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# Numerical Calculation of Wind Tip Vortex Formation for Different Wingtip devices

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**ABSTRACT**

In this study numerical calculations are conducted to understand implementation of different wingtip device for wingtip vortexes formation. Numerical methods are performed over NACA 0012 winglet at the varying Reynolds numbers from $0.5\text{x}10^6$ to $1\text{x}10^6$ with the angle of attack 10° and compared with other study. Implementations of winglet are divided into four categories and these are one winglet up or down sloping, split winglet up and down sloping, and single winglet with two-step inclined. First, up and down sloping winglet are designed and simulated then split winglet are investigated numerically with the varying angle. Finally, winglets with two step inclined angles are investigated. For the up sloping winglet, wingtip vortexes formation is reduced considerably as the angle with wing surface approaches 90 degrees. But vortexes formation is clearly happening at the angle starting less than 90° and beyond 135 degree. For the down sloping, while there is a visible vortex formation below 90 degrees but more uniform flow is observed compared to conventional wing tips at around 90 degrees. For the split winglet configurations, less vortex formation is observed generally compared to other. As a result, single or split winglet up or down sloping perpendicular or wider angle with lateral surface decreases wingtip vortex formations.

**KEYWORDS** : *wingtip device, wingtip, vortexes, fuel efficiency, vortices,*

**NOMENCLATURE**

| | |
|---|---|
| $c_P$ | Pressure coefficient |
| $c_L$ | Lift coefficient |
| $P$ | Static pressure |
| d | Distance to closest wall |
| $P_\infty$ | Free stream pressure |
| $U_r$ | Relative velocity |
| $U_\infty$ | Free stream velocity (wind velocity) |
| $u$ | Velocity field x component |
| $v$ | Velocity field y component |
| $c$ | Airfoil chord length |
| $t$ | Percentage of the maximum thickness |
| $k$ | Turbulence kinetic energy |
| $l_{ref}$ | Reference length scale |
| L | Length scale of flow |
| $\varepsilon$ | Turbulence dissipation rate |
| $\omega$ | Specific dissipation rate |
| $\omega_t$ | Wall vorticity at the trip |
| $\rho$ | Density |
| $\rho_\infty$ | Freestream density |
| $\mu$ | Dynamic viscosity |
| $S$ | Magnitude of the vorticity, |
| $\mu_{eff}$ | Effective dynamic viscosity |
| $\alpha$ | Angle of attack |
| $\emptyset$ | Scalar quantity of the flow |
| NACA | National Advisory Committee for Aeronautics |
| NASA | National Aeronautics and Space Administration |

## 1 PAPER CONTENT

### 1.1. Introduction

Wingtip vortices are circular patterns of air that arise pressure difference between top and bottom surface of the wing. The high-pressured air in the lower surface of the wing moves to upper surface and it rolls up into large vortices near the wingtip. A wingtip vortex, especially during takeoff and landing phases of flight, is important for the safety of other aircraft. Therefore, especially by aircraft manufacturers, a lot of research has been done to reduce wingtip vortex.

Numerical methods were performed over NACA0012 at the Reynolds numbers of $1.2\times10^6$ to visualize evolution of a large vortex formation at a wingtip and obtained results were compared with experimental data to demonstrate the applicability of methods [1]. The primary vortex as well as characteristic jet and pressure distribution on the model wing surface is positively correlated with the experiment. A Reynolds stress relaxation model, in particular a Lag Reynolds stress transport model, was applied to calculate a vortex flow at the wing tips [2] and its performance is evaluated and checked with other aviation standard turbulence models. Investigation shows that Reynolds stress transport turbulence model has the ability to predict average flow results like the Spalart-Allmaras model, which performs well with streamline curvature as well as correction for system rotation. Numerical simulation of wingtip vortices was performed to presents a feasibility of hybrid RANS LES approach [3]. NACA 0012 was considered due to availability of previously published experimental and numerical data. A hybrid RANS LES method was a better deal with the wind tunnel experiment, so this approach was proposed to be recommended for numerical simulation of the wake of an airliner. Two types of winglet used in air transport system were examined thoroughly and compared with each other by using three different CFD simulation models. Numerical results suggest that there were some fundamental differences between these two types of devices on lift-drag rate, induced drag, wing root bending moment, and pitching moment [4]. Numerical calculation was conducted to predict downstream trailing vortex of aircraft wingtip by using linear and non-linear eddy-viscosity models [5]. Study indicates these both shows a very rapid deterioration of the vortex core and only stress transport (or second moment) model satisfies the "two-component limit". High-resolution computational methodology was developed for solving the compressible Reynolds-Averaged Navier-Stokes equations and used to investigate the effect of span-wise blowing as a method of wingtip vortex control [6]. For the vortex evolution problems, the equations were solved on multiple overflow grids to provide sufficient resolution efficiently and a detailed study of underlying physics of span-wise blowing was presented. In other studies, numerical calculations were conducted on Cessna winglet by using NACA2412 [7] and rectangular wing of NACA 653218 [8] airfoil to investigate improvement for aerodynamics characteristics of lift and drag coefficient. Multi-objective optimization process was employed to design winglets [9,10] to improve aerodynamic efficiency of aircraft but there were no studies in which different shapes and number of winglets were comparatively investigated at varying angle.

