

Numerical Study of Flow Separation Control by Tangential and Perpendicular Blowing on the NACA 0012 Airfoil

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Abstract

In this study, tangential and perpendicular steady blowing at the trailing edge of NACA 0012 airfoil is investigated numerically to flow separation control and to study the effects of blowing amplitude and blowing coefficient on airfoil aerodynamic characteristics. Flow was fully turbulent with the Reynolds number of 5×10^5 and the turbulent employed model was the Menter's shear stress model. Blowing on airfoil is modeled in tangential (tangential blowing) and perpendicular (perpendicular blowing) form and length of blowing jet is 3.5 percent of chord length. Considering previous studies, blowing jet is optimum in two distances on the airfoil surface, one around 40 percent and the other around 80 percent of chord length from the leading edge, which in this study blowing jet is placed at 80 percent of the chord length from the leading edge. Blowing velocity from 0.1 to 0.5 is considered of freestream velocity. Results of tangential blowing show that by increasing amplitude of blowing, lift and drag coefficients changes are inconsiderable. Maximum increase of lift to drag ratio in amplitude of 0.5, around 16.5 percent, but in perpendicular blowing lower amplitude of blowing is more appropriate. Also tangential blowing has no effect on stall angle and cause gradual stall of NACA 0012 airfoil, whereas perpendicular blowing improve stall angle from 14 to 16 degrees.

Keywords: Blowing, Blowing Amplitude and Coefficient, Flow Control, NACA 0012 Airfoil, Lift and Drag Coefficients.

1. INTRODUCTION

The presence of boundary layer cause major problems in different fields of fluids mechanics. However, most of studies had focused on boundary layer effects on lift and drag forces, especially on wings. Developed methods for boundary layer management, lift coefficient increase and drag coefficient reduction are known as flow separation control or boundary layer control. The scope of flow separation control on an airfoil is to achieve more lift coefficient and less drag coefficient and consequently, airfoil higher performance by increasing the lift to drag ratio. Control methods of boundary layer are divided into two categories: passive flow separation control, requiring no auxiliary power and no control loop, and active flow separation control, requiring energy expenditure. Normal uniform suction and blowing which is among passive flow separation control, has been considered in recent years and most of studies have been concentrated on oscillatory suction/blowing near leading edge. However, effects of suction/blowing parameters variation that could provide a suitable research area, hasn't been considered appropriately.

Many studies have been conducted on flow separation control. Prandtl was the first scientist who employed boundary layer suction to indicate its significant impacts on stream lines in 1904. He used suction on cylindrical surface to delay boundary layer separation. Boundary layer separation would be eliminated almost entirely by suction through a slot on the back of the cylinder [1]. First experiments on flow separation control on an airfoil were done in late 1930's to 1940. The effect of suction on boundary layer separation using slots on airfoil surface in wind tunnels was evaluated by NACA Langley memorial scientists. The first flight experiments in which seventeen suction slots were installed between 20 and 60 percent of the chord length was done. Employed airplane in this experiment was B-18 airplane [2]. Investigation on suction theoretical solution by Inverse boundary-Value problem was examined by Abzalilov et al. [3]. The efficiency of tangential unsteady suction and blowing in flow separation control on an airfoil TAU0015 was studied by Ravindran [4]. He also evaluated the effects of Zero Net Mass Flux Oscillatory Jet (Synthetic Jet) on lift coefficient increase and flight conditions in his study were Mach 0.15, Reynolds number 1.2 million at the angle of attacks 22 and 24 degree. Result showed that Lift coefficient increased from 23 percent (angle of attack 22 degree and suction coefficient is 0.0005) to 55 percent (angle of attack 24 degree and same suction coefficient). Also some researchers by analytical methods [5, 6 and 7] , experimentally [8, 9, 10, 11, 12 and 13] and some numerically [14, 15 and 16] showed that using flow separation control, such as suction, blowing and synthetic jets, causes the larger lift coefficient on thick and NACA airfoils.

Huang et al. [17] studied on flow separation control on an NACA 0012 airfoil by using suction and blowing with angle of attack 18 degree and Reynolds number of 5 Million in 2003. They proved that when jet location and angle of attack were combined, perpendicular suction at the leading edge, from 0.075 to 0.125 chord length, increased lift coefficient better than other suction situations. It has been also stated that tangential blowing at downstream locations, around 0.371 to 0.8 chord length, leads to the maximum increase in the lift coefficient value. Resendiz [18] investigated on the numerical simulation of flow separation control by oscillatory fluid injection and his result demonstrated that the use of synthetic jets on an NACA 0012 airfoil elevated the lift coefficient up to 93 percent. The application of evolutionary algorithm in order to optimize the flow separation control has been studied by Beliganur & Raymond [19] in 2007. Results of their study showed that the use of two suction jets along with two blowing jets for an NACA 0012 airfoil was able to enhance the lift to drag ratio by 12 percent. Flow separation control by synthetic jets on an NACA 0015 airfoil by using Large Eddy Simulation method was done in 2008 by You and Moin [20]. Outcomes presented that lift coefficient increased 70 percent and drag coefficient decreased 18 percent while flow separation control parameters were changed. Akcayoz & Tuncer [21] examined the optimization of synthetic jet parameters on an NACA 0015 airfoil in different angle of attack to maximize the lift to drag ratio and their results stated that optimum jet location moved toward leading edge and optimum jet angle went up while angle of attack increased. Kim et al. [22] used synthetic jets to flow separation control on an NACA 23012 airfoil. They focused on angle of attack, jet velocity and jet frequency for relatively high Reynolds numbers. This study showed, the maximum lift was obtained when the separation point coincided with the synthetic jet location and the non-dimensional frequency was one. Although the small vortex generated in the low frequency range beneficially affected the separation control and the lift enhancement, it caused the local flow structure to be easily destabilized by external disturbance or gust.

