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Effects of Simultaneous Suction and Blowing over an Airfoil on Flow Behavior and Aerodynamic Coefficients

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ABSTRACT

In this study, the simultaneous effect of suction and blowing on the boundary layer and the effect of control parameters on the flow separation from a NACA 0012 airfoil is numerically analyzed. Reynolds number is considered 500000 , and the shear stress transport (SST) k-w turbulence model is used to estimate eddy viscosity. The airfoil is supposed to be 2-D. To validate the numerical results, they were compared with reported experiments. In the flow control by simultaneous suction and blowing, the location of the suction jet was 0.1 of the airfoil chord from the fixed leading edge, and that of the blowing jet was 0.5, 0.7, and 0.9 of the airfoil chord from the leading edge. When the blowing location is at 0.5 of the airfoil chord, better results are observed than I n; other locations. An increase in suction jet velocity increases the lift-drag ratio between 22% and 55%. Also, increasing the blowing jet velocity increases this ratio between 43% and 55%. Horizontal blowing has the most negligible effect on improving aerodynamic characteristics. Based on the results, at the angle of attack of 16°, blowing is most effective in the flow control at 30° with an approximate velocity of half the free stream velocity. In this condition, vertical suction has the best effect , and the lift-drag ratio will increase by 76%.

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INTRODUCTION

Due to the great significance and massive use of airfoils, it is essential to study the separation of the boundary layer in them. The separation of the boundary layer leads to the emergence of undesirable aerodynamic characteristics such as energy loss, which causes the reduction of the lift coefficient and an increase in the drag coefficient. So, it is necessary to delay the separation of the boundary layer by applying some methods [1, 2]. In this concept, flow control mechanisms must be introduced. Aerodynamic characteristics can be improved by flow control. In other words, the lift and drag coefficients can be increased and decreased , respectively which can lead to lower energy consumption.

Flow control is performed in both active and passive methods. The passive control methods , such as changing the airfoil geometry and modify the flow field without energy consumption, so that flow separation will be delayed. Active control methods like suction and blowing of the flow perform this by energy consumption [3].

Prandtl applied suction around a cylinder and succeeded in delaying the separation of the boundary layer. He introduced himself as a pioneer in this area [4]. Subsequently, the research were continued by studying the suction and blowing over airfoils. In this concept, You and Moin [5] studied the flow separation with a synthetic jet on NACA 0015 airfoil using the large eddy simulation (LES) method, and they increased the lift coefficient by 70% and decreased the drag coefficient by 18%. Piperas [6] numerically investigated the flow separation control on NACA 4415 airfoil, and by controlling suction, he reduced the lift coefficient by 20%. Lu et al. [7] studied the flow separation by numerical simulation of synthetic jets and reduced the drag coefficient. Genc et al. [8] numerically analyzed the effect of suction and blowing over NACA 2415 airfoil in a transient state. Although the separation bubble in the suction and blowing simulation

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was not completely vanished, it was reduced. They also showed that if several blowing jets were used, better results would be obtained than one jet. The idea of simultaneous suction and blowing was first proposed by Cheng et al. [9] as a way to reduce the energy consumption of the aircraft. Huang et al. [10] studied the separation of the flow over an airfoil by blowing and suction of the flow with a Reynolds number of 5000000 at the angle of attack of 18°. They proved that by combining the jet location and the angle of attack, the suction perpendicular to the leading edge, which is in the range of 0.075-0.125 of the airfoil chord length, increases the lift coefficient. It was also found that the tangential blowing in the downstream results in a maximum increase of the lift coefficient. By the numerical simulation of simultaneous blowing and suction over a Clark airfoil; Chang [11] indicated that the pressure coefficient could be increased at various angles of attack. Zha [12] increased the lift coefficient between 113% to 220% by the experimental simulation of blowing and suction over the NACA 0025 airfoil. It was also observed that a lower chordwise slot length (0.65 of the chord length) yields better results. By modeling suction and blowing over a two-dimensional airfoil, Noor et al. [13] changed the free stream and overcame the adverse pressure gradient. Dano et al. [14] experimentally analyzed the simultaneous suction and blowing of the flow. They located the suction and blowing jets near the leading edge and the trailing edge of an airfoil, and they observed that the flow would be be more turbulent when the momentum coefficient is high. Anoosha et al. [15] simulated the simultaneous suction and blowing of the flow over the NACA 0025 airfoil using a numerical approach. In this way, they increased the lift coefficient by 343% at the angle of attack of 32°. In 2017, Ethiraj [16] controlled the flow appropriately. He has conduct this experiment using a numerical simulation of high-pressure air blowing near the leading edge with the same air suction amount (using a pump) near the trailing edge.

