma Actuator *With Plasma Actuator*

2° Angle of Attack

At 2° angle of attack, the coefficient of drag and coefficient of lift without the plasma actuator were 0.02553 and 0.30307 respectively. With the use of plasma actuator, the results were cd=0.02016 and cl=0.48994 which was 21% reduction in drag coefficient and 61.6% increase in lift coefficient.



Without Plasma Actuator *With Plasma Actuator*

4° Angle of Attack

At 4° angle of attack, the coefficient of drag and coefficient of lift without the plasma actuator were 0.02813 and 0.48319 respectively. With the use of plasma actuator, the results were cd=0.01963 and cl=0.71223 which was 30% reduction in drag coefficient and 47.4% increase in lift coefficient.

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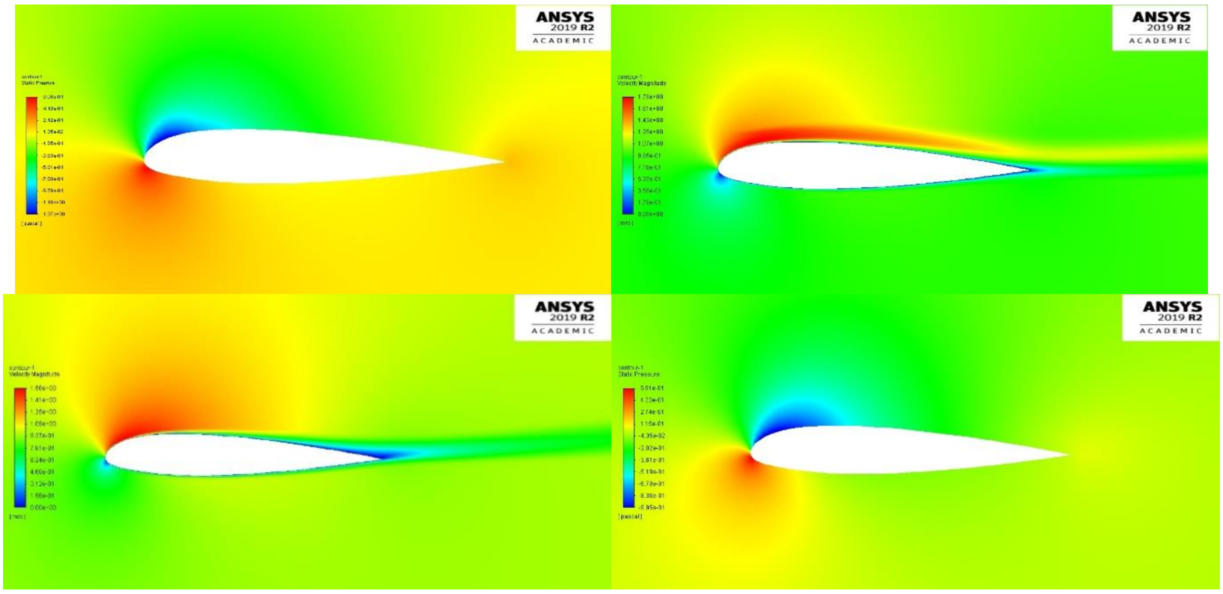
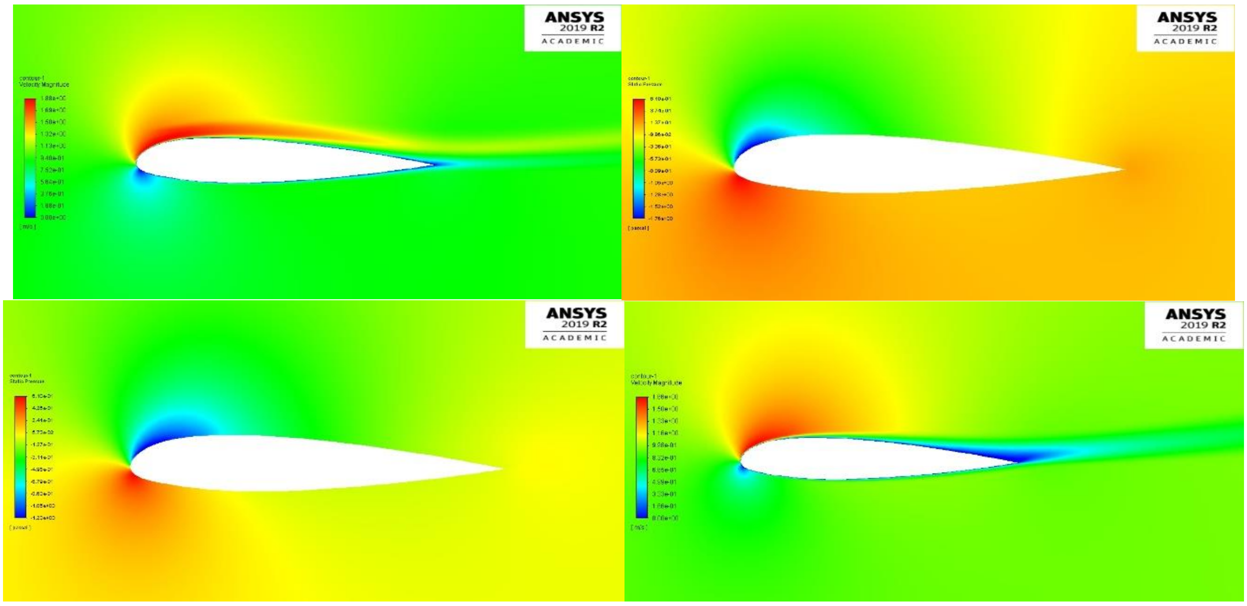