Piperas [23] in 2010 studied on flow separation control on an NACA 4415 airfoil through different suction arrangements and increased the maximum lift coefficient value by 20 percent. Genc et al. [24] studied on the numerical effects of suction and blowing on the NACA 2415 airfoil at transition zone in 2011. Although separation bubbles were not entirely eliminated in suction and blowing simulation, they either reduced or moved into the downstream. For synchronic suction and blowing, separation bubbles were exterminated completely, lift coefficient increased and drag coefficient decreased. They also showed the best results were obtained with the single suction jet, intermediate results were obtained with the multi jets and the worst results were obtained with the blowing jets. Yagiz et al. [25] worked on drag optimization on Rae5243 airfoil in transonic conditions through suction. By optimum parameters selection they increased the lift coefficient, 3.17 percent, and decreased the total drag coefficient, 3.13 percent. In addition, Yousefi et al. [26]

in 2012 reviewed the investigations on used methods in suction and blowing systems to increase or decrease drag and lift coefficient.

2. GOVERNING EQUATIONS

In this study the flow is assumed to be steady, incompressible and two-dimensional. So momentum and continuity equations become:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] \quad (2)$$

$$\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] \quad (3)$$

The Menter's shear stress transport turbulence model (K – ω SST) was used to solve turbulence equations. This model which includes both K – ω and K – ϵ standard models improved the calculations of boundary layer flows with separation and removed the sensitivity of K – ω model in external flows. The transport equations in Menter's shear stress turbulence model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho U_i k) = \tilde{P}_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right] \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho U_i \omega) = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (5)$$

In these equations, F_1 is blending function, S is the invariant measure of the strain rate, β^* is 0.09 and $\sigma_{\omega 2}$ is 0.856. Blending function is equal to zero away from the surface (K – ϵ model), and switches over to one inside the boundary layer (K – ω model). A production limiter, \tilde{P}_k , is used in the Menter's shear stress transport turbulence model to prevent the build-up of turbulence in stagnation regions. In addition, it is important to note that the all constants are computed by a blend from the corresponding constant of the K – ϵ and the K – ω model via α , σ_k , σ_ω and etc [27 and 28].

$$F_1 = \tanh \left\{ \left\{ \min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500v}{y^2 \omega} \right), \frac{4\rho \sigma_{\omega 2} k}{CD_{k\omega} y^2} \right] \right\} \right\} \quad (6)$$

$$CD_{k\omega} = \max \left(2\rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (7)$$

$$P_k = \mu_t \frac{\partial U_i}{\partial x_j} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \quad (8)$$

$$\tilde{P}_k = \min (P_k, 10\beta^* \rho k \omega) \quad (9)$$

3. PARAMETERS SELECTION

In this study, the numerical code was used for simulation. Values for Reynolds number of flow and free stream velocity were 5×10^5 and 7.3037 m/s, respectively, and the used fluid was air. Geometry of NACA 0012 airfoil, blowing jet location (L_j), blowing angle (θ) and blowing jet length (h) has been shown in Figure 1. The chord length of the airfoil is 1 m and blowing slots located at 80 percent of the chord length from the leading edge. Previous studies [17] shows that blowing jet location is optimum in two distances on the airfoil surface, one around 37.1 percent and the other around 80 percent of chord length from the leading edge. Also considering previous studies [17, 18 and 21], blowing jet at the trailing edge is more appropriate of the leading edge. So in this study blowing jet is located at 80 percent of chord length from leading edge. The blowing jet

length is 3.5 percent of the chord length in tangential and perpendicular blowing and also blowing amplitude (the blowing velocity to free stream velocity ratio) considered as 0.1, 0.3 and 0.5 in experiments. Examined angles of attack also are 12, 14, 16 and 18 degrees. In our investigation, the blowing amplitude and blowing jet velocity are set as:

$$A = \frac{u_j}{u_\infty} \quad (10)$$

$$u = A \cdot \cos(\theta + \beta) \quad (11)$$

$$v = A \cdot \sin(\theta + \beta) \quad (12)$$

Where β is the angle between free stream velocity direction and the local jet surface and θ is also the angle between the local jet surface and jet output velocity direction. Note that negative θ represents suction condition and positive θ indicates blowing condition. Since tangential and perpendicular blowing is investigated, θ is 90 and 0 degrees. Finally, blowing coefficient equals:

$$C_\mu = \frac{\rho \cdot h \cdot v_j^2}{\rho \cdot C \cdot u_\infty^2} = \frac{h}{C} \times \frac{u_j^2}{u_\infty^2} \quad (13)$$

$$H = \frac{h}{C} \quad (14)$$

$$C_\mu = H \cdot A^2 \quad (15)$$

As it has been presented in equation (15), blowing coefficient is related to two factors: blowing amplitude (A) and blowing jet length (H). On the other hand variation of those values cause changes in suction coefficient value. Over 220 numerical simulations have been performed to cover all the cases.

