Numerical Simulation of Stall Flow Control Using a DBD Plasma Actuator in Pulse Mode

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Abstract A numerical simulation method is employed to investigate the effects of the unsteady plasma body force over the stalled NACA 0015 airfoil at low Reynolds number flow conditions. The plasma body force created by a dielectric barrier discharge actuator is modeled with a phenomenological method for plasma simulation coupled with the compressible Navier-Stokes equations. The governing equations are solved using an efficient implicit finite volume method. The responses of the separated flow field to the effects of an unsteady body force in various inter-pulses and duty cycles as well as different locations and magnitudes are studied. It is shown that the duty cycle and inter-pulse are key parameters for flow separation control. Additionally, it is concluded that the body force is able to attach the flow and can affect boundary layer grow that Mach number 0.1 and Reynolds number of 45000.

Keywords: flow control, pulse plasma actuation, unsteady flow, low Reynolds number, numerical simulation

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(Some figures may appear in colour only in the online journal)

1 Introduction

Flow separation over a solid surface occurs by means of an adverse pressure gradient and/or geometric aberration. The solution to this problem has been highly sought after in the computational fluid dynamics community for almost a century [1]. Different methods for flow separation control including active and passive techniques have been presented.

Much research has been carried out on low Reynolds number aerodynamics over the past decade. Micro Air Vehicles (MAVs) are an example of the application of this research, in which the performance is highly affected by the flow conditions [2]. Interest in research and application of the Dielectric Barrier Discharge (DBD) plasma actuator has increased in recent years. This active flow control device has distinctive potentials such as reduction in size, weight and drag, increasing reliability, low cost, no moving parts, wide frequency bandwidth, rapid on-off capability, low energy consumption, increasing stealth, without bumps or gaps over the airfoil surface, operating in both steady or unsteady mode and low power input. The applications of aerodynamic flow control using a DBD actuator include separation control in high and low angles of attack [3,4], airfoil lift enhancement [5], flow control over a hump [6], stabilizing the laminar boundary layer [7], control of transitional and turbulent flows [8], control of vortical flows [9], and so on.

The DBD actuator is a plasma-based technique that operates in a frequency range of 1–50 kHz and voltage amplitude of 1–20 kV. The actuator consists of two electrodes with different geometrical characteristics, separated by a layer of dielectric material, normally kapton or glass. The schematic of a DBD plasma actuator is shown in Fig. 1. The AC current with a wave form of kHz frequency is applied on two electrodes at atmospheric pressure. The AC voltage partially ionizes the air particles above the dielectric and the plasma forms on the dielectric layer above the exposed electrode. The plasma accelerates in the effect of the electric field between two electrodes in the surrounded electrode. The compaction of the collision between the ionized particle and neutral air particles, and the momentum of the plasma is transmitted to the neutral air particles near the surface of the dielectric.

![Fig.1 Diagram of a DBD plasma actuator](image-url)
the input voltage switches on/off at a lower frequency of approximately a few Hertz. The interesting point about the unsteady mode of the DBD actuator is that the input energy consumption in unsteady mode is less than steady mode. More details about the working conditions of this control device are described in Ref. [10]. In this study, a DBD actuator in the operational unsteady mode is assumed.

There are two major modeling approaches applied for simulation of the DBD plasma actuator: first-principles approaches and phenomenological or simplified approaches. The main objectives of the phenomenological modeling are the plasma simulation and the survey of plasma effect on the fluid. However, the plasma physics cannot be confidently predicted and described in this method, in contrast to the first-principles approaches. Many different models from phenomenological approaches have been created. These models are rather simple and cost effective, so they are very appropriate for simulation of the effects of plasma on the fluid [11].

The Shyy model is one of the most well-known phenomenological approaches that has been employed in several two and three-dimensional fluid dynamics problems [7,8,12–14]. The numerical results using this model have been compared with the experimental data in Ref. [15]. The effect of the plasma on the fluid flow is assumed as a body force in the plasma formed region. The electric and plasma body force fields are linearized in this region. The constant electric field lines are parallel in the plasma region except in the small space near the cathode. The electric field lines are constantly distributed from the cathode to the anode. The strength of the electric field lines decreases with increasing the distance from the cathode [11,16].

