International Journal of Natural and Engineering Sciences 8 (3): 52-57, 2014
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Improving the Aerodynamic Performance of a Wing with Winglet

Zabihollah NAJAFIAN ASHRAFI[1*] Ahmad SEDAGHAT[2]
[1] Department of Mechanical Engineering, University of Tehran, Tehran, Iran
[2] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran

*Corresponding author:
Email: z_najafian@ut.ac.ir

Received: October 12, 2014
Accepted: November 23, 2014

Abstract

In this paper, a wing has been investigated in two cases of with and without winglet. Two types of simple and semi-circular winglet were considered. A numerical simulation based on Control Volume Method was conducted to study the effect of utilization of a winglet on a rectangular wing with NACA 65_3-218 cross sectional airfoil. The wing consists of 330 mm span and 121 mm chord length. A comparison was made on aerodynamic features such as lift coefficient, drag coefficient, lift/drag ratio and tip vortices. It is observed that the addition of the simple and semi-circular winglet with cant angle of 45 degree gives a greater lift coefficient and higher lift/drag ratio in comparison to the baseline wing alone. Semi-circular winglet is the best design candidate here giving about 13.67 percent increase in lift coefficient and 8.9 percent reduction in drag coefficient at 8 degree angle of attack.

Keywords: tip vortex, winglet, wing, CFD, Control Volume Method.

INTRODUCTION

A winglet is a vertical or angled extension at the tips of each wing. Winglets increase the effective aspect ratio of a wing without adding greatly to the structural stress and hence the weight of its structure. It has been a long time that engineers are seeking for ways to reduce fuel consumption of the aircrafts. One way of achieving this goal is utilization of wingtip devices. Wingtip devices are served for enhancing the efficiency of aircraft.

The winglet test program conducted at Dryden in 1979-80 followed several years of wind tunnel tests and analytical studies by Whitcomb at NASA Langley [1]. Whitcomb had studied the original winglet concept developed by British aerodynamicist F.W. Lancaster in the late 1800s. Whitcomb took that concept by making the vertical surface a refined airfoil that reduces drag by interacting with the wingtip airflow circulation and vortex. Studies at Langley also included tests of a DC-10 model in a wind tunnel that showed that the winglets on the model reduced overall drag by 5% compared to the model without the devices. These tests were followed by a Boeing engineering study of a 747 with winglets, and a prediction that a 4% drag reduction would result. These positive conclusions, coupled with Whitcomb's work, prompted the U.S. Air Force to consider the possible installation of winglets on KC-135 and C-141 transport aircraft. The winglet flight test program brought together NASA, the U.S. Air Force, and Boeing, which began the effort with configuration studies and contractual work to design and manufacture the test articles, which measured 9 feet high and 6 feet across at the base. Wind tunnel results predicted a 6% drag reduction on the winglet-equipped test aircraft [2].

Winglets have many applications in the aviation industry [3-9]. Mattos et al. [10] studied the design of winglets. They investigated different aspects of winglet designs. They showed that using winglet is becoming a necessitate issue in the aircraft market. Hossain et al. [11, 12] analyzed the drag of an aircraft wing model in two cases of with and without winglet. They used NACA 65_3-218 rectangular wing. Their experimental study for the aerodynamic features of the model has been done. Three different values of Reynolds numbers have been used. It was concluded that using winglet leads to an increase in lift coefficient and a decrease in drag coefficient for all angles of attack.

Recently, many researchers have studied the formation of vortices behind the wing [13-17]. Voevodin [18] studied the effect of winglets on the vortex wake numerically. He divided the wake into three regions of near, intermediate and far flow fields. He compared the results with the case of wing with no winglet.

In this paper, the effect of installation of winglet to the end of the wing has been investigated numerically. To this aim, two types of simple and semi-circular winglet have been considered. The aim is to investigate the effect of utilization of winglet on parameters like lift and drag coefficients, lift/drag ratio and the amount of generated vortices at the end of the wing. The experimental results for the case of wing with no winglet are available. To assure the accuracy of the study our numerical results are compared with those of the experiment.

NUMERICAL METHODS

For the prediction of wing aerodynamics, the Shear Stress Transport (SST) $k-\omega$ model has been chosen to capture the turbulence. The SST model was chosen for accurate boundary layer detection due to its ability to capture the influence of different factors that affect transition such as the free-stream turbulence and pressure gradients. In order to control and reduce the numerical solution errors, the upwind scheme method has been selected.