In previous studies in the field of active flow control methods, mostly, aerodynamic coefficients have been explored and the flow structure has not been analyzed precisely. Also, a few studies have been done regarding the simultaneous use of suction and blowing. Moreover, In this research, the effect of blowing and suction parameters have limited to the position of the jet, and other parameters of the jet such as jet angle and blowing intensity has not been investigated. Therefore, to fill the gap in previous research, in the present study, the simultaneous blowing and suction have been studied numerically and different parameters such as the jet location, jet intensity, and jet angle are investigated. Moreover, to understand the effect of applying jet, flow structure, aerodynamics coefficients variation, and velocity field over airfoil were critically analyzed.

The paper is organized as follows: in section 2, the governing equation, cases, numerical setup and validation are discussed. In section 3, part 4, the jet parameters and their effects are introduced. In section 4, the results regarding the control effects on aerodynamic efficiency and flow structure are carried out. In section 5 the concluding discussion is presented.

NUMERICAL SOLUTION

Governing equations

In the present study, the flow is supposed to be steady-state, incompressible, and two-dimensional. The continuity and momentum equations are used as governing equations. The governing equations of conservation are written as follows:

$$\frac{\partial \mathrm{u_i}}{\partial \mathrm{x_i}} = 0 \tag{1}$$

$$\frac{\partial (\mathrm{u}_i)}{\partial \mathrm{t}} = -\frac{1}{\rho}\frac{\partial \mathrm{p}}{\partial \mathrm{x_i}} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} - \frac{\partial}{\partial \mathrm{x_i}}\left(u_\mathrm{i} u_\mathrm{j} - \overline{\mathrm{u'}_\iota \mathrm{u'}_\mathrm{j}}\right) \tag{2}$$

In the above relations ρ, u, p are the density, the fluid velocity, and static pressure, respectively. x_i and x_j indicate the direction of flow and the direction perpendicular to the flow. u_i and u_j are components of velocity, and $(\overline{u_i' u_j'})$ is the Reynolds stress.

For modelling the turbulence effects is used from the shear stress transport (SST) k-ω turbulence model. The k-ω -SST model is used to model turbulence. This model uses equations that provide excellent results for wall-based flows in the aerodynamic analysis. Another feature of this model is that it represents the boundary layer and adverse pressure gradient very well. The equations of turbulent kinetic energy denoted by k and turbulence specific dissipation rate shown by ω are as following:

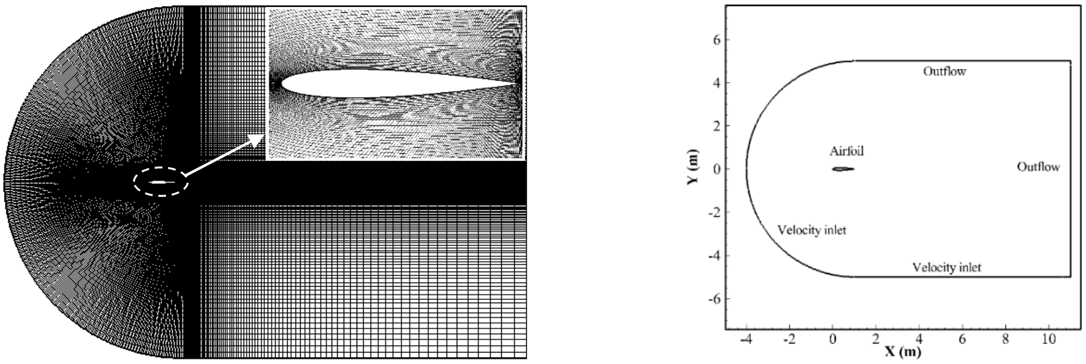
$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu_l + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right] + P_k - \mathrm{C_k} + \mathrm{S_K} \tag{3}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu_l + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + P_\omega - \mathrm{C_\omega} + \mathrm{S_\omega} + \mathrm{G_\omega} \tag{4}$$

where the μ_t refers to turbulent viscosity and σ_k ‘$\sigma_\omega$are constant values. Pk represents the turbulent kinetic energy (k) and Pω denotes the specific dissipation rate (ω). CK and Cω respectively shows the dissipation K and ω due to turbulence. Gω represents the cross-diffusion term. Sk and Sω denotes to user-defined source terms.

Solution settings

In this study, airflow with a Reynolds number of 5×10^5 is assumed. The flow is considered over the NACA 0012 airfoil at the chord length of 1 m. The flow analysis is performed by commercial Ansys-Fluent software. Uniform velocity is assumed for inlet boundaries (bottom and left). on walls, the no-slip condition is applied. The boundary conditions and structured grid used are shown in Figure 1 The SIMPLE coupled algorithmis used to



(a) (b)

Figure 1. a) Airfoil mesh, b) boundary flow conditions over the airfoil

couple velocity with pressure. All simulations have continued until complete convergence of drag and lift coefficients has been achieved. For all governing equations, the convergence condition is satisfied when the residual reaches 10^{-6}.

