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Numerical Investigation of Improved Aerodynamic Performance of a NACA 0015 Airfoil Using Synthetic Jet

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Abstract**—**Numerical investigations are performed to analyze the flow behavior over NACA0015 and to evaluate the efficiency of synthetic jet as active control device. The second objective of this work is to investigate the influence of momentum coefficient of synthetic jet on the flow behaviour. The unsteady Reynolds-averaged Navier-Stokes equations of the turbulent flow are solved using, k-ω SST provided by ANSYS CFX-CFD code. The model presented in this paper is a comprehensive representation of the information found in the literature. Comparison of obtained numerical flow parameters with the experimental ones shows that the adopted computational procedure reflects nearly the real flow nature. Also, numerical results state that use of synthetic jets devices has positive effects on the flow separation, and thus, aerodynamic performance improvement of NACA0015 airfoil. It can also be observed that the use of synthetic jet increases the lift coefficient about 13.3% and reduces the drag coefficient about 52.7%.

Keywords**—**Active control, CFD, NACA airfoil, synthetic jet.

I. Introduction

THE active and passive controls are two different methods that were used to improve the airfoil performance. The active control using synthetic jet takes great importance. Many researchers are carrying out studies of the effectiveness of synthetic jet on separation over airfoils under different flow conditions. Among them, [1]-[5] have studied the effect of active control on boundary layer separation, pressure coefficients, and lift and drag coefficients. Buchmann et al. [6] investigated the spatio-temporal flow structure associated with zero-net-mass-flux (ZNMF) jet forcing at the leading edge of a NACA-0015 airfoil (Re = 3x104). Measurements indicated a 45% increase in lift over the unforced case. Tuck and Soria [7] conducted an experimental study on active flow control over a NACA 0015 Airfoil using a ZNMF Jet. The largest lift increases were observed when a non-dimensional frequency of 1.3 and an oscillatory momentum blowing coefficient of 0.14% were employed. Hui Tang et al. [8] conducted a study to improve the aerodynamic performance using a new design of synthetic jet arrays. Their experimental measurements showed that the synthetic jet arrays are able to retard the flow separation which increases the lift coefficient by 27.4% and reduces the drag coefficient about 19%.

Several numerical studies reported the synthetic jet flow behavior and their effectiveness to control laminar and turbulent boundary layer. Guoqing and Qijun [9] have performed numerical investigation on the effects of synthetic jet control on separation and stall over rotor airfoils, in which the results indicate that the jet control efficiency is influenced by the synthetic jet locations, frequencies, and blowing directions. The improvement is saved when the synthetic jet is placed close to the separation point with great values of frequencies and a jet angles (40° or 75°). The best enhancement of aerodynamic performance is found by use of synthetic jet arrays. It is found that the lift coefficient is increased by 100%. Results obtained by Seifert et al. [10] affirmed that the synthetic jet is more efficient when it is located close to the flow separation location.

Esmaeili et al. [11] showed that a tangential synthetic jet can improve the aerodynamic performance of a NACA23012 airfoil, taking into account an oscillating frequency (Fj+=0.159 and 1), a blowing ratio (Vj/U∞), included between (0 to 5) and a synthetic jet orientation of an angle (αj), included between (0° to 83°). It was concluded that the lift and drag ratios (Cl, Cd) increase with the increase of the blowing ratio. Kianoosh and Reza [12] have studied the effects of slot distributions (center suction and tip suction) on the roof of NACA 0015 airfoil for several jet lengths (0.25 to 2) of the chord length. They have concluded that the center suction is more efficient to improve the aerodynamic performance of airfoil, and the lift and drag ratios increase with increasing the suction jet length. Recently, Giorgi et al. [13] conducted a comparison study on active flow control using continuous jet and synthetic jet. From their results, the active flow control on a NACA 0015 airfoil with synthetic jet performs better than that of continuous jet, whereas the total pressure is reduced by twice for the synthetic jet as compared to continuous jet.