The purpose of this paper is to simulate the flow over a stalled NACA0015 airfoil under the impact of the unsteady plasma body force. The results are then compared with the other numerical results in the literatures. The effects of the duty cycle and interpulse period on the flow field and separation control are studied. The effects of the pulse body force by changing the strength scale and locations of the actuator on the flow field are also studied.

2 Numerical solution method

2.1 Governing flow equations

Based on Ref. [17], it has been reported that the compressibility effects may play an important role in the momentum coupling process. Thus, two-dimensional unsteady compressible Navier-Stokes equations are employed to describe the flow field, which is augmented by source terms representing the plasma forcing of the DBD actuator. The flow equations can be written in the conservation form in a Cartesian coordinate system as follows:

$$\frac{\partial X}{\partial t} + \frac{\partial F_I}{\partial x} + \frac{\partial G_I}{\partial y} = \frac{\partial F_V}{\partial x} + \frac{\partial G_V}{\partial y} + S,$$  \hspace{0.5cm} (1)

where $X = \{ \rho, \rho u, \rho v, p, \rho e \}$ is the vector of dependent variables. The terms $F_I$ and $G_I$ are the convective fluxes, and $F_V$ and $G_V$ are the diffusion fluxes. The term $S$ is the source vector including the plasma force which is described with more details in the next section. The convective and diffusive flux vectors can be written as follows:

$$F_I = \begin{bmatrix} \rho u \\
\rho u^2 + p \\
(\rho e + p) u \end{bmatrix}, G_I = \begin{bmatrix} \rho e \\
\rho uv \\
(\rho e + p)v \end{bmatrix},$$  \hspace{0.5cm} (2)

$$F_V = \begin{bmatrix} 0 \\
\tau_{xx} \\
(u\tau_{xx} + v\tau_{xy}) + K \frac{\partial T}{\partial x} \end{bmatrix}, \hspace{0.5cm} G_V = \begin{bmatrix} 0 \\
\tau_{xy} \\
(u\tau_{xy} + v\tau_{yy}) + K \frac{\partial T}{\partial y} \end{bmatrix},$$  \hspace{0.5cm} (3)

where $\rho, p, t, c, T$ and $K$ represent the density, pressure, time, total energy per unit value, temperature and heat conduction coefficient, respectively. $u$ and $v$ are the velocity vector components in $x$ and $y$ directions, respectively. $\tau_{yy}, \tau_{xx}, \tau_{xy}$ and $\tau_{yx}$ are stress tensor components. All mentioned values are non-dimensional based on the following scaling:

$$\rho^* = \frac{\rho}{\rho_{ref}}, U^* = \frac{U}{a_{ref} \sqrt{\gamma}}, p^* = \frac{p}{p_{ref}}, e^* = \frac{e}{\rho_{ref}},$$

$$\mu^* = \frac{\mu}{\mu_{ref}} \sqrt{\gamma}, T^* = \frac{T}{T_{ref}},$$  \hspace{0.5cm} (4)

where the subscript ref and superscript * denote the reference and non-dimensional values, respectively. $U, \mu, \gamma$ and $a_{ref}$ represent the velocity vector, the molecular viscosity coefficient, ratio of specific heats and the speed of sound, respectively. The perfect gas condition is assumed and the molecular viscosity coefficient is calculated by Sutherland’s law [12].

2.2 DBD actuator modeling

The source term vector in Eq. (1) is written as follows:

$$S = \begin{bmatrix} 0 \\
D_c \beta e_A(t) \\
\beta D_c A(t) (uE_x + vE_y) \end{bmatrix},$$  \hspace{0.5cm} (5)

where $E_x, E_y$ are the components of electric field vector in the Cartesian coordinate system. $\rho_c$ is the charge number density and $A(t)$ is a parameter between 0 and 1 that shows the strength of the actuator in unsteady mode. $\beta$ is the parameter either 0 or 1, which shows the effect of the energy produced and work done by
body force. Actually, the work done by plasma force is very small, so \( \beta \) is assumed to be zero in this study. More details in this regard are described in the paper by Gaitonde et al. \( D_e \) is the non-dimensional plasma force magnitude parameter, which is defined as:

\[
D_e = \frac{\varrho_e \alpha \bar{E} \Delta t \bar{A}}{p_{ref}}. \tag{6}
\]