The independence of the results from the number of cells has been investigated to ensure that the results are valid. Figure 2 shows the variation of the drag and lift coefficients with the number of cells at angles of attack of 10, 12, and 14 degrees. According to this figure, by increasing the number of cells, the aerodynamic coefficients converge, which confirms the independence of the results from the cells. When the number of cells reaches 60000, the lift coefficient does not change significantly. Hence the number of 60000 cells is considered for the numerical analysis.

Validation of the computational model

To verify the numerical results of the present study, two experimental works are used as references. Figure 3 compares numerical drag and lift coefficients with experimental ones. According to this figure, the numerical results agree with the experimental results achieved by Critzos and Jacobs [17, 18].

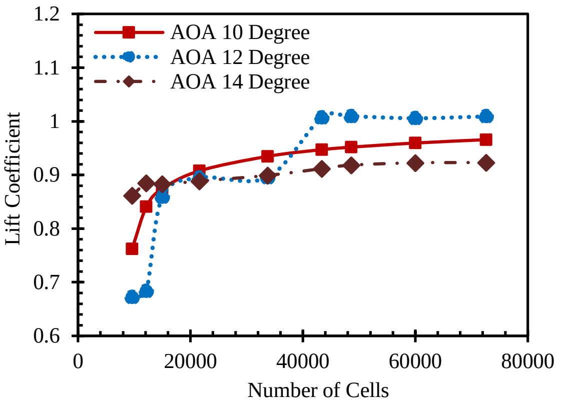


Figure 2. Independence of the lift coefficient from the number of cells

PARAMETERS

The purpose of this study is to investigate the effect of different parameters of simultaneous blowing and suction on the flow. Some parameters should be defined accordingly. These parameters include the location of the flow jet (*Lj*), jet angle (*θ*), and jet intensity (*I*) which are shown in Figure 4. The jet intensity is the ratio of the jet velocity to the free stream velocity. Also, the local jet location is expressed in terms of the airfoil chord length, in a way that the beginning of the airfoil is considered as the origin, and determines the jet location.

$$I = \frac{u_{jet}}{u_{\infty}} \tag{5}$$

$$u = u_{jet}\ \cos(\theta + \alpha) \tag{6}$$

$$v = u_{jet}\ \sin(\theta + \alpha) \tag{7}$$

θ is the angle between the local jet velocity and local jet surface, and α is the angle between the local jet surface and the horizon (Figure 4). In the present paper, the negative and positive θ represent suction and blowing, respectively.

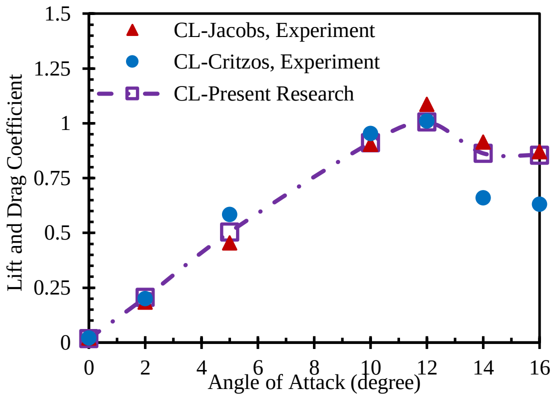


Figure 3. Comparison between experimental lift and drag coefficients [17, 18] and numerical coefficients of the present study

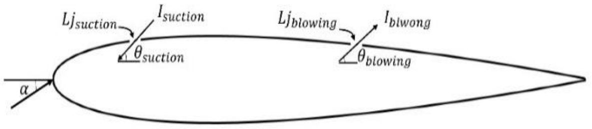


Figure 4. Jet Parameters over the NACA 0012 airfoil

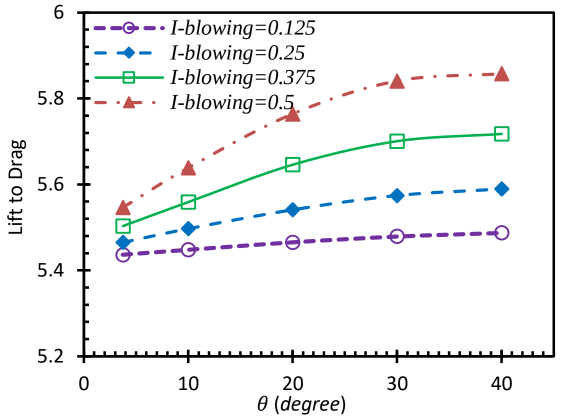
According to Dannenberg and Weiberg [19], the optimum chordwise slot length is about 2.5% of the airfoil chord length, and the lift coefficient will decrease if the chordwise slot length reduces by less than 2.5% of the chord length. They also found that increasing chordwise slot length to more than 2.5% of the chord length is almost ineffective in variations of the lift coefficient. So the chordwise slot length here is assumed constant.