Without Plasma Actuator *With Plasma Actuator*

6° Angle of Attack

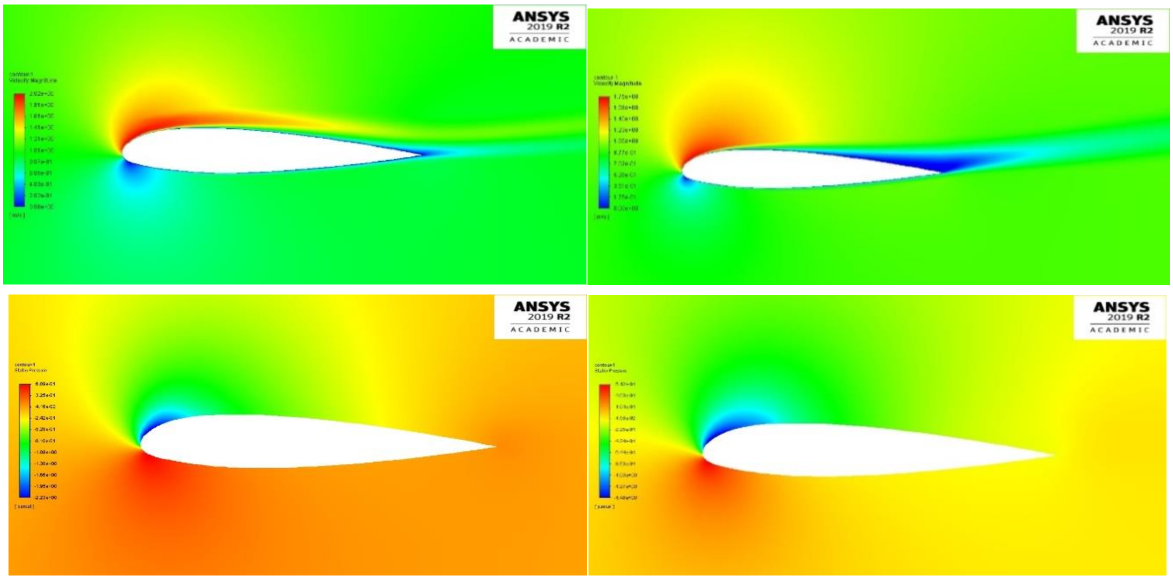
At 6° angle of attack, the coefficient of drag and coefficient of lift without the plasma actuator were 0.03245 and 0.65314 respectively. With the use of plasma actuator, the results were cd=0.02053 and cl=0.92687 which was 36.7% reduction in drag coefficient and 41.9% increase in lift coefficient. The results seem really promising with the use of plasma actuators for laminar flow separation control.