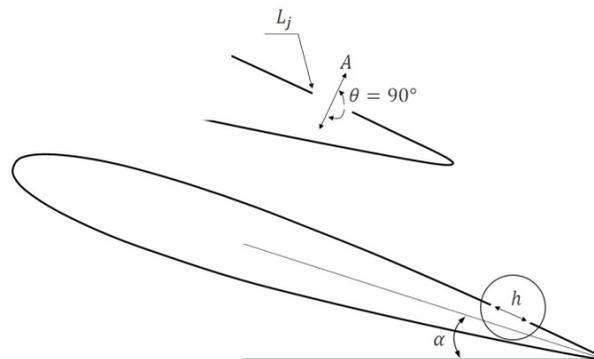


FIGURE 1: Blowing Parameters.

4. NUMERICAL SOLUTION METHOD

First and second order upwind method was employed to discretized the governing equations. First, equations are discrete by the use of first order upwind method, and the resulting system of equations is then solved using the SIMPLE method. Solution procedure is terminated when a convergence criteria of $O(5)$ reduction in all dependent variable residuals is satisfied. Afterwards, second order upwind method was employed to discrete of equations and again, while SIMPLE method was employed to solve them. Convergence accuracy at this step is to the extent in which lift and drag coefficients fully converged, which happens usually at $O(7)$. The key point here is that answers obtained from the first order upwind method was used as initial assumption for the second order upwind method. It is an attempt to consider the characteristics of laboratory wind tunnel, so the stream turbulence intensity is less than 0.1 percent. Airfoil computational area (C-type structured mesh) is considered as multizonal blocks in order to make structured mesh (Figure 2). The computational area grid extends from -4 chord upstream to 11 chord downstream and the upper and lower boundary extends 4 chord from the profile. In order to check the mesh

independence of the calculated results, lift and drag coefficients have been studied at angles of attack 10, 14 and 16 degrees with different size grids. Table 1 presented lift and drag coefficients at angle of attack 16 degrees and Figure 3 and 4 showed meshes independent for different angles of attack. Consequently, the grid size giving the grid independent results is selected and the total number of cells is adopted as 41,000 nodes (Table 1, Figure 3 and 4).

Number of Meshes	Lift Coefficient	Drag Coefficient
8096	0.64594	0.20889
17160	1.05134	0.12544
24480	1.09073	0.11567
40640	1.12352	0.10938
58080	1.12319	0.11187

TABLE 1: Evaluation of Mesh Independence at Angle of Attack 16 Degree.

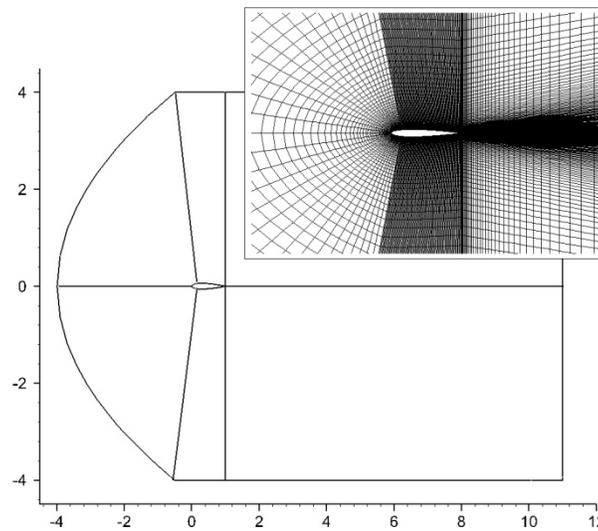


FIGURE 2: C-type Structured Mesh With Multizonal Blocks.

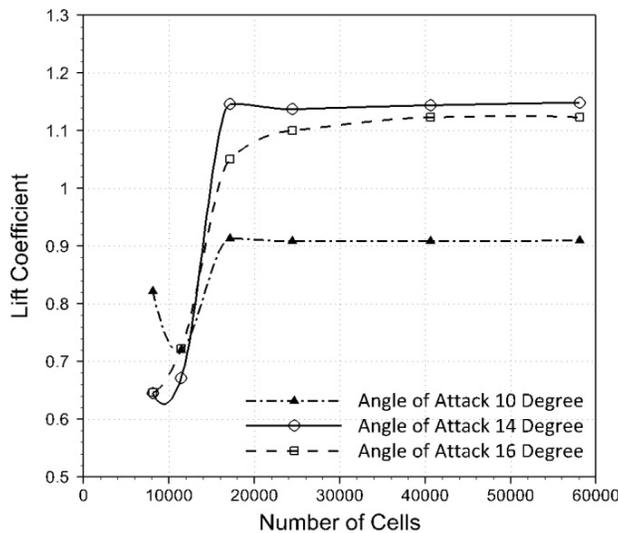


FIGURE 3: Mesh Independency For Lift Coefficient.