The results of separate suction and blowing show that suction is best effective near the leading edge, and blowing near the trailing edge [10]; hence, the suction here is located at $Lj_{suction} = 0.1$. Also, blowing is studied in the $0.5 \leq Lj_{blowing} \leq 0.9$. The results of reference [10] show that blowing at low angles and vertical suction has a desirable effect on aerodynamic coefficients. Hence, the suction jet angle is held constant at $\theta = -90°$, but the angle of the blowing jet is considered to be in the range of $3.75° \leq \theta \leq 40°$. To investigate the effect of jet intensity, the suction and blowing intensities are assumed in these ranges: $0.25 < I_{suction} < 0.5$ and $0.125 < I_{blowing} < 0.5$.

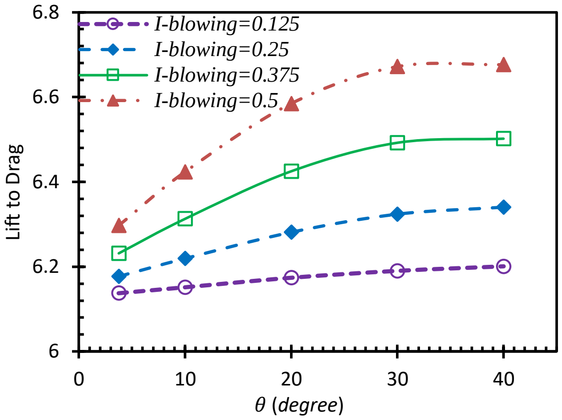
RESULTS AND DISCUSSION

The purpose of this study is to investigate the effect of different parameters of simultaneous blowing and suction on the aerodynamic coefficients and the flow structure. As stated in the introduction, active control methods are used to delay the separation of the flow. In the following, the results of simultaneous blowing and suction on the airfoil are scrutinized.

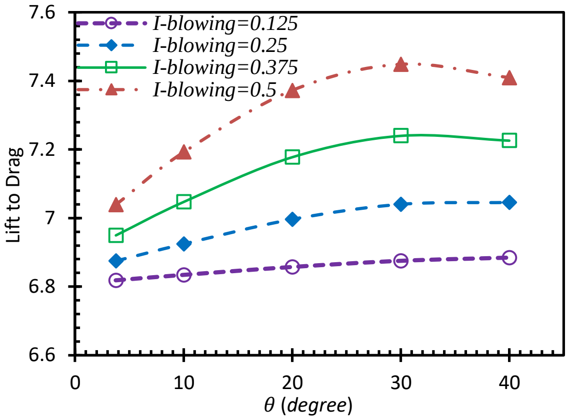
According to Figure 5, using suction and blowing jets simultaneously, causes a significant improvement in the ratio of aerodynamic coefficients. According to obtained results, when the suction and blowing jet intensities are increased, the lift-drag ratio significantly increased. The ratio of the lift coefficient to the drag coefficient (L / D) in the no-jet condition is 4.8, but after applying simultaneous jets with $I_{blowing} = I_{suction} = 0.5$ and $\theta = 40°$, this ratio increases by 32% and reaches 7.4. This ratio is also increased by increasing the angle of the blowing jet, as at $\theta = 40°$, $I_{suction}$ changes from 0.25 to 0.5, and L/D increases from 5.9 to 7.4. However, when $I_{suction} = 0.5$, an increase in the angle of the blowing jet after $\theta = 30°$ reduces the lift-drag ratio.