Without Plasma Actuator *With Plasma Actuator*

8° Angle of Attack

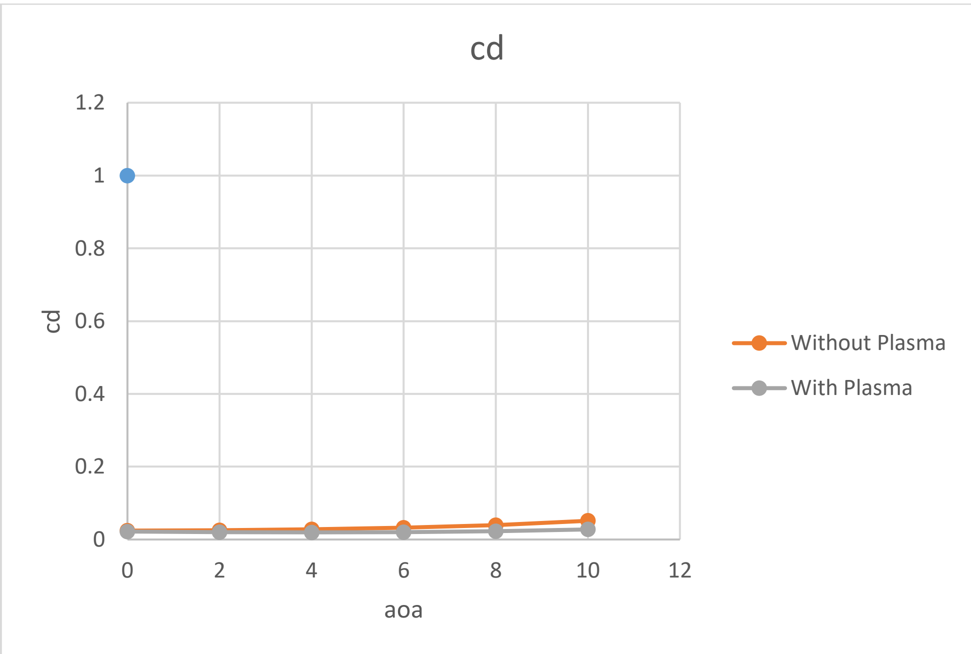
At 8° angle of attack, the coefficient of drag and coefficient of lift without the plasma actuator were 0.03941 and 0.79713 respectively. With the use of plasma actuator, the results were cd=0.02293 and cl=1.12972 which was 41.8% reduction in drag coefficient and 33.2% increase in lift coefficient. There was significant reduction in laminar flow separation bubble with plasma source in action.



Without Plasma Actuator *With Plasma Actuator*

10° Angle of Attack

At 10° angle of attack, the coefficient of drag cd=0.05141 and coefficient of lift cl=0.89969 without the plasma actuator. With the use of plasma actuator, the results were cd=0.02765 and cl=1.31233 which was 46.2% reduction in drag coefficient and 45.8% increase in lift coefficient. This was a leap in percentage increase of lift coefficient as compared with lift coefficient at 8° angle of attack. The results show that as angle of attack increases, the percentage reduction in drag coefficient was increased. This indicates that there was significant reduction in drag coefficient with increase of angle of attack with the use of plasma actuator. Moreover, the airfoil yielded more lift with the use of plasma actuator as compared to without the plasma actuator and the pressure reduced on upper curve of airfoil and flow accelerated on upper curve with the use of plasma actuator which increased performance of airfoil as compared without plasma actuator.