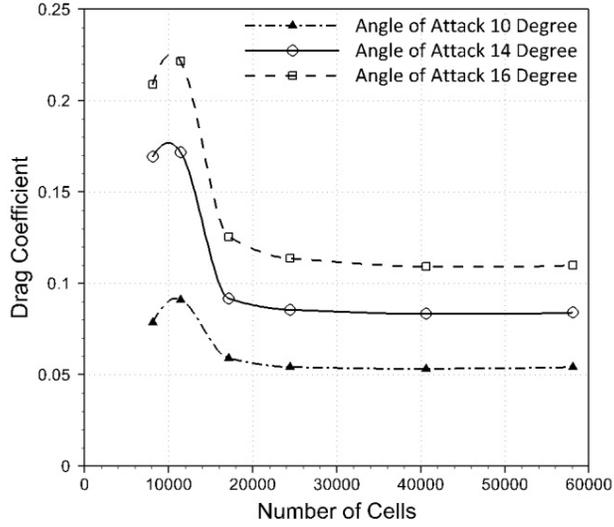


FIGURE 4: Mesh Independency For Drag Coefficient.

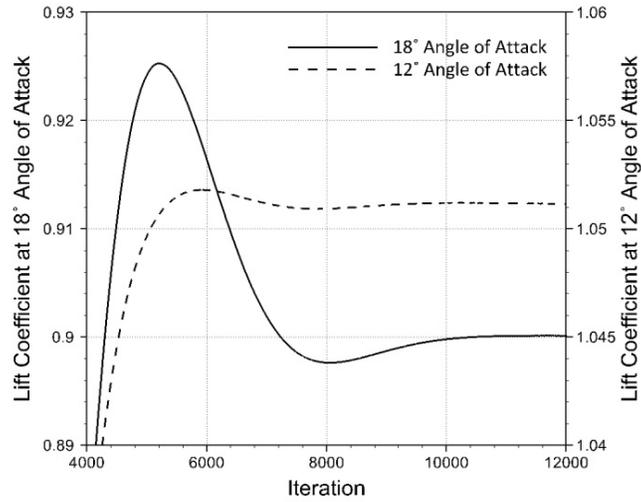


FIGURE 5: Lift Coefficient Convergence.

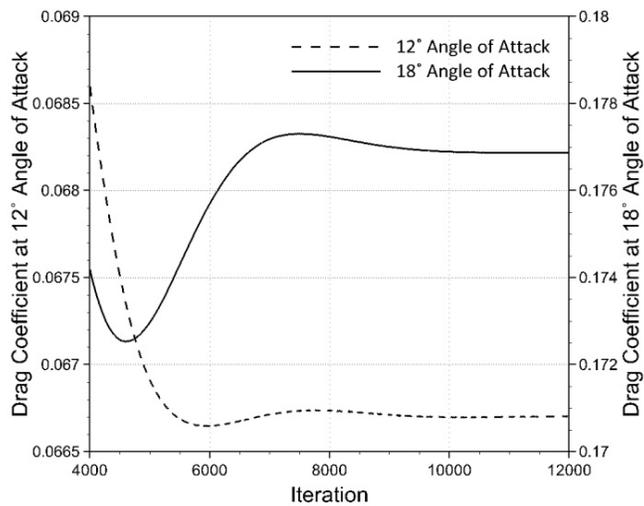


FIGURE 6: Drag Coefficient Convergence.

As demonstrated in Figure 5 and 6, the solutions in all cases, continued until lift and drag coefficient fully converged. Then, the results were compared with the results of numerical solution of Huang et al. [17] and experimental values of Critzos et al. [29] and Jacobs et al [30]. Huang et al. investigated on flow separation control using suction and blowing on NACA 0012 airfoil where the angle of attack and Reynolds number were 18 degree and 5×10^5 , respectively. Parameters like jet location, suction and blowing amplitude and angle of attack were also examined by numerical method. In order to model the suction, a jet with 2.5 percent of the chord length as width was placed on the upper surface of airfoil. The GHOST code, based on finite volume, was used in this study. Critzos et al. examined aerodynamic characteristics of a NACA 0012 airfoil in laboratory experiments where Reynolds numbers were 0.5×10^5 and 1.8×10^6 and the angles of attack changed from 0 to 180 degrees. E. Jacobs et al investigated on a symmetrically NACA airfoils in wind tunnel over a wide range of the Reynolds number. The results of these four solutions are compared in Figure 7. As it is seen, computation results are near the numerical simulation of Huang et al and experimental data of Jacobs et al. The highest recorded error was 8 percent, at 14 degree angle of attack for numerical simulation and 15 percent for experimental data of Jacobs et al. Also stall angle in both method were angle of attack 14 degree. However, the results of laboratory measurements indicated that NACA 0012 airfoil stall occurs at 12 degree angle of attack. We compare our computation results at low angle of attack (less than 10 degree) with the experimental data [29, 30 and 31] in Table 2 (all experimental data at Reynolds number of 5×10^5). It can be seen that most of all the experimental data are higher than computation results. The reason can be attributed to the closer wall effects in experiment which lead to the increase of lift. It also important that turbulence model selection has a significant influence on stall angle changes. So, the selection of $K - \epsilon$ realizable model at the same condition changes the stall angle to 16 degree. Menter's shear stress transport turbulence model always gives better results than $K - \epsilon$ two-equation model. Prediction by $K - \epsilon$ realizable model is quite good in the pre-stall region, while it fails to predict both the stall condition and post-stall phenomena accurately. In the $K - \epsilon$ model, the maximum error at the angle of attack 14 degree for lift coefficient and drag coefficient were 17 percent and 25 percent, respectively. In addition, the results of performed studies showed that although Menter's shear stress transport turbulence model is more suitable model for lower Reynolds number, with larger Reynolds number $K - \epsilon$ model gives more reliable results.