(a) $I_{suction} = 0.25$



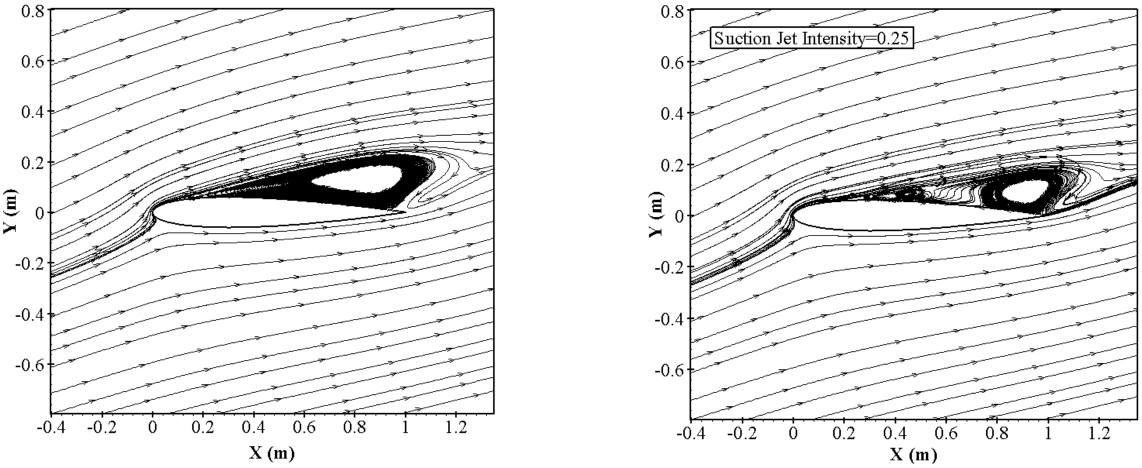
(b) $I_{suction} = 0.375$



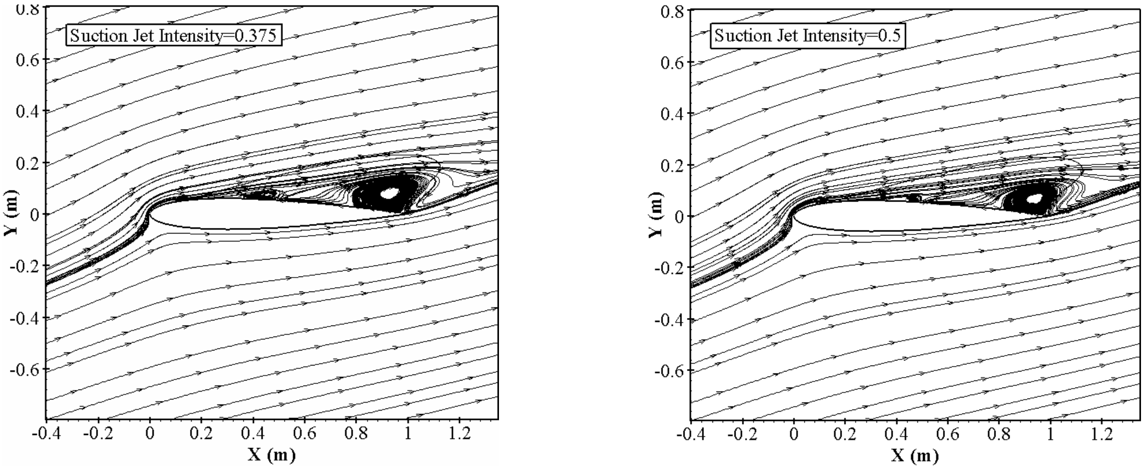
(c) $I_{suction} = 0.5$

Figure 5. Variations of the lift-drag ratio in $Lj_{blowing} = 0.5$ and $Lj_{suction} = 0.1$

Figure 6 shows the variation of the flow pattern in different control conditions of the suction jet intensity. It can be observed that by increasing the suction jet intensity, the boundary layer is well controlled, and the flow separation is delayed. Also, the vortex flows are very weak. Therefore, the suction jet intensity is one of the determining parameters in flow control.



(a) No–suction and –blowing condition (b) $I_{suction} = 0.25$



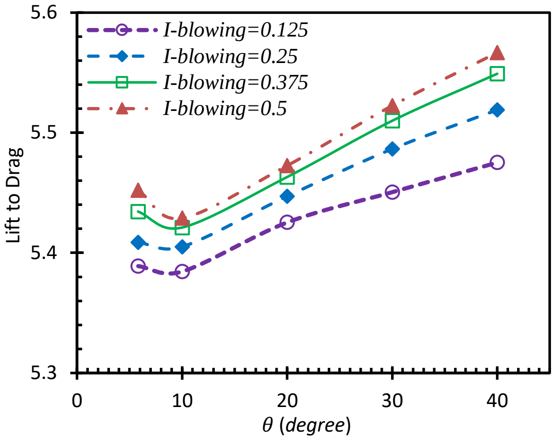
$(c)\ I_{suction} = 0.375$ $(d)\ I_{suction} = 0.5$

Fgure 6. Streamlines for the angle of attack 16°, $Lj_{blowing} = 0.5$, $\theta_{blowing} = 30°$, and $I_{blowing} = 0.5$

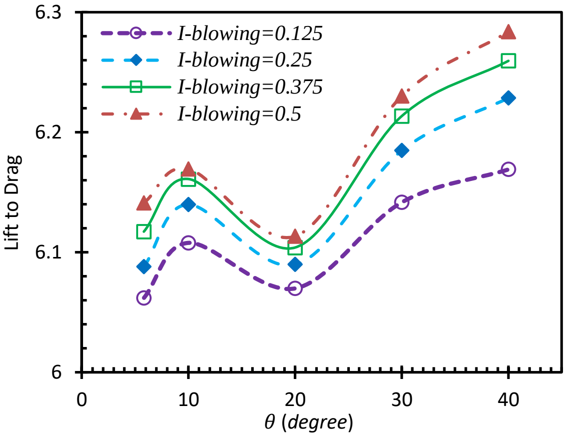
The effect of jet intensity and jet location on the flow control is indicated in Figure 7. This figure shows the variation of the lift-drag ratio at different angles and different jet intensities for $Lj_{blowing} = 0.7$. It is clear that the relationship of this ratio with both the suction and blowing jet intensities is direct. Applying suction and blowing jets, with $I_{suction} = 0.5$ and $I_{blowing} = 0.5$, changes the lift-drag ratio (L/D) between 5.58 and 7 and increases this ratio between 16% and 46% compared to the no–suction and –blowing condition. According to Figure 7 (b), by increasing $\theta_{blowing}$ (from 10° to 40°), the value of L/D first decreases, and then after $\theta_{blowing} = 20°$ it has an ascending behavior. But the behavior of L/D variations versus $\theta_{blowing}$ was ascending trend in Figure 5.