The aim of the present work is to analyze the flow behaviour over NACA 0015 and to evaluate the efficiency of synthetic jet as an active control device to improve aerodynamic performance of airfoil NACA 0015.

II. Numerical Procedure

A. Geometry and Computational Grid

The problem treated is active control flow around NACA0015, which was the same configuration of the experimental work realized by Gilarranz et al. [1]. The

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geometry and detailed dimensions and orientation are shown in Fig. 1. Based on the free stream velocity and the airfoil chord (c=0.375 m), the flow Reynolds number of the problem treated is 896,000. As shown in Fig. 1, the jet flow was inclined with respect to the airfoil surface (αjet= 30°). The imposed boundary condition that describes the velocity USJ of the jet at the exit of the actuator's is given by:

$$U_{sj}(t) = U_{max}.\sin(2.\pi.f.t)$$

where U_{max} is the velocity amplitude and f is the oscillation frequency of the membrane. In our study, the frequency is stated as $f = 1.2U_\infty/C$ which corresponds to 120 Hz. The strength of the synthetic jet is determined using its momentum coefficient, which defined as the ratio between the momentum of synthetic jet and that of free jet:

$$C_\mu = \frac{n\bar{I}_j}{\frac{1}{2}\rho U_{cj}^2 D^2}$$

where $\bar{I}_{sj}$ is the time-averaged synthetic jet momentum that is generated during the out-stroke and averaging over the entire period, as presented in:

$$\bar{I}_{sj} = \frac{1}{T}\rho d_{sj}\int_0^\pi U_{sj}^2(t)dt$$

The governing equations for heat and fluid flow were solved for sets of momentum coefficients and for different jet locations. The time step is based on membrane oscillation frequency for 360 time steps per cycle, $\Delta t = \frac{1/f}{360}$

The airfoil NACA0015 and external domain were constructed and meshed by using ICEM 14.0. In this case, we chose the hexahedral mesh with multi blocks. The mesh is refined in areas of high gradient as presented in Fig. 1.

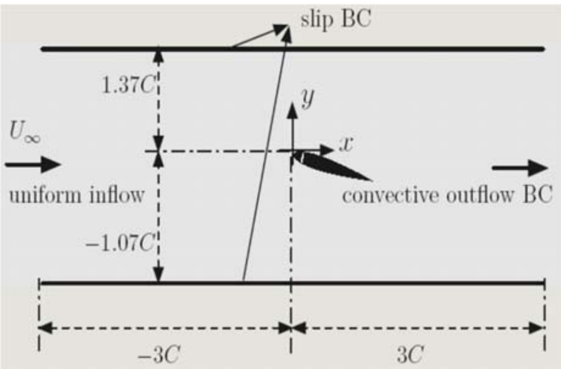

Fig. 1 Computational domain [4]

B. Turbulence Modeling

In the present study, a numerical investigation of active control around airfoil NACA0015 has been performed. Turbulent quantities in the Navier-Stokes equations are treated by using k-ω-Shear Stress Transport (SST) model [15]. To reduce the computing time, the flow computing domain is considered to be two dimensional, and the fluid is incompressible, unsteady, and turbulent in nature. The fluid is Newtonian with constant density ρ and dynamic viscosity μ. The Reynolds Averaged Navier–Stokes (RANS) equations can be written as:

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial\rho u_i}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = \frac{\partial\tau_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} \quad (2)$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial(\rho u_j E)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\tau_{ij}u_i\right) \quad (3)$$

Investigation of the flow turbulence quantities was conducted by using the well-known SST model. The latter has a robust and reasonably accurate and it has many sub models for compressibility, buoyancy and combustion.