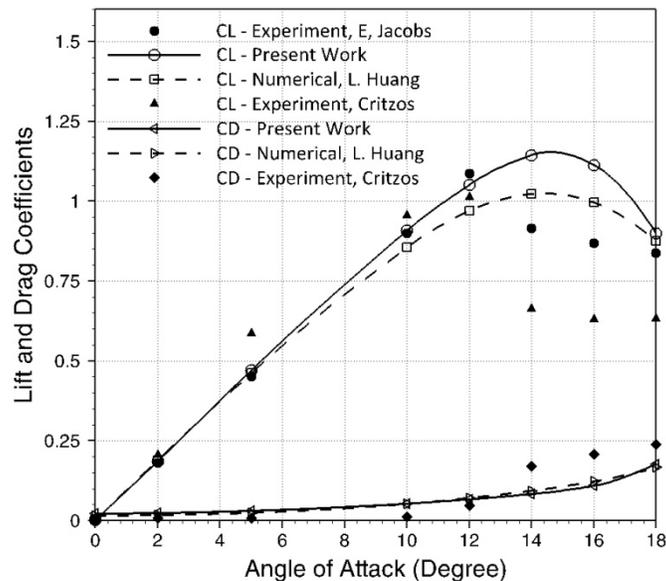


FIGURE 7: Comparison between lift and drag coefficients of present work with Huang et al. [17] numerical work and Critzos et al. [29] and Jacobs et al. [30] experimental results.

Angle of Attack	Computation Results	Experiment Critzos [29]	Experiment Jacobs [30]	Experiment Sheldahl [31]
0°	0.0021	0.0	0.0	0.0
2°	0.1853	0.2053	0.1807	0.22
5°	0.4715	0.5855	0.4511	0.55
10°	0.9087	0.9542	0.9019	1.003

TABLE 2: Comparison of computation results and experimental at angles of attack less than 10 degree.

5. RESULTS AND DISCUSSION

In the present study, first we examine tangential blowing at the trailing edge of the airfoil. Blowing slot is placed at the distance of 80 percent of the chord length from leading edge and length of blowing jet (slot) is 3.5 percent of the airfoil chord. The effect of blowing amplitude and blowing coefficient on the lift coefficient, drag coefficient and lift to drag ratio is indicated in figures 8, 9 and 10. In these figures, three blowing amplitude, 0.1, 0.3 and 0.5 with blowing coefficients of 0.00035, 0.00315 and 0.00875 are considered. By increasing blowing coefficient, lift coefficient increases a little and drag coefficient grows to 16 degree and then decreases, generally tangential blowing at the trailing edge of the airfoil increases the drag force. The effect of tangential blowing on lift and drag coefficients in angles of attack less than 10 degrees is so inconsiderable that by blowing coefficient of 0.00875 lift and drag coefficients increase only 0.5 and 5 percent respectively, but lift to drag ratio decreases about 5 percent which is unfavorable. In angles of attack less than 14 degrees (stall angle), tangential blowing causes reduction in lift to drag ratio and in angles of attack larger than 14 degrees it causes increasing. Because of this we focus on blowing effects on large angles of attack. Greatest increase of lift to drag ratio occurs in blowing coefficient of 0.00875 which increases around 16.5 percent in angle of attack of 18 degrees that in this situation lift coefficient increase by 7 percent and drag coefficient decrease by 9 percent. A considerable note about tangential steady blowing at the trailing edge of airfoil is that changes of amplitude of blowing and of blowing coefficient have very little effect on aerodynamic characteristics of NACA 0012 airfoil and increases of blowing amplitude from 0.1 to 0.3 and 0.5 cause changes less than 0.1 percent in lift and drag coefficient. This is also shown by Huang et al. [17] in tangential steady blowing near leading edge and in distance of 0.371 of chord length from leading edge. As we give energy to boundary layer by using tangential blowing, so contrary to suction [17 and 32], in blowing by increasing blowing coefficient changes of lift and drag coefficients and lift to drag ratio are almost stable.

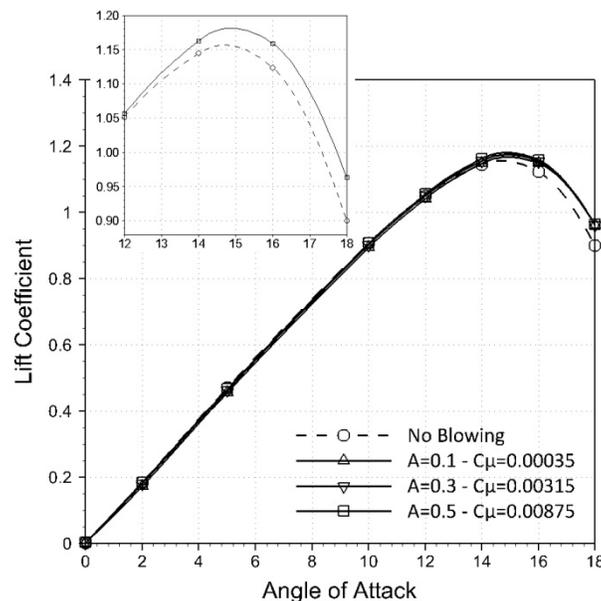


FIGURE 8: Effect of Blowing Amplitude and Blowing Coefficient On Lift Coefficient For Tangential Blowing.