In this equation, \( \varrho_e \) denotes the electronic charge (electrons) and \( L \) is the chord length of the airfoil. In this study, the Shyy model is employed to simulate the effect of plasma force on the flow field. In this model, it is assumed that the plasma region is a triangular area downstream the exposed electrode on the dielectric layer (see Fig. 1). The strength of the plasma body force depends on \( D_e \) and the size of the triangular region (a, b in Fig. 1). Plasma body force is assumed to be constant in the Shyy model with steady state assumptions. However, the continuous actuation increases the energy consumption, so in the present study the actuator operates in unsteady mode. In this condition, the actuator turns on/off periodically in a defined pattern. The duty cycle \( (D) \) is the time interval the actuator is switched on \((T_{on})\) divided by the total time interval the actuator is on or off \((T_{on} + T_{off})\) multiplied by one hundred in percents \( [18] \):

\[
D = \frac{T_{on}}{T_{on} + T_{off}} \times 100\%. \tag{7}
\]

A schematic of the duty cycle and inter-pulse period are shown in Fig. 2. The total time period \((T_e)\) is calculated as follows:

\[
T_e = \frac{C}{U_{\infty}}. \tag{8}
\]

Where \( C \) and \( U_{\infty} \) are chord length and free-stream velocity. It should be noted that without DBD control, the separated flow field is complex and the flow is transitional, so the flow field is unsteady \([7]\) and the starting time of the actuator is very important. In Fig. 2 the starting time is \(0.8T_e\). In this paper the body force is calculated simply by the following relation:

\[
\bar{F} = D_e \alpha \bar{E} \Delta t \bar{A}(t), \tag{9}
\]

where \( \alpha, \theta \) are parameters for collision efficiency between ionized and neutral particles and input voltage frequency. Parameter \( \alpha \) is assumed unity, \( \Delta t \) is the small time period that the plasma discharge occurs. The plasma formation time \((\Delta t)\) is assumed equal to 67 \( \mu s \). \( \bar{E} = \{E_x, E_y\} \) is the electric field vector. Electric field vectors and lines are assumed to be parallel in the plasma region, similar to the force field lines. The electric field vector \( \bar{E} \) is obtained as following:

\[
\bar{E} = \left( \frac{|E| k_2}{\sqrt{k_1^2 + k_2^2}}, \frac{|E| k_1}{\sqrt{k_1^2 + k_2^2}} \right), \tag{10}
\]

where \( |\bar{E}| \) is the value of the electric field \((|\bar{E}| = E_0 - k_1 x - k_2 y)\) and \( E_0 \) is the maximum value of the electric field \((E_0 = \frac{V}{k})\) in the gap between the two electrodes. \( V, d \) are the applied voltage and distance between two electrodes in \( X \) direction (Fig. 1). \( k_1 = (E_{on} - E_0) \) and \( k_2 = (E_0 - E_{off}) \) are two positive parameters. The plasma region is a triangle area, where the strength of the electric field is above breakdown electric field value \((E_0)\). It is assumed that in the rest of the domain, the strength of the electric field is zero. Length \( (b) \) and height \( (a) \) of the triangular area are shown in Fig. 1. Further details regarding the Shyy model can be found in Refs. \([11,16]\). In the present study, the values of \( \theta = 3 \text{ kHz}, \varrho_e = 10^{11} / \text{cm}^3, E_0 = 30 \text{ kVcm}, \) \( a/L=0.018, b/L=0.024 \) and \( D_e = 33.6 \) are used \([13]\). The \( A(t) \) parameter in unsteady mode is assumed zero if the actuator is switched off and is set to one if the actuator is switched on. In the starting and ending point of working period, \( A(t) \) is obtained through the following relation \([14]\):

\[
A(t) = at^5 + bt^4 + ct^3 + dt^2 + et + f, \tag{11}
\]

where \( t \) is time and \( a, b, c, d, e, f \) parameters are obtained from the following relations \([14]\):

\[
a = -\frac{6}{D}, b = \frac{15(t_1 + t_2)}{D}, c = \frac{-10(t_1^2 + 4t_1t_2 + t_2^2)}{D},
\]

\[
D = (t_1 - t_2)^5, d = \frac{30t_1t_2(t_1 + t_2)}{D}, e = \frac{-30t_1^2t_2^2}{D},
\]

\[
f = \frac{t_1^3(t_1^2 - 5t_1t_2 + 10t_2^2)}{D}. \tag{12}
\]
In the steady mode, $A(t)$ is assumed to be 1. It is mentioned that, in all cases, the non-dimensional time step was fixed at $5 \times 10^{-5}$ in order to study the effects of the parameters in Eq. (12).