Plot 1: cd v/s aoa plot

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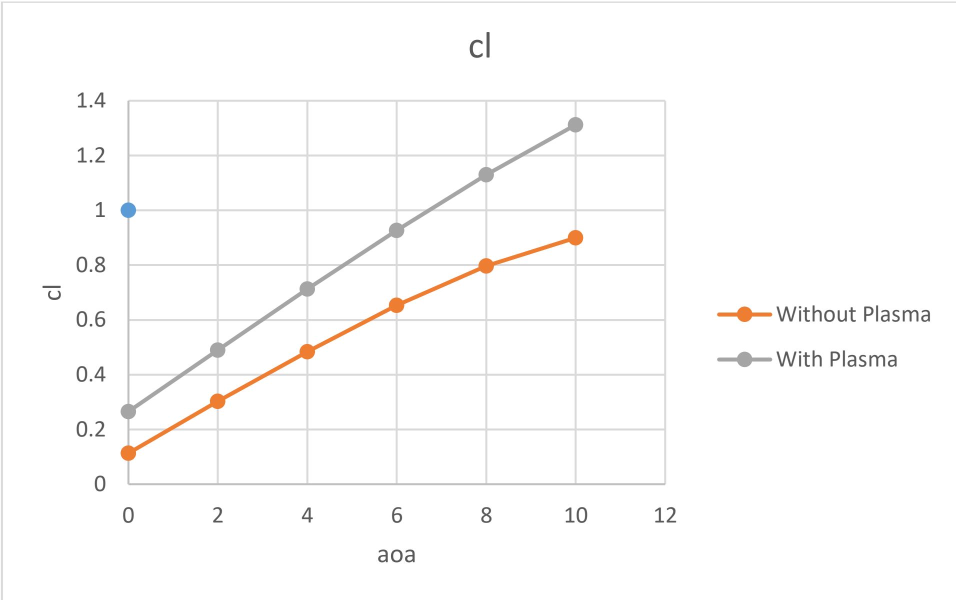
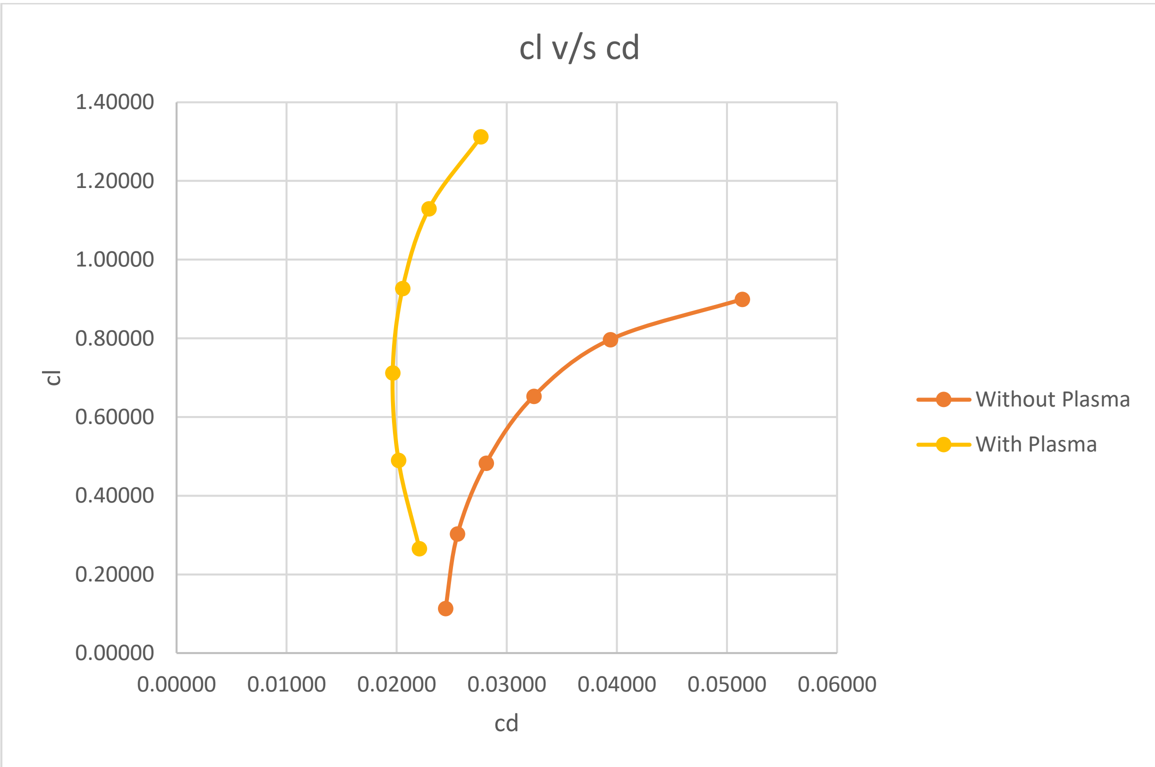