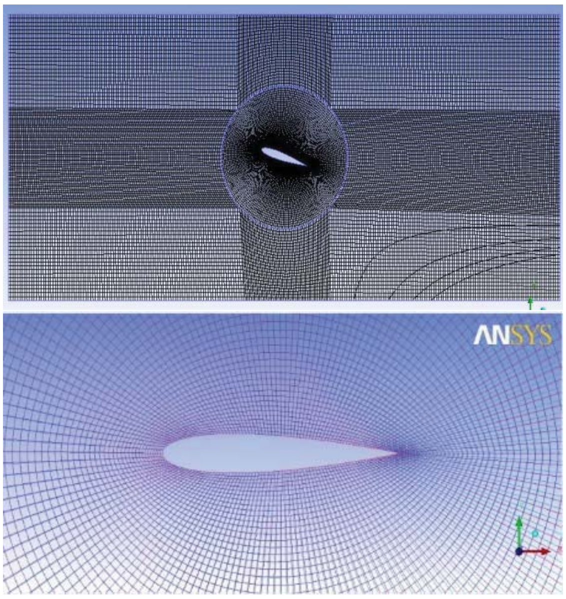

Fig. 2 Mesh generation in computational domain

This model is known to provide a good compromise by combining the k-ω model of Wilcox in the near wall region and the high Reynolds k-ε model in the outer region.

To build the SST model, the Wilcox model is multiplied by a blending function F_1 and a transformed version of the k-ε model by a function ($1 - F_1$). F_1 is equal to one near the solid walls and decreases to a value of zero outside the boundary layer [14]. At the boundary layer edge and outside the boundary layer, the standard k-ε model is therefore recovered. Then, the corresponding k and ω equations are added to give the new model formula given by (4) and (5).

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

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho U_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t}P - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad (5)$$

The φ coefficients of k-ω SST model are presented in the following form:

$$\varphi = F_1\varphi_1 + (1 - F_1)\varphi_2$$

The constants of SST model are mentioned below:

$$\beta_1 = 0.07,\ \beta_1^* = 0.09,\ \sigma_{k1} = 2,\ \sigma_{\omega 1} = 2,\ \alpha_1 = 5/9$$
$$\beta_2 = 0.0828,\ \beta_2^* = 0.09,\ \sigma_{k2} = 1,\ \sigma_{\omega 2} = 1/0.856,\ \alpha_2 = 0.44$$

The eddy-viscosity for this model is given by:

$$\nu_t = \rho\frac{a_1 k}{max(a_1\omega, SF_2)}$$

III. Results and Discussion

Computational model is tested for one configuration of uncontrolled airfoil with angle of attack equal 16.6°. Comparison of computational results with those obtained experimentally by [1] is illustrated in Fig. 3. As shown in this figure, the pressure coefficient computed agrees well with the experimental values. So, the stall angle of attack and pressure coefficient are well simulated.

Pressure distribution is plotted in Fig. 4 at four selected angles of attack of 0°, 12°, 18°, and 30° and for the controlled flow case. The effect of the blowing and suction phenomenon on the extrados of the airfoil is clearly seen. As can be observed, the use of synthetic jet modifies the pressure coefficient area, and this pressure distribution leads to improve the aerodynamic performance of the NACA0015.