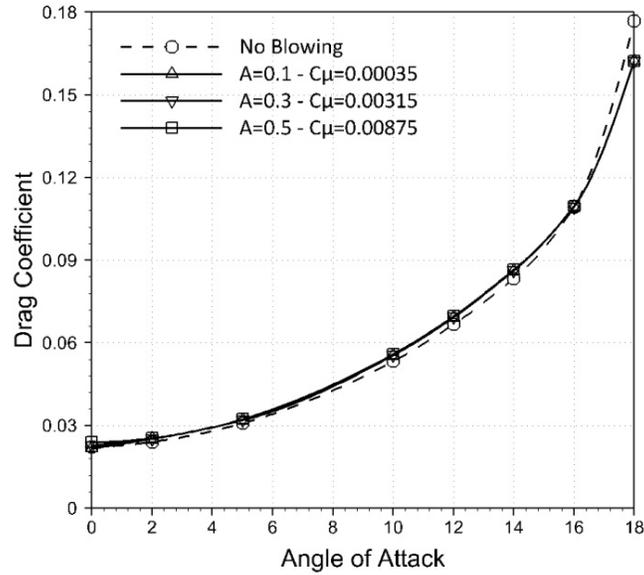


FIGURE 9: Effect of Blowing Amplitude and Blowing Coefficient Blowing On Drag For Tangential Blowing.

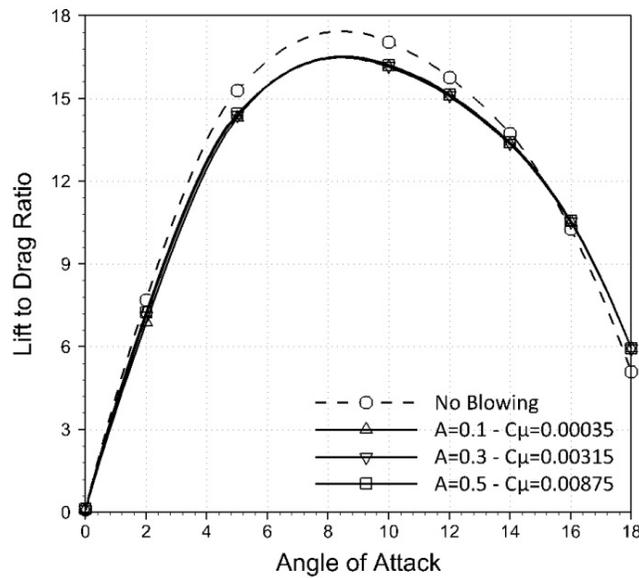


FIGURE 10: Effect of Blowing Amplitude and Blowing Coefficient On Lift To Drag Ratio For Tangential Blowing.

Another considerable note in tangential blowing is that by increasing blowing coefficient stall angle has no change and stall occur at the same angle of 14 degrees. In the airfoils it is tried to prevent sudden changes of lift coefficient after stall or sudden stall itself. Generally, airfoils with thickness of 6 to 10 percent of chord length have sudden stall and those with thickness of more than 14 percent of chord length have a gradual stall [33, 34 and 35]. Using tangential blowing results in 9 percent slower stall, however, experimental investigations show that NACA 0012 airfoil has a sudden stall [29, 30 and 31]. In our studies, lift coefficient during no-blowing situation after stall has about 10 percent decreases (lift coefficient difference percentage between angles of attack of 14 and 16 degrees), by using tangential blowing, lift coefficient has declined less than 0.4 percent. So by using steady tangent blowing as well as increasing lift to drag ratio by 16.5 percent, stall is also happening slower. On the other hand, it should be noted that by using tangential blowing separation is delayed on the airfoil. When there is no tangent blowing on the

airfoil, at the angle of attack 18 degrees, separation occurs in a distance equals to 0.103 of chord length from leading edge while by using blowing coefficient of 0.00875 separations occur in distance of 0.152 of chord length from leading edge. Streamlines around the airfoil with angle of attack 18 degrees for different blowing coefficient are shown in figure 11. As it can be seen by increasing blowing coefficient or blowing amplitude, vortices formed at the back of airfoil are decreased but not eliminated.

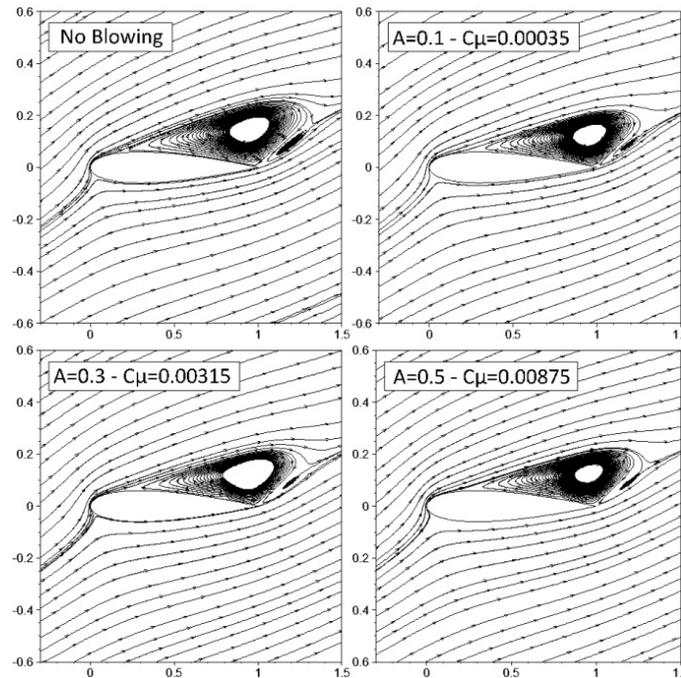


FIGURE 11: Streamlines around the airfoil with angle of attack of 18 degrees and different blowing coefficient for tangential blowing.