The effect of the blowing jet angle, and the suction and blowing jet intensities on the changes in the lift-drag ratio are shown in Figure 8 for $Lj_{blowing} = 0.9$. Based on the results, by increasing each of the parameters $\theta_{blowing}$, $I_{blowing}$, and $I_{suction}$, the ratio is improved. Also, the behavior of variations of L/D in each diagram is approximately similar to the condition in which the blowing jet is located at $Lj_{blowing} = 0.5$. The results show that when $\theta_{blowing} = 40°$ and $I_{blowing} = 0.5$ L/D increases between 12% and 38% by increasing $I_{suction}$.

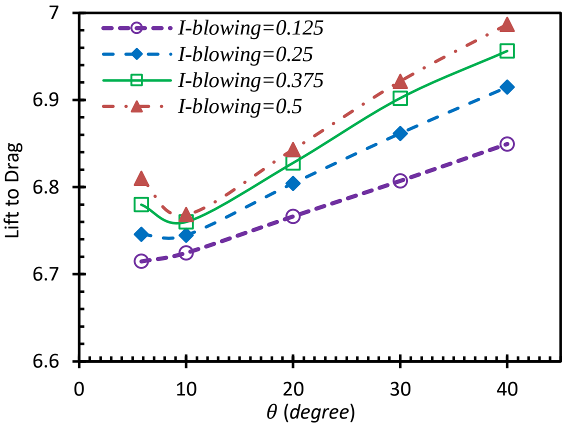
To determine the best control conditions, the effect of location, angle, and intensity of simultaneous suction and blowing jets are investigated in Figures 5, 7, and 8. Hence, based on Figures 5, 7, and 8, the variations of lift-drag ratio at $Lj_{suction} = 0.1$ with $I_{suction} = 0.5$ are plotted in Figure 9 for various angles and locations of the blowing jet. It is obvious that when the jet is located near the end of the airfoil, the lift-drag ratio decreases.



(a) $I_{suction} = 0.25$

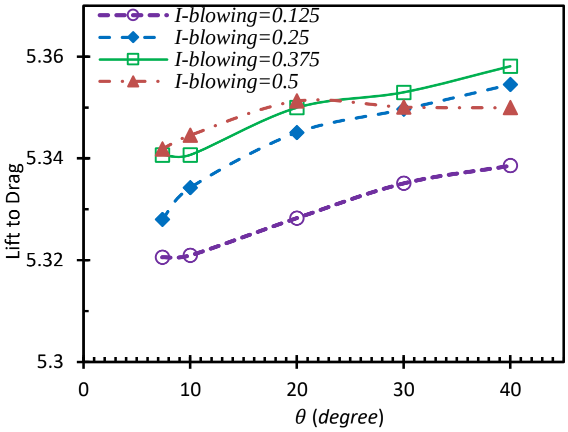


(b) $I_{suction} = 0.375$

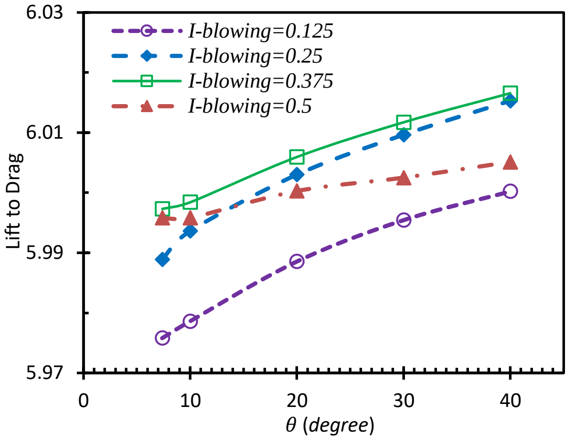


(c) $I_{suction} = 0.5$

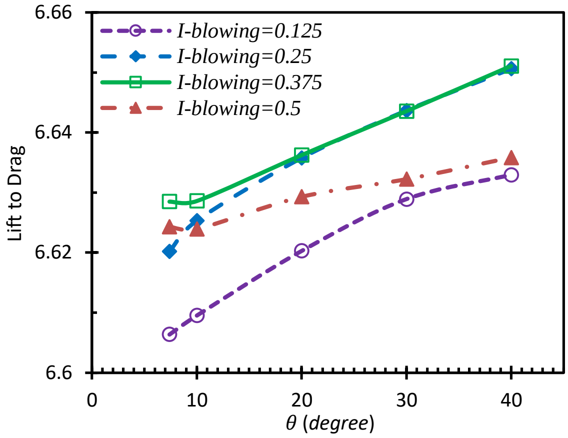
Figure 7. Variations of the lift-drag ratio in $Lj_{blowing} = 0.7$ and $Lj_{suction} = 0.1$