2.3 Numerical flow simulation method

Two-dimensional unsteady Navier-Stokes equations are performed in all of the simulations. The compressible version of the equations is used because accelerated flows are present in some areas of the domain particularly at higher angles of attacks. A cell-center finite-volume implicit method is employed following the work of Jahangirian et al. [19] to discretize the governing equations. Although at low Reynolds number conditions the flow behavior is often laminar, in high angle of attack cases that are considered in this study the flow assumed to be turbulent while the actuator is not active. However, by switching the plasma actuator on, the flow is attached and its behavior becomes laminar. An unstructured grid generation method is employed and the generated grid around NACA0015 airfoil is shown in Fig. 3. The grid has 8845 points and 17414 cells. The normal distance of the first node is taken equal to 0.0002 at the leading edge and 0.0008 at the trailing edge of the airfoil. The algebraic Prandtl turbulence model is also used for flow simulation in turbulent conditions [20].

Fig. 3 Unstructured generated viscous grid

For viscous flows, no-slip boundary conditions are imposed on the body surface. Non-reflecting boundary conditions are also used in the far-field based on the characteristic method [19].

3 Results

Two test cases are presented here. The first one is the flow over NACA0015 airfoil without control actuator in order to validate the numerical method. These results are compared with the numerical results of Asada and Fujii [21]. The second test case is the flow over NACA0015 airfoil at stall conditions using the DBD plasma actuator to study the effects of this device. In all simulations, the laminar Prandtl number is 0.72 and the ratio of the specific heats is 1.4. The actuator is placed at the 2.8% chord from the leading edge.

3.1 Flow without control

![Fig. 4](image)

Fig. 4 Results over NACA0015, $M_{\infty} = 0.2$, $Re = 63000$, $\alpha = 14$, without control

In this case, the flow over NACA0015 airfoil at Mach number 0.2, Reynolds number of 63000 and the angle of attack of 14 degrees is considered. The nature of the flow is unsteady due to the flow separation that occurs and vortices shedding downstream of the flow. To validate the computational method, the mean pressure coefficient ($C_p$) distribution around the airfoil is shown in Fig. 4(a) compared with the numerical and experimental data [21,22]. It is noted that the surface pressure coefficients are approximately similar for laminar and turbulent flow calculations. More details
regarding the validation of the results without control are described in a study by Khoshkhoo et al. The smooth distribution of the mean pressure coefficients on the upper surface of the airfoil indicates the fully separated flow throughout this region. Fig. 4(b) shows the mean friction coefficient \( C_f \) distribution on the airfoil surface. This figure shows that the shear layer is separated at approximately 2% of the chord from the leading edge.

### 3.2 The effect of plasma actuator in steady mode

The second case is a DBD controlled flow around NACA0015 airfoil. To compare the results with the reference data, the angle of attack is set to 15 degrees and the Reynolds number and Mach number are set to 45000 and 0.1, respectively. The actuator is installed at 2.8% of the chord length from the leading edge and assumed to be in steady mode. The results show that the separation is initiated at 2.4% of the chord length from the leading edge which is comparable with the results reported by Visbal.

### 3.3 The effect of plasma actuator in unsteady mode

The response of the similar flow over the NACA0015 airfoil is studied with plasma actuator operating in unsteady mode with a duty cycle of 20% and inter-pulse of 0.7\( T_c \). The mean surface pressure coefficient \( C_p \) obtained from the present method are compared with two and three dimensional Large Eddy Simulation (LES) results of Gaitonde in Fig. 6. There is a difference between two and three dimensional results due to the spanwise instabilities and edge-effects of a finite span. More details are described in Refs. [7, 13].

After several time characteristics \( T_c \), the flow field reaches an asymptotic state. Fig. 7 shows the asymptotic state of mean \( u \)-velocity contours with 20% duty cycle and inter-pulse of 0.7\( T_c \). Fig. 7(a) depicts the switch-off situation of the duty cycle that demonstrates a fully separated flow along the upper surface of the airfoil. Upon switching on the actuator in Fig. 7(c) and 7(d), a positive momentum is exerted on the flow particles near the plasma actuator that tends to suppress the flow separation initiated from this area. Consequently several unsteady vortices are generated that propagate downstream to the trailing edge area of the airfoil. This phenomena repeats in the same time intervals until flow separation controls and the lift coefficient increases (see Fig. 7(h)).