Thereafter we study the effect of blowing amplitude and blowing coefficient on lift and drag coefficients for perpendicular steady blowing (perpendicular blowing) at the trailing edge of NACA 0012 airfoil. Lift and drag coefficient changes and lift to drag ratio changes with angles of attack in blowing amplitudes of 0.1, 0.3 and .05 are shown in figures 12, 13 and 14. In perpendicular blowing, contrary to tangential blowing, the increase of amplitude and/or blowing coefficient make the condition worse so that using blowing amplitude of 0.1 in angle of attack 14 degrees decreases lift to drag ratio by 6.5 percent and using blowing amplitude of 0.5 decreases lift to drag ratio by 17 percent. Generally, using perpendicular blowing makes the situation worse, before stall angle perpendicular blowing decrease lift to drag ratio intensively and after stall and in angle of attack of 18 degrees cause 25 percent increase in lift to drag ratio. Blowing increase the boundary layer momentum [36] and turbulence is increased by the energy added to the boundary layer by perpendicular blowing, so the more blowing amplitude or blowing coefficient increases, the larger are the turbulence of flow and vortex and eventually the more lift to drag ratio decreases. In figure 15 tangential and perpendicular steady blowing in angles of attack 16 and 18 degrees and blowing amplitude of 0.5 are compared. As it can be seen, perpendicular blowing at the trailing edge of airfoil causes larger vortices. There is two substantial points in controlling the flow separation in perpendicular blowing at the end of the airfoil, first by using perpendicular blowing stall angle changes from 14 to 16 degrees, and second by increasing angle of attack influence percent of perpendicular blowing goes up and even in angle of attack 18 degrees results in 25 percent increase of lift to drag ratio. Changes of lift to drag ratio with blowing amplitude of 0.1 compared to no blowing status are shown in table 3.

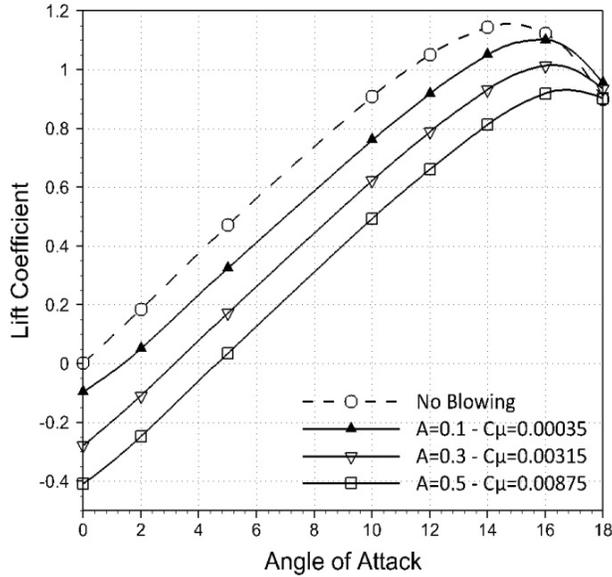


FIGURE 12: Effect of Blowing Amplitude and Blowing Coefficient On Lift Coefficient For Perpendicular Blowing.

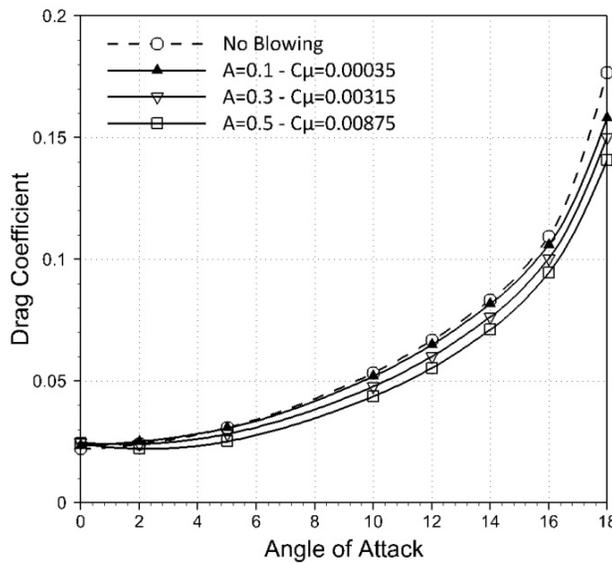


FIGURE 13: Effect of Blowing Amplitude and Blowing Coefficient On Drag Coefficient For Perpendicular Blowing.