Governing equations

Mass and momentum conservation equations are written in dimensionless form as follows:

$$\nabla . \mathrm{u} = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + u.\nabla u = -\Delta p + \nabla.\left[\frac{1}{\mathrm{Re}_{eff}}\left(\nabla u + \nabla u^T\right)\right] + S \qquad (2)$$

where u is the fluid velocity and S is a source term, zero in this paper. p is the non-dimensional pressure, Re_{eff} is the effective Reynolds number, defined as:

$$p = \frac{P_{abs}}{\rho U_0^2} + \frac{2}{3}k \qquad (3)$$

$$\mathrm{Re}_{eff} = \frac{U_0\, L}{\nu + \nu_t} \qquad (4)$$

where P_{abs} is the absolute pressure, U_0 and L are the free-stream velocity and characteristic length respectively, ν_t is the turbulent eddy viscosity, and k is the turbulent kinetic energy. It is worth mentioning that the characteristic length is the chord of the airfoil.

Turbulence modeling

The turbulence is modeled using a Shear Stress Transport (SST) $k-\omega$ model [19], in which the turbulent kinetic energy k and specific dissipation rate ω are:

$$\frac{\partial k}{\partial t} + \left(u - \sigma_k \nabla \nu_t\right).\ \nabla k - \frac{1}{P_k}\nabla^2 k + s_k = 0 \qquad (5)$$

$$\frac{\partial \omega}{\partial t} + \left(u - \sigma_\omega \nabla \nu_t\right).\ \nabla \omega - \frac{1}{P_\omega}\nabla^2 \omega + s_\omega = 0 \qquad (6)$$

where the turbulent viscosity and effective Peclet numbers are defined as:

$$\nu_t = \frac{k}{\omega},\ P_k = \frac{1}{\frac{1}{\mathrm{Re}} + \sigma_k \nu_t},\ P_\omega = \frac{1}{\frac{1}{\mathrm{Re}} + \sigma_\omega \nu_t} \qquad (7)$$

In addition, the source terms for k and ω are:

$$s_k = -G + \frac{k^{3/2}}{l_{k-\omega}} \qquad (8)$$

$$s_\omega = -\gamma \frac{\omega}{k} G + \beta^* \omega^2 - 2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\nabla k.\nabla \omega \qquad (9)$$

where the length scale is $l_{k-\omega} = \sqrt{k} / \left(\beta^* \omega\right)$ and the kinetic energy production is $G = \nu_t\ \tau : \nabla u$. There is also $\beta^* = 0.09$, $\sigma_{\omega 2} = 0.856$.

$$F_1 = \tanh\left[\left(\min\left(\max\left(\frac{\sqrt{k}}{0.09\omega\delta}; \frac{1}{\mathrm{Re}}\frac{500}{\delta^2 \omega}\right); \frac{4\sigma_{\omega 2} k}{CD_{k\omega}\delta^2}\right)\right)^4\right] \qquad (10)$$

where δ is the distance to the nearest no slip surface and $CD_{k\omega} = \max(2\sigma_{\omega 2}\frac{1}{\omega}\nabla k.\nabla \omega\ ;\ 10^{-20})$. The SST model then requires wall refinement to satisfy $y^+ \leq 1$.

Numerical processes

Computational domain is composed of the front half of semicircle and the back half of rectangle, which the radius of semicircle is 10 times of the chord length (10*c) and the side length of rectangle was 20*c and 10*c. The wing is located at the center of semicircle, Figure 1.

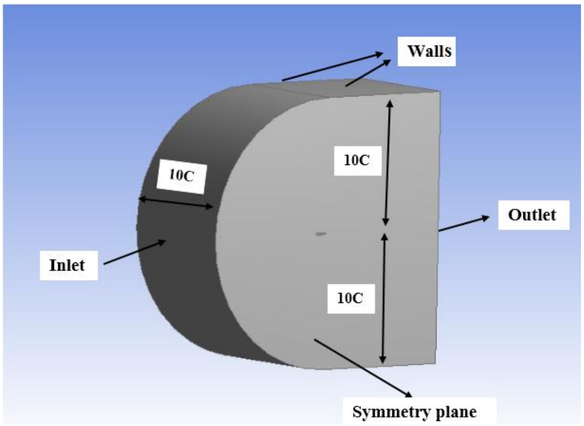


Figure 1. Computational domain

An unstructured grid is applied in the wing domain. Due to the importance of the turbulence model near the wing, the applied grid near the boundary layer is denser. The mesh of the computational domain in symmetry plane is shown in Figure 2.