The mean \( C_p \) and \( C_f \) distributions in steady and unsteady modes of the DBD actuator is shown in Fig. 8. Also the mean \( u \)-velocity contours and stream-lines in steady and unsteady modes are exhibited in Fig. 9. It is clear that, although both DBD plasma actuators have succeeded to remove the flow separation from the leading edge area of the airfoil, the
Fig. 7  Asymptotic response of mean u-velocity contours with duty cycle of 20% and inter-pulse period of 0.7$T_c$, $M=0.1$, $Re=45000$, $AOA=15^\circ$

Fig. 8  Mean $C_p$ and $C_f$ distributions in steady and unsteady modes with duty cycle 20% and inter-pulse period of 0.7$T_c$, $M=0.1$, $Re=45000$, $AOA=15^\circ$

Fig. 9  Mean u-velocity contours and stream lines in steady mode and unsteady mode with duty cycle of 20% and inter-pulse period of 0.7$T_c$, $M=0.1$, $Re=45000$, $AOA=15^\circ$
steady mode shows stronger impact. However, it should be noted that the pulse plasma DBD actuator consumes only 20% input energy compared with the steady mode. Thus, the DBD plasma actuator in the pulse mode may be more favorable when energy consumption restrictions have to be considered. Furthermore, the DBD pulse plasma actuator naturally makes unsteady flow features which, at the same time, can control the early flow separation from the leading edge area of the airfoil with lower energy consumption. Of course, the values of the duty cycle and inter-pulse have considerable effects on the efficiency of the flow control in the pulse mode and further studies have to be carried out to explore their effects on the performance of the DBD pulse plasma actuator. Thus, in the following sections the effects of different parameters including duty cycle, inter-pulse, strength of the electric field and the location of the actuator are investigated.

### 3.4 Duty cycle effect

It was mentioned that duty cycle is a key factor in the energy consumption of the DBD actuator. By reducing the duty cycle, energy consumption will be reduced \[^{10,13}\]. Also, the duty cycle has a deep effect on the structure of the flow. The effect of the duty cycle on the flow is shown in Fig. 10 with an inter-pulse of 0.7\(T_c\). In this figure, the mean surface pressure coefficient \((C_p)\) distribution in different duty cycles is shown. It is clear that in low duty cycles (less than 20%) the effect of plasma actuator is not considerable. However, in the high duty cycles (more than 40%), the flow is forced to attach, but further increasing this parameter no longer seems to affect the flow conditions. Thus, one can argue that there should exist an optimum duty cycle based on the energy consumption and the obtained lift.

The mean \(u\)-velocity contours and stream-lines in the two different duty cycles are compared in Fig. 11. It is obvious that by increasing the duty cycle, the flow separation controls and the flow velocity increases on the airfoil above the plasma actuator location.

![Fig.10](image-url) Effect of different duty cycles on mean \(C_p\) distribution with inter-pulse period of 0.25\(T_c\), \(M=0.1\), \(Re=45000\), AOA=15\(^\circ\)

### 3.5 The inter-pulse effect

Inter-pulse is an important factor to appoint the duty cycle in unsteady mode. It seems that we can best find a starting point by evaluating the attached flow after cessation of the body force \[^{13}\]. In the flow around NACA0015 airfoil with \(Re = 45000\), \(M = 0.1\) and angle of attack 15 degrees, the separation occurs after about 0.7\(T_c\) in the leading edge \[^{12,14}\]. After several characteristic times, an asymptotic state occurs. By switching the actuator on and off, the acoustic waves and consequently the vortices generate on the upper surface of the airfoil periodically and diffuse towards the trailing edge. To study the effects of these features on lift generation, different tests are defined. Fig. 12 shows the mean \(u\)-velocity in two inter-pulse periods. By increasing the inter-pulse period, the boundary layer develops due to the generated separation, so by decreasing inter-pulse, the plasma body force increases near the plasma actuator location, and the separation is decreased in the boundary layer and the velocity increases. Fig. 13 exhibits the mean surface pressure coefficient \((C_p)\) distributions in different inter-pulse values from 0.25\(T_c\) to 0.7\(T_c\). In all cases, a 20% duty cycle is considered. The mean surface pressure coefficient \((C_p)\) distributions are approximately similar in all cases and no significant changes exist, but by
decreasing inter-pulse, the DBD pulse plasma actuator has a greater effect over flow near the plasma actuator location.