Angle of Attack	Lift Coefficient	Drag Coefficient	Percent of Lift to Drag Ratio Increase/Decrease
10°	0.76067	0.05197	16.5 percent decrease
12°	0.91897	0.06488	11.2 percent decrease
14°	1.05061	0.08167	6.71 percent decrease
16°	1.10173	0.10589	1.23 percent decrease
18°	0.95459	0.15812	18.6 percent increase
20°	0.68146	0.27497	3.31 percent increase

TABLE 3: Changes of lift to drag ratio with blowing amplitude of 0.1 compared to no blowing situations in different angles of attack.

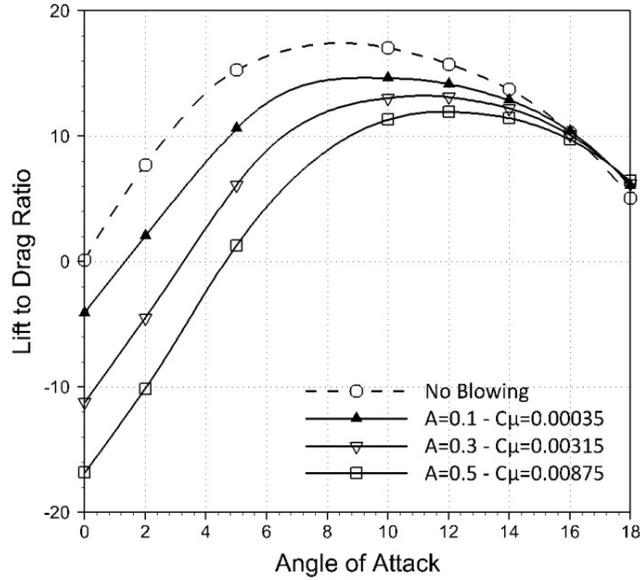


FIGURE 14: Effect of Blowing Amplitude and Blowing Coefficient On Lift To Drag Ratio For Perpendicular Blowing.

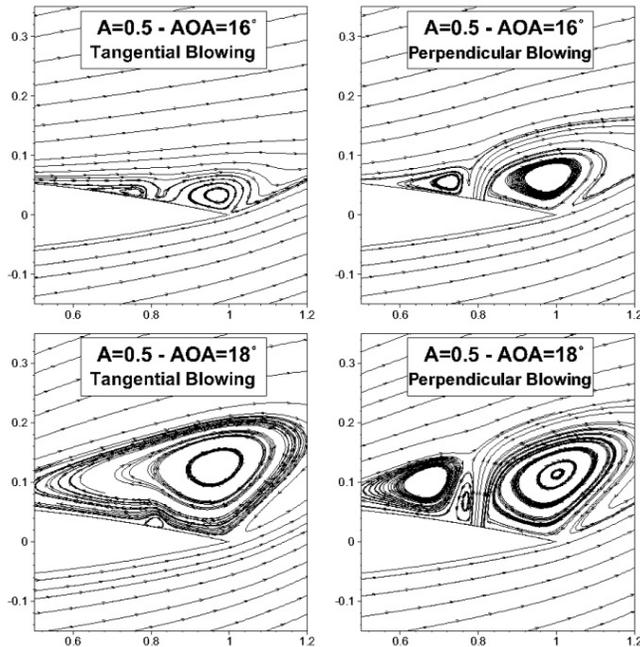


FIGURE 15: Comparing Tangential and Perpendicular Steady Blowing.

6. CONCLUSION

In this study the effects of tangential and perpendicular steady blowing on NACA 0012 airfoil are examined and analyzed to flow separation control. To do this the effect of changing parameters of blowing amplitude and blowing coefficient are modeled numerically and following results are gained. In tangential blowing by increasing blowing amplitude lift to drag ratio grows and separation point is transferred downstream, while increasing blowing amplitude makes situation worse in perpendicular blowing and causes larger vortexes. In other words, in perpendicular blowing smaller value of blowing amplitude or blowing coefficient are more appropriate. In

tangential blowing greatest increase of lift to drag ratio occur in blowing amplitude of 0.5 and blowing coefficient of 0.00875 which in this situation and with angle of attack 18 degrees, airfoil back vortexes are declined. On the other hand, using perpendicular blowing makes situation worse than no blowing status. Results showed that in small angles of attack flow separation control by using blowing has no favorable effect on aerodynamics characteristics. Also using tangential blowing on airfoil causes no change in airfoil stall angle but results show slower stall, but perpendicular blowing changes airfoil stall angle from 14 to 16 degrees.

Also, in this numerical simulation the maximum lift coefficient increase by 7 percent and lift to drag ratio increase by 16.5 percent for tangential blowing, in blowing coefficient of 0.00875, blowing amplitude of 0.5 and 18 degree angle of attack. Perpendicular blowing was useful just for angles of attack larger than stall angle, in the situation of blowing coefficient of 0.00875, blowing amplitude of 0.5 and 18 degree angle of attack, lift to drag ratio increase by 18.5 percent.

7. FUTURE RESEARCH DIRECTIONS

Although several studies have been carried out experimentally and numerically on suction and blowing on the airfoil, some important suction and blowing parameters like the number of suction and blowing slots, slot arrangements, slots entrance or exit angle, oscillatory suction and blowing and also synthetic jet parameters have been not fully examined. Laboratory studies on suction and blowing parameters are limited and the majority of previous investigations have been performed on the streams with low Reynolds numbers. Therefore, future studies could be concentrated on flows with high Reynolds numbers.

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