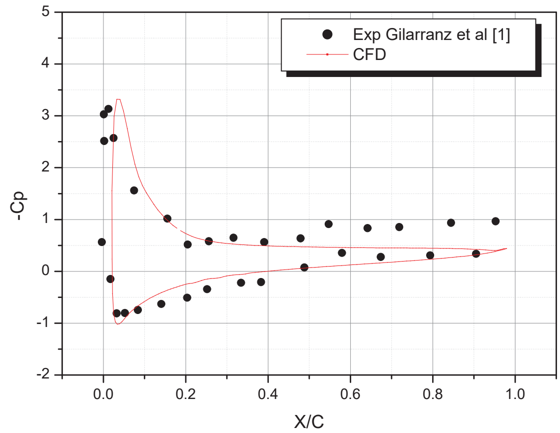

Fig. 3 Comparison between CFD results and experimental data

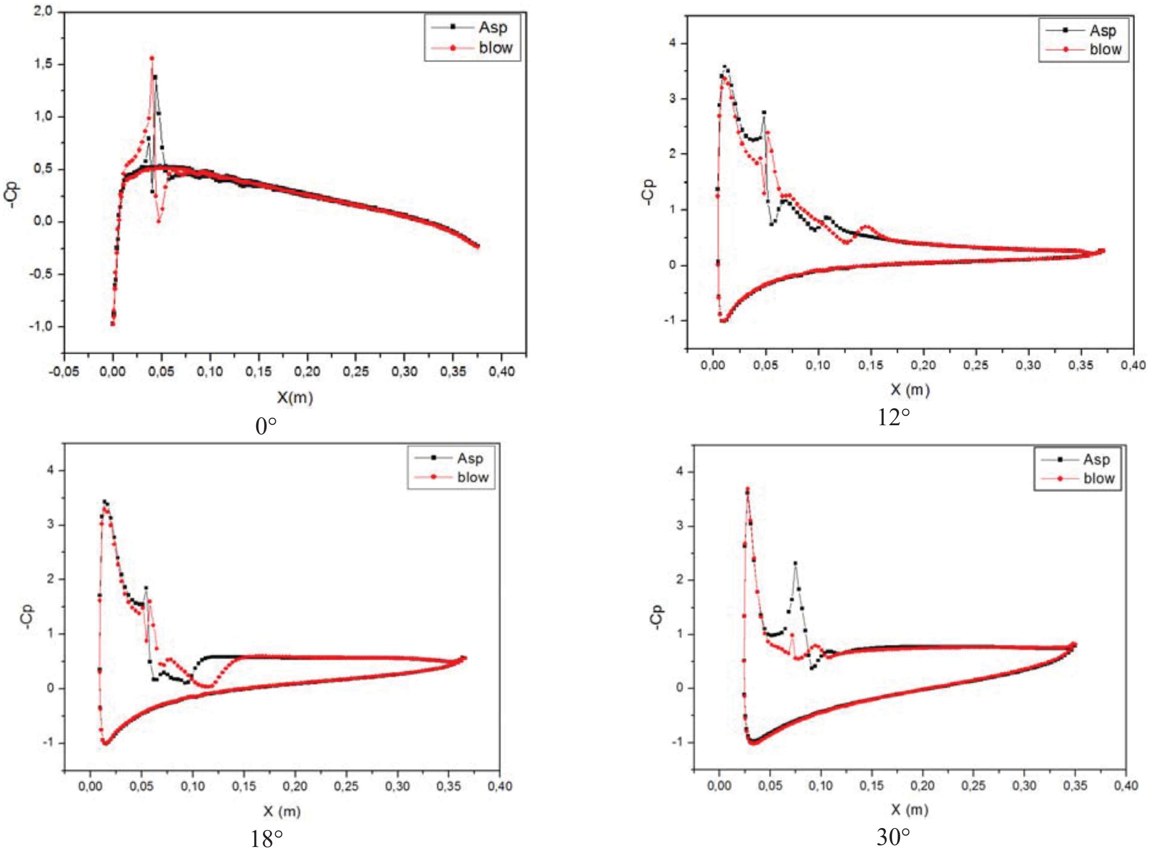

Fig. 4 Comparison of pressure coefficient, the blowing and suction phenomenon

In order to explore the effect of the jet momentum coefficient on the airflow distribution over NACA 0015 airfoil, three momentum coefficients ($0.07*10^{-2}$, $0.3*10^{-2}$ and $1.22*10^{-2}$), are examined for one synthetic jet position (12% of the chord). Fig. 5 presents an instantaneous image of the velocity around airfoil at angle of attack 16.6°, in which each column represents a certain time evolution (t_0+nT, with T=1/frequency and n is the cycle number), while each row shows different momentum coefficient. The synthetic jet effect on the flow behavior is clearly seen comparing with the uncontrolled airfoil. By the end of the third cycle (t0+3T) and for Cμ=$1.22*10^{-2}$, the vortex has been separated from the airfoil and displaced downstream, contrary to the lowest momentum coefficient (Cμ=$0.07*10^{-2}$, Cμ=$0.0.3*10^{-2}$).