(a) Inter-pulse period of 0.7\(T_c\)

(b) Inter-pulse period of 0.25\(T_c\)

**Fig.12** Mean \(u\)-velocity contours, \(M=0.1, Re=45000, AOA=15^\circ\)

**Fig.13** Effect of different inter-pulse periods on mean \(C_p\) distributions, \(M=0.1, Re=45000, AOA=15^\circ\)

### 3.6 The effect of the body force magnitude \((D_c)\)

The effect of the body force is studied by changing the strength of the electric field \((D_c)\) in the unsteady mode. The mean \(C_p\) distributions with different electric field strengths are illustrated in Fig. 14. In all cases, the inter-pulse period of 0.7\(T_c\) and duty cycle of 20\% are assumed. Also, the mean \(u\)-velocity contours and stream-lines in two different strengths of the electric field are exhibited in Fig. 15. It is obvious that by increasing \(D_c\) the magnitude of the momentum transferred to the flow particles in this area is increased. Thus, it leads to increasing the velocity magnitude along the body surface which in turn, further decreases the surface pressure coefficient in the plasma actuator location and strengthens the suction in this area. It can be seen that the maximum \((C_p)\) variation also occurs near the plasma actuator location.

**Fig.14** Mean \(C_p\) distributions by changing the electric field strength \((D_c)\), \(M=0.1, Re=45000, AOA=15^\circ\)

(a) \(D_c = 16.8\)

(b) \(D_c = 50.4\)

**Fig.15** Mean \(u\)-velocity contours and stream-lines in the two different strengths of the electric field, \(M=0.1, Re=45000, AOA=15^\circ\)
3.7 The effect of plasma actuator location

The effect of the location of plasma actuator \((X)\) on the flow characteristics in unsteady mode is shown in Fig. 16. In all cases, a duty cycle of 20\% and inter-pulse 0.7\(T_c\) are assumed. Fig. 16(a) shows the results when the plasma actuator is located near the separation point (0.018 to 0.028 of the chord length). Fig. 16(a) indicates that the Mean \(C_p\) distributions are similar in all cases except near the plasma actuator location which seems to be insignificant. Fig. 16(b) shows the surface pressure distributions when the plasma actuator is placed downstream of the separation point. By increasing the distance between the plasma actuator location and the separation point, the lift will decrease and the suction will occur in the actuator location. The mean \(u\)-velocity contours and stream-lines for two plasma actuator locations are compared in Fig. 17. It is clear that placing the plasma actuator near the separation point can remove the occurrence of the separation in the leading edge. However, by placing the actuator further downstream, the separation is formed again near the leading edge of the airfoil.

![Fig. 16](image1.png)  
(a) Near separation point  
(b) After separation point

**Fig. 16** Mean \(C_p\) distributions by changing the actuator location, \(M=0.1, Re=45000, AOA=15^\circ\)

4 Conclusions

The effect of the plasma body force in the pulse mode on the flow over a stalled NACA 0015 airfoil was simulated at Reynolds number of 45000. The plasma body force was formed by the DBD actuator in unsteady mode. Two-dimensional unsteady compressible Navier-Stokes equations were employed for flow simulation and the Shyy model was used to simulate the unsteady plasma body force. The responses of the separated flow field to the different inter-pulse periods, duty cycles, actuator locations and magnitudes of body force were investigated. Our results showed that increasing the duty cycle makes the flow attached. By increasing the inter-pulse period, the boundary layer will grow in the leading edge, but overall it does not significantly affect the mean pressure distribution. The body force magnitude has a direct effect on the flow control, so that increasing the plasma force can decrease the separation and boundary layer growth over the airfoil. Finally, the locations of the actuator near the separation point have a positive effect on the flow field compared with the no actuator flow field while changing the location just near the separation point has not changed the flow characteristics. However, locating the actuator far downstream of the separation point did not show any positive improvement in the separation control.
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