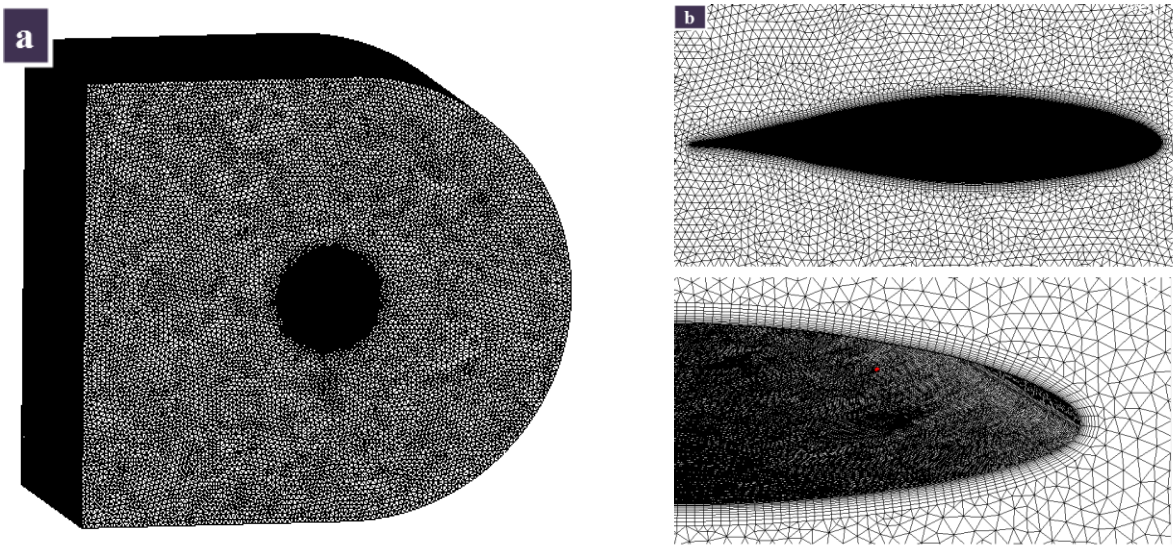


Figure 2. a) The final mesh, b) Part grid of NACA 65_3-218

Moreover, the 3-D boundary of the computational flow domain is dimensioned in the root chord length and placed remotely away from surface to ensure no significant effect on the aerodynamics. The grid independency test shows that the optimized grid is achieved at 2782500 elements. The growing prism inflation layer option has been implemented on fluid–solid boundaries with the first cell above the wall set at $y^+ \leq 1$. The inlet velocity magnitude of 21.36 m/s and 32.15 m/s which equals to Re = 1.7×10^5 and 2.5×10^5 respectively is specified at the inlet. Pressure boundary condition is applied at the outlet. The average static pressure method is used in order to allow pressure to vary locally on the boundary. The angle of attack is varied between 0 to 14 degrees. The walls and wing surface have been set to no-slip-solid wall boundary condition. The turbulence intensity of 5% with automatic wall function is fully employed to solve the viscous flow.

Characteristic of wing

The NACA 65_3-218 airfoil has been used for the structure of wing and winglet. The simple and semi-circular winglet design is depicted in Figure 3.

The aircraft wing model has a span of 0.33 m and a chord of 0.121 m without winglet. Reference area in three cases are calculated and shown in Table 1.

Table 1. Reference area (mm^2) for different case studies

Wing without winglet	Wing with simple winglet	Wing with semi-circular winglet
79860	94380	93589

Lift and drag coefficients are dimensionless numbers used to measure the aerodynamic lift and drag forces that vary with the angle of attack (α) and the shape of the airfoil. They can be defined as follows:

$$C_l = \frac{L}{1/2\rho V^2 A} \quad (11)$$

$$C_d = \frac{D}{1/2\rho V^2 A} \quad (12)$$

where L and D are lift and drag forces suffered by wing, ρ is air density, V is the free stream velocity and A is the reference area of the wing.