Plot 2: cl v/s aoa plot

Above graphs show drag and lift coefficient plotted across angle of attack with and without plasma actuator. It's clear from the plots that performance difference is really high and distinct. Plasma source boosted the traditional simulation results and enhanced the usability and benchmarked the results. The pressure and velocity contour results were crossed to set a new high benchmark with the use of plasma actuator. The flow separation at higher angles of attack were controlled with ease by the plasma source and flow was stuck to airfoil for most of the chord length with use of plasma actuator as compared to without use of plasma actuator.



Plot 3: cl v/s cd plot

Above plot shows the cl v/s cd curve with and without the use of plasma actuator. Without the plasma source, drag coefficient increased exponentially with increase in lift coefficient. Whereas, when plasma source was induced, there was very minute increase in gradient of drag coefficient with increase in lift coefficient. The curve explicitly proves the significance of plasma actuator for flow control and to step-up the performance.

There was more than 45% increase in lift to drag ratio as a whole with use of plasma actuator as compared to without plasma actuator. Moreover, there were no negative effects created on flow field due to introduction of plasma source with plasma actuator as it does not protrude off the surface. Ultimately, plasma actuator effectively added necessary benefit to the performance of NACA 23012 airfoil.

V. CONCLUSION

The objective of this study was to investigate and demonstrate the effectiveness of aerodynamic plasma actuators for flow separation control on airfoil for various angles of attack. The NACA 23012 airfoil as surface showed astonishing results with leap in performance with introduction of plasma source. The plasma source handled the flow separation effectively without any question and its best choice for the active flow separation control. There was above 45% performance leap in lift to drag ratio with use of plasma actuator. Plasma source flow acceleration was effective and laminar flow separation bubble size reduced tremendously with the work of plasma. Plasma source has handled flow separation with ease at higher angles of attack and effectively reduced the drag which helps to increase the stalling angle. As plasma source is employed at leading edge, there was flow separation at trailing edge but effective region has to be selected based on airfoil and requirement for optimal performance. Moreover, the space occupied and energy used by plasma actuator is negligible compared to their usefulness and work effectiveness. Although, in real conditions plasma actuator efficiency and effectiveness may be changing but it will be a very small change that it does not impact its consideration for use.

The ability of the plasma source in handling the flow separation considering the high response rate and the benefit it produces by increasing the performance makes the plasma actuators essential part for efficient functioning of airfoil or wing. Instead going for passive flow control techniques, active plasma actuators are need to be employed. Plasma actuators have their applications in other fields of aerodynamics too where the fluid involves. More research is going on regarding their applications for various problems and situations considering its efficiency and effectives in controlling the flow.

VI. APPENDIX

UDF are written in C language and compiled by Fluent. Below is the sample code.

```
//written by Lee Ming Wei, School of Aerospace Engineering in Universiti Sains Malaysia
//UDF are written in C and compiled by FLUENT using visual studio
//INFORMATION
//define plasma as a rectangle source in momentum to simplify the code
//DECLARATION
//NO validation is done!!
//-----------------------------------------------------------------------------------------------------------------------
#include "udf.h" //udf library in C language
DEFINE_SOURCE(plasma_source, c, t, dS, eqn) //define macro
{
real xc[ND_ND]; //declaration of cell coordinate
real source, x, y; //declaration of plasma, x-coordinate and y-coordinate
C_CENTROID(xc, c, t); //centroid of cell
x = xc[0]; //x as the 1st array of xc
y = xc[1]; //y as the 2nd array of xc24
if ((x > 0.048285011) && (y > 0.058866676) && (x < 0.14667337) && (y < 0.11919238)) //define the plasma region
{
source = 5.0; //the value of plasma source
dS[eqn] = 0; //explicit solution
}
```

```
else
{
source = 0;
dS[eqn] = 0;
}
C_UDMI(c, t, 0) = source; //adding effect
return source;
}
```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