(a) $I_{suction} = 0.25$



(b) $I_{suction} = 0.375$



(c) $I_{suction} = 0.5$

Figure 8. Variations of the lift-drag ratio in $Lj_{blowing} = 0.9$ and $Lj_{suction} = 0.1$

Increasing $\theta_{blowing}$ increases the L/D ratio; however, at $Lj_{blowing} = 0.9$, an increase in this ratio is negligible compared to other conditions. Based on the results, horizontal blowing jets have the most negligible effect on improving the aerodynamic characteristics. Figure 9 also shows that blowing jet at $Lj_{blowing} = 0.5$ with $I_{suction} = 0.5$, $I_{blowing} = 0.5$, and $\theta_{blowing} = 30°$ has the best effect on the flow separation control. Also, the blowing at

$Lj_{blowing} = 0.7$ with $I_{suction} = 0.5$, $I_{blowing} = 0.5$ and $\theta_{blowing} = 40°$ can control the flow well. The blowing at $Lj_{blowing} = 0.9$ with $I_{suction} = 0.5$, $I_{blowing} = 0.375$, and $\theta_{blowing} = 40°$ increases the L/D ratio. The streamlines at different locations of the blowing jet are shown in Figure 10. They are plotted for the best control conditions, which confirms the above results.

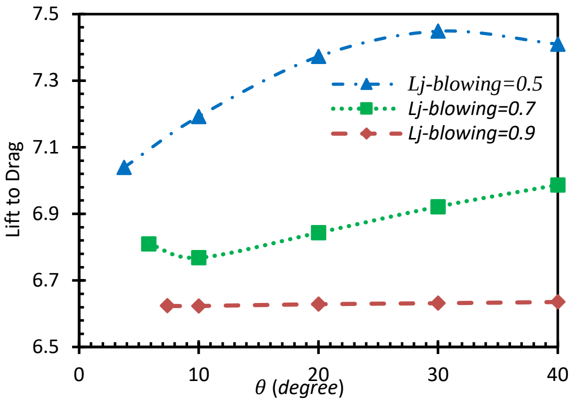
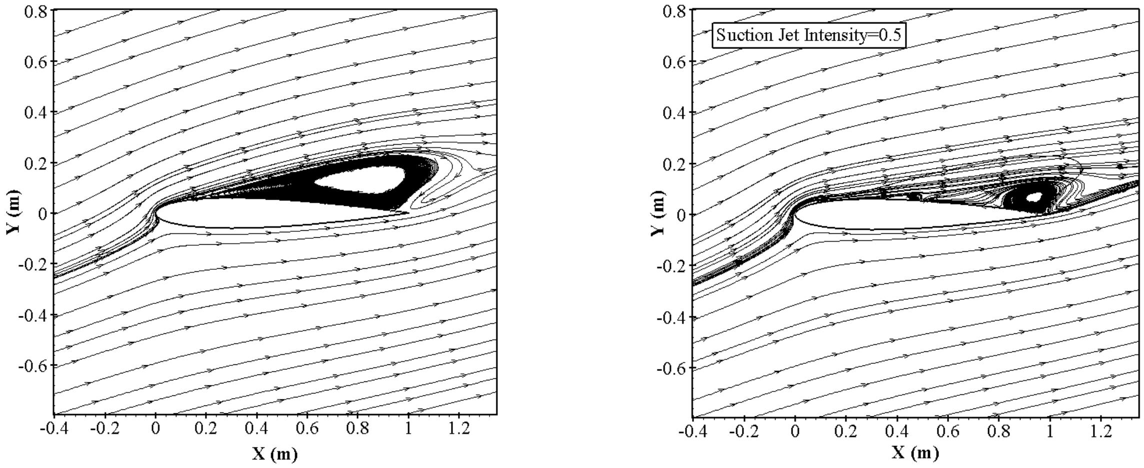
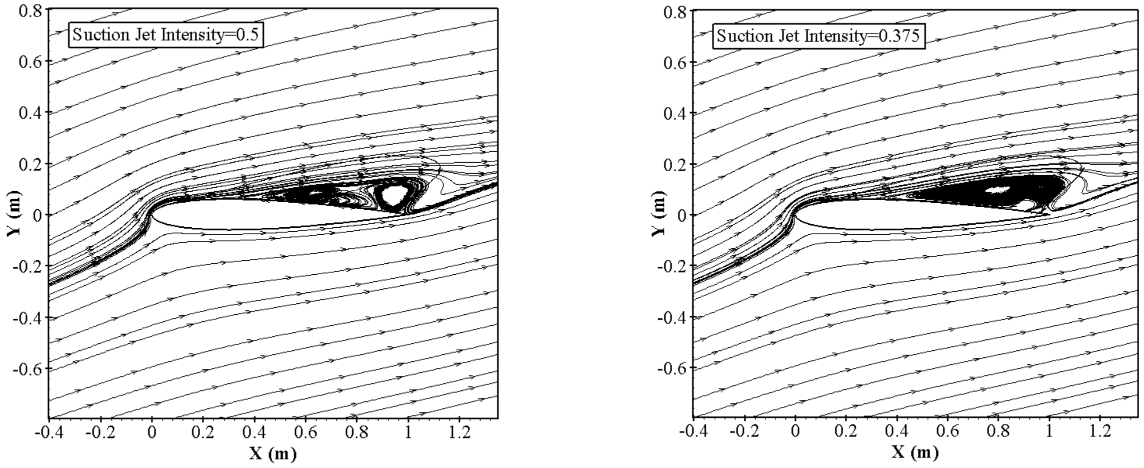