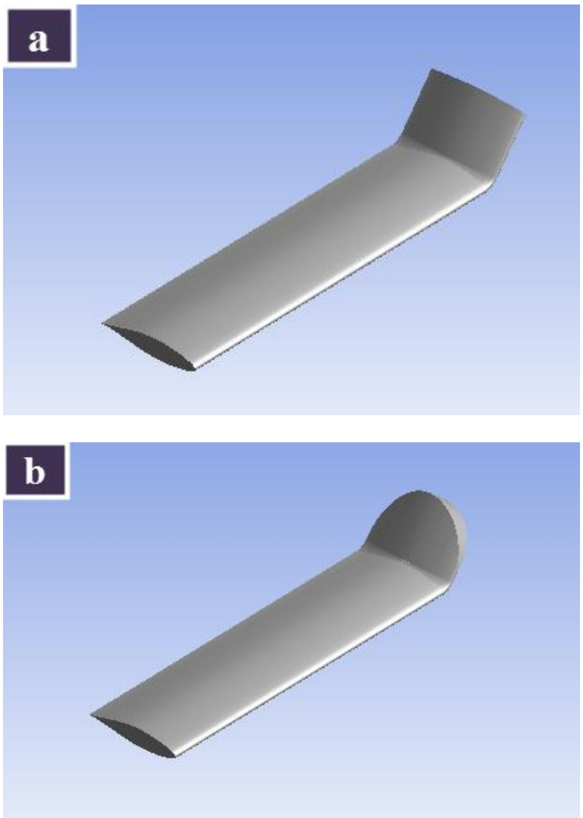


Figure 3. a) Simple, b) Semi-circular winglet with cant angle of 45 degree

Reynolds number defined on the chord length is defined as:

$$Re = \frac{\rho_\infty V c}{\mu_\infty} \quad (13)$$

The air viscosity μ_∞ is determined using the Sutherland's equation [20]:

$$\mu_\infty = 1.458 \times 10^{-6} \frac{T^{1.5}}{T + 110.4} \quad (14)$$

Results validation

The model validation against the previously published experimental results is presented in Figure 4 which shows that the lift and drag coefficient for the present study compared with the results of Hossain et al. [11] are in a good agreement.

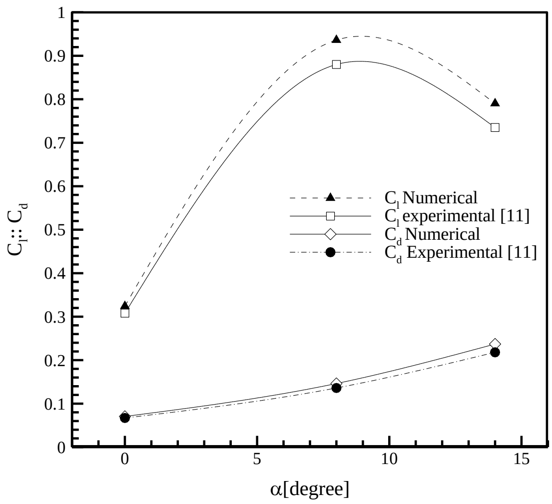


Figure 4. Comparison the lift and drag coefficients of present study with previous results [11]

RESULTS AND DISCUSSION

The results of rectangular wing of NACA 65_3 -218 airfoil in two cases of wing with and without winglet are compared with each other. The aerodynamic characteristics including lift and drag coefficient, lift/drag ratio and tip vortices are studied in this paper. Different values of angles of attack i.e. 0-14 degree as well as two velocities of 21.36 m/s and 32.15 m/s are used in this study.

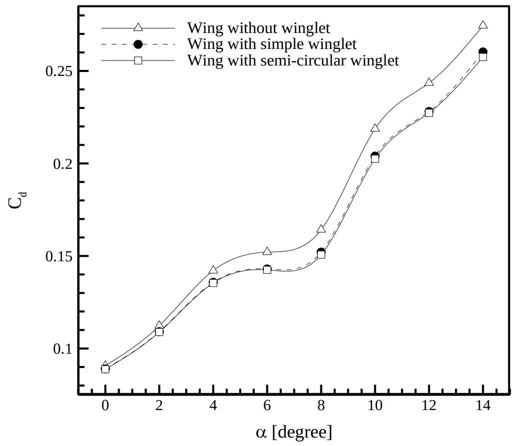
Figure 5 shows the lift coefficient changes with angle of attack for all winglet and rectangular wing models at velocity of 21.36 and 32.15 m/s respectively.

It can be seen that as it is expected in all cases the increase in Reynolds number leads to an increase in lift coefficient. Lift coefficient is increased in 8 degrees angle of attack in comparison with α= 0 but it can be seen that the coefficient reduces for α=14 and it can be justified by the stalling angle which is 12 degree for this airfoil.