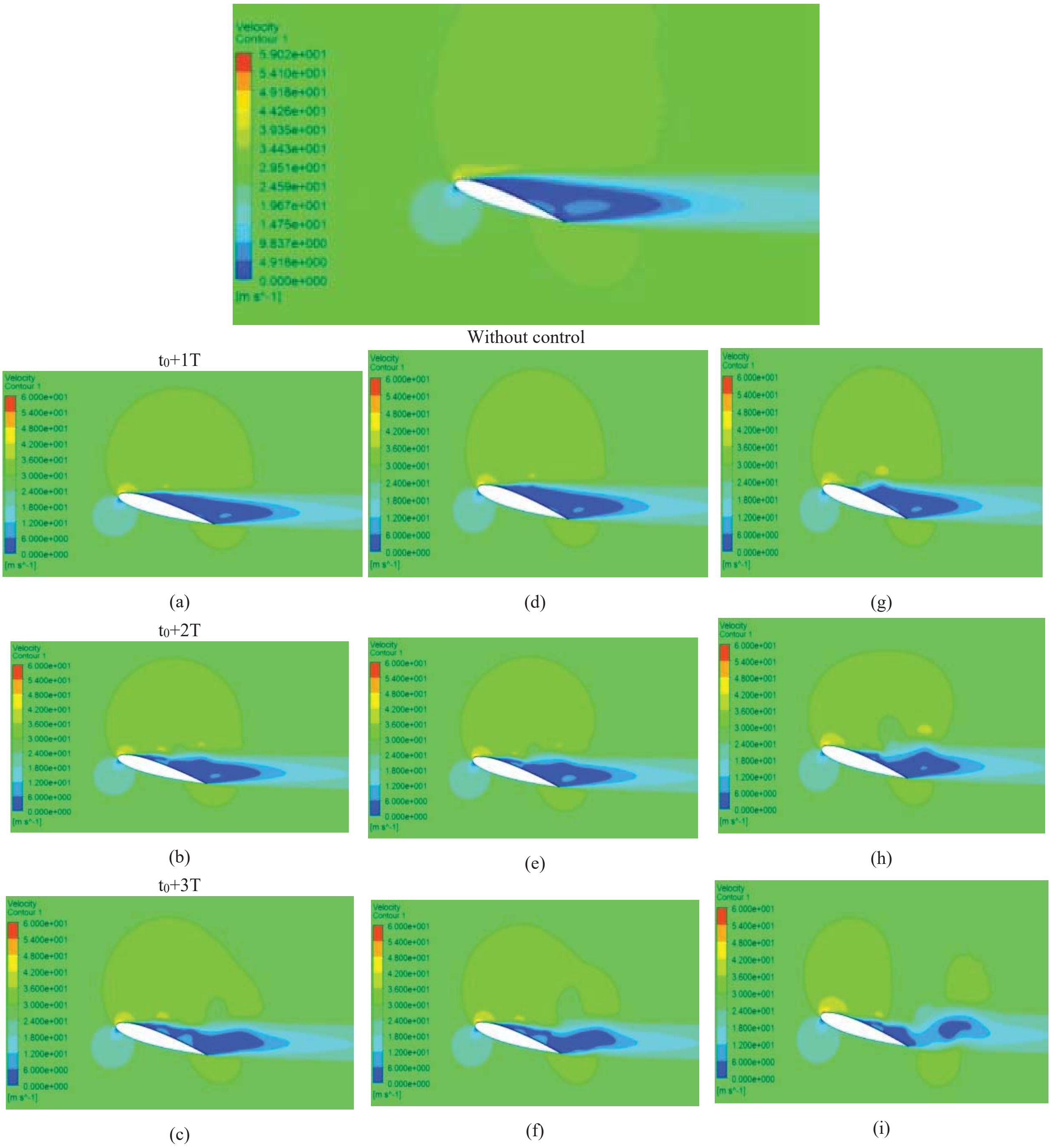

Fig. 5 Velocity contours at different Cycle, at α=16.6°, for Cμ=0.07*10-2 (a)-(c), Cμ=0.0.3*10-2 and (d)-(f) Cμ=1.22*10-2 (g)-(i)

Ranges of incidence angle between [0°, 30°] with increment of 2 degree are examined on CFD to determine the lift and drag coefficients. Each case was simulated with the same Reynolds number (896,000) to collect the maximum information as presented in Fig. 6. Increasing the angle of attack increases lift, and it also increases drag, which is an inconvenient outcome. The active control using the synthetic jet is used in this study to enhance aerodynamic characteristics of a NACA 0015 airfoil and thus to increase the lift coefficient and to reduce the drag coefficient as presented in Figs. 6 and 7.

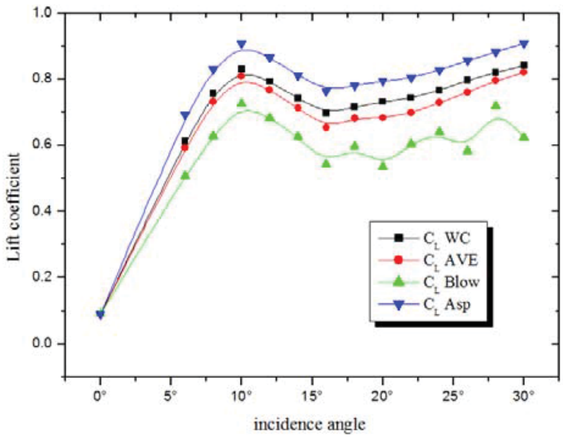

Fig. 6 Comparison of lift coefficient

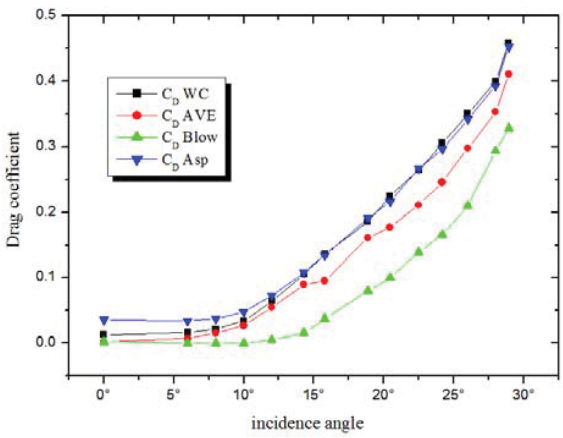

Fig. 7 Comparison of drag coefficient

IV. Conclusion

In this paper, models with and without control were created and validated to show how the boundary layer of an airfoil is modified with angle of attack (α) and to analyze the active flow control over a NACA 0015 airfoil using synthetic jet. The results confirm that the synthetic jet has an important effect on the flow separation and thus to improve the aerodynamic performance of NACA0015 airfoil.

Effects of three momentum coefficients ($C\mu=0.07*10^{-2}$, $C\mu=0.0.3*10^{-2}$, and $C\mu=1.22*10^{-2}$) are examined. It is only for the value of $1.22*10^{-2}$ that the synthetic jet has effects on the flow separation.

The main conclusion of this study is that the use of synthetic jet can increase the lift coefficient about 13.3% and reduces the drag coefficient about 52.7% above the uncontrolled flow.

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