Figure 9. Lift-drag ratio ratio at $Lj_{suction} = 0.1$ and $I_{suction} = 0.5$ for various angles and locations of the blowing jet



(a) No-suction and –blowing condition

(b) $Lj_{blowing} = 0.5$



(c) $Lj_{blowing} = 0.7$

(d) $Lj_{blowing} = 0.9$

Figure 10. Streamlines in the best control conditions for various locations of the blowing jet

SUMMARY AND CONCLUSION

In this paper, the effect of simultaneous blowing and suction on the flow structure, and the relationship of controlling parameters (location, intensity, and jet angle) with the aerodynamic coefficients are investigated. The present numerical analysis has been carried out using the Fluent commercial solver. The two-dimensional steady-state flow is modeled with Reynolds number 500000 over the NACA 0012 airfoil. The results are as follows:

- The numerical results are in good agreement with the experimental results.
- Simultaneous use of blowing and the suction jet has a considerable effect on the flow separation control. Because applying the controlling jets increases the lift-drag ratio in all conditions. This ratio is equal to 4.8 in uncontrolled conditions.
- The intensities of suction and blowing jets have a direct relationship with the lift-drag ratio. At $Lj_{suction} = 0.1$, $Lj_{blowing} = 0.5$, $\theta_{blowing} = 30°$ with $I_{blowing} = 0.5$, an increase in the suction jet intensity increases the L/D ratio between 22% to 55%. Also, at $Lj_{suction} = 0.1$, $Lj_{blowing} = 0.5$, $\theta_{blowing} = 30°$ with $I_{suction} = 0.5$, by increasing the jet velocity, L/D ratio increases between 43% to 55%.
- The velocity over the airfoil increases by applying the control jets. When $Lj_{blowing} = 0.5$, this increase is higher than in other conditions.
- Investigating the effect of the jet angle on the aerodynamic performance showed that at $Lj_{suction} = 0.1$ and $Lj_{blowing} = 0.5$, $I_{suction} = 0.5$ and $I_{blowing} = 0.5$, by increasing the blowing jet angle, L / D increases between 47% to 54%. It is also found that the lowest effect of the blowing jet on improving aerodynamic performance is obtained when the jet is horizontal.
- At the angle of attack of 16°, the control jets applied in $Lj_{suction} = 0.1$ and $Lj_{blowing} = 0.5$ with $I_{suction} = 0.5$, $I_{blowing} = 0.5$, and $\theta_{blowing} = 30°$ are best effective in the flow field and increase L/D by 76%.

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Persian Abstract

چکیده

در این مطالعه، اثر همزمان مکش و دمیدن بر روی لایه مرزی و تأثیر پارامترهای کنترلی بر جداسازی جریان از ایرفویل NACA 0012 به صورت عددی تحلیل می‌شود. عدد رینولدز ۵۰۰۰۰۰ در نظر گرفته می‌شود و از مدل تلاطم k-w انتقال تنش برشی (SST) برای تخمین ویسکوزیته گردابی استفاده می‌شود. ایرفویل قرار است ۲ بعدی باشد. برای تایید نتایج عددی، آنها با آزمایش های گزارش شده مقایسه شدند. در کنترل جریان با مکش و دمیدن همزمان، محل جت مکش ۰,۱ وتر ایرفویل از لبه جلوی ثابت و جت دمنده ۰,۵، ۰,۷ و ۰,۹ وتر ایرفویل از لبه جلو بود. هنگامی که محل دمیدن در ۰,۵ وتر ایرفویل باشد، نتایج بهتری نسبت به I n مشاهده می شود. مکان های دیگر افزایش سرعت جت مکش، نسبت بالابر-کشش را بین ۲۲ تا ۵۵ درصد افزایش می‌دهد. همچنین افزایش سرعت جت دمیدن این نسبت را بین ۴۳ تا ۵۵ درصد افزایش می دهد. دمیدن افقی ناچیزترین اثر را در بهبود مشخصات آیرودینامیکی دارد. بر اساس نتایج، در زاویه حمله ۱۶ درجه، دمیدن در کنترل جریان در ۳۰ درجه با سرعت تقریبی نیمی از سرعت جریان آزاد بیشترین تأثیر را دارد. در این شرایط مکش عمودی بهترین اثر را دارد و نسبت بالابر به درگ ۷۶ درصد افزایش می یابد.