The semi-circular winglet with cant angle of 45 degree has highest lift coefficient in comparison with other types of winglets. The simple winglet gives the second highest lift coefficient. Both the semi-circular and simple winglets show an increase in the lift coefficient.

It can be seen from Figure 5b, at constant Reynolds number of 2.5×10^5 and in the case of semi-circular winglet the highest increase in the percentage of the lift coefficient is 13.67 at the angle of attack α=8 among all cases.

a



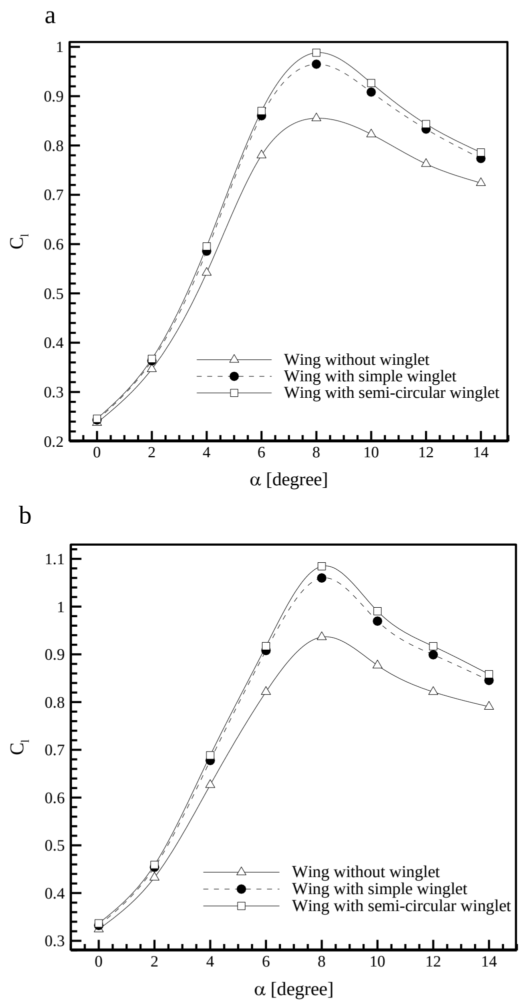


Figure 5. Lift Coefficient versus angle of attack at a) $Re=1.7\times10^5$, b) $Re=2.5\times10^5$.

Figure 6 shows the drag coefficient changes with angle of attack for simple and semi-circular winglets and rectangular wing models at velocity of 21.36 and 32.15 m/s. From Figure 6, it was observed that in all cases the increase in Reynolds number leads to a reduction of drag coefficient. Drag coefficient increases as the angle of attack is increased. It is also observed that the semi-circular winglet has the lowest drag coefficient. Both semi-circular and simple winglets show a decrease in the drag coefficient in comparison with the case of no winglet.

b

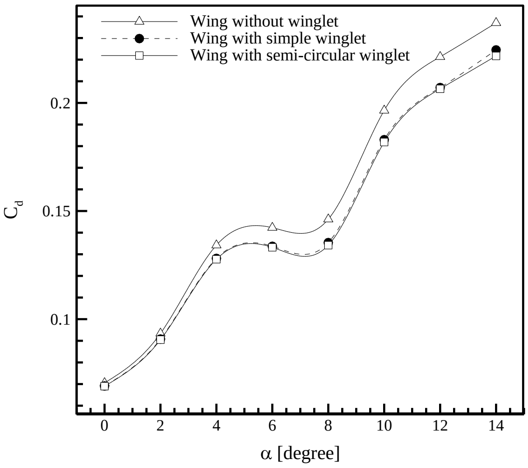
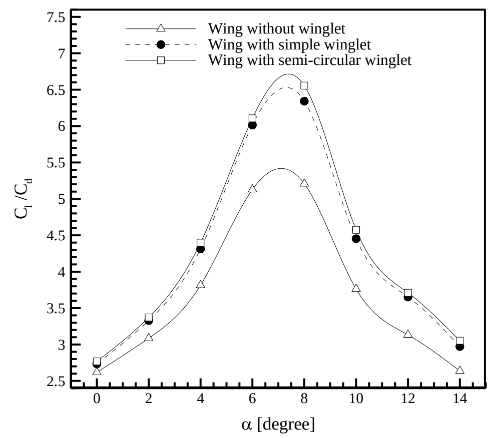


Figure 6. Drag Coefficient versus angle of attack at a) $Re=1.7\times10^5$, b) $Re=2.5\times10^5$

It can be seen from Figure 6b that at constant Reynolds number of 2.5×10^5 and in the case of semi-circular winglet the most value of reduction in the percentage of the drag coefficient is 8.9 at the angle of attack α=8 among all cases.

It was observed from Figure 7 that the lift/drag ratio for all the configurations considered increases with an angle of attack to its maximum value and thereby it decreases with further increase in angle of attack for Reynolds numbers of 1.7×10^5 and 2.5×10^5.

a



b

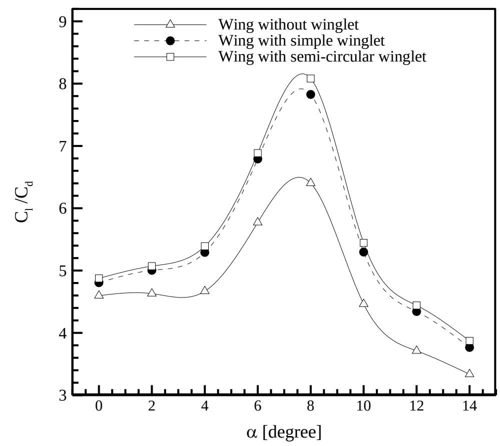


Figure 7. Lift/Drag ratio versus angle of attack at a) $Re=1.7\times10^5$, b) $Re=2.5\times10^5$

All the simple and semi-circular winglets show an increase in lift/drag ratio in comparison with the case of no winglet. It can also be seen that at angle of attack of 8 degree the highest increase in lift/drag percentage equals to 8.08.

Tip vortices

The generation of tip vortices requires energy and one approach to calculate the induced drag is through determining how much energy is contained in the trailing vortex system.

Figure 8 represents the vortices cloud view of flow over the studied winglets at maximum velocity of 32.15 m/s and angle of attack of 8 degree.

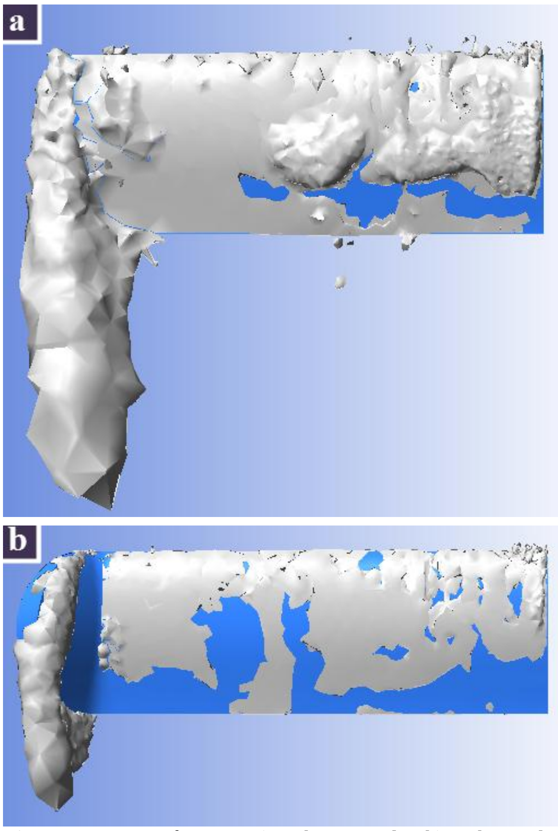


Figure 8a. Vortex for wing a) without winglet, b) with winglet at α = 8°

These vortices are focused at the wingtip where tip vortices occur. The tip vortices become stronger at high angle of attacks particularly when an aircraft takes off or lands.

From the observation, the rectangular wing without winglet produces greater trailing vortices compared to the wing with semi-circular winglet.

CONCLUSION

In this paper, a 3D wing with and without winglet has been studied in two cases of simple and semi-circular winglets using Control Volume Method. By installing the winglets it is observed that lift coefficient value will increase and drag coefficient reduces significantly. Trailing vortices are reduced in comparison with the case of no winglet installed. Regarding to low cost of installation of the winglets and no main change in the structure of the wing, their utilization is recommended. Some of the advantages of installing the winglets are as follows:

- Reduction of wingtip vortices
- Increment of lift coefficient and reduction of drag coefficient
- Higher cruise speed
- Increased fuel economy
- Reduction in noise levels around airports on takeoff

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