In this paper, effects of the winglet on the wingtip vortex are investigated numerically and compared with varied configurations. Numerical calculations are conducted by using with the SST turbulence model. The winglets are divided into 5 different categories such as up or down sloping, split single winglet up and down sloping and two step inclined with up or down sloping are designed and investigated numerically with the varying angle with lateral surface. Numerical results are compared with previously made study.

### 1.2. Computational Method

In this calculation SST turbulence model is used. SST (Shear Stress Transport) turbulence model is a widely used in Computational Fluid Dynamics. Shear Stress Transport model was introduced by Menter in 1994 [11] This model combines the k-omega and k-epsilon turbulence model and k-omega is used in the inner region of the boundary layer and changes to the k-epsilon in the free shear flow. Shear Stress Transport model equations are expressed in terms k and ω with Eq.1 and Eq.2 [12-14].

$$\rho\frac{\partial k}{\partial t}+\rho u.\nabla k=P-\rho{\beta_0}^{*}k\omega+\nabla.((\mu+\sigma_k\mu_T)\nabla_k) \qquad (1)$$

$$\rho\frac{\partial \omega}{\partial t}+\rho u.\nabla\omega=\frac{\rho\gamma}{\mu_T}P-\rho\beta\omega^2+\nabla.\left((\mu+\sigma_\omega\mu_T)\nabla_\omega\right)+2(1-f_{v1})\frac{\rho\sigma_{\omega^2}}{\omega}\nabla\omega.\nabla k \qquad (2)$$

Where, P is the static pressure and can be represented with the Eq.3.

$$P=\min(P_k,10\rho{\beta_0}^{*}k\omega) \qquad (3)$$

The turbulent viscosity is represented by Eq.4.

$$\mu_T=\frac{\rho a_1 k}{\max(a_1\omega,Sf_{v2})} \qquad (4)$$

Where, S is the typical magnitude of the average velocity gradients, $f_{v2}$is interpolation functions.

SST default model constants are given by,

$$\beta_1 = 0.075, \gamma_1 = \frac{5}{9}, \sigma_{k1} = 0.85, \sigma_{\omega 1} = 0.5, \beta_2 = 0.0828, \gamma_2 = 0.44, \sigma_{k2} = 1.0, \sigma_{w2} = 0.856, {\beta_0}^* = 0.09, \sigma_1 = 0.31$$

The SST model has the same default initial guess as the standard k-ω model and for this study, flow over the entire airfoil boundary conditions is assumed to be turbulent and no slip boundary condition is applied on the surface of the airfoil. A computational domain is a prismatic domain size of 60x60x100m. The wing length is 40 meters and chord length changed from 0.5 to 1m. The upstream, top and bottom border of computational domains are situated at least 30m away from winglet and conventional wingtip to minimize the effect of the applied boundary circumstances. Computational domain is shown in Fig.1.

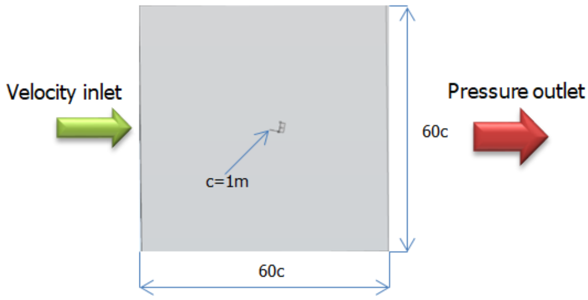



**Figure 1: Computational domain**

Commercial CFD software COMSOL 5.2 is used for numerical analysis. To eliminate distortions around wing and winglet, high concentrated mesh is used for aerodynamic object and for the domain. The mesh density is doubled by using the refine option for areas near the wing. Even though almost the same mesh distribution is used for all models but there is slight differences. Because as changing up or down sloping angle of winglet, sometimes program gives mesh error when the previous mesh distribution is used. Mesh distribution around the domain is shown in Fig.2.

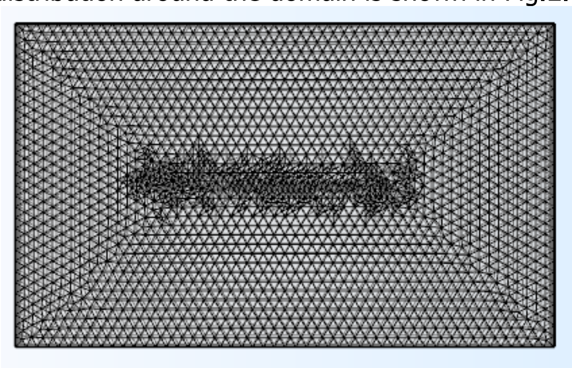


**Figure 2: Mesh distribution around domain**

For managing and diminution numerical error, upwind layout method is chosen. The boundary conditions are inlets, walls and outlet boundary. Free stream velocity is set to 10 m/s and which is always subsonic due to low range. Reynolds number is changed from $0.5\text{x}10^6$ to $1\text{x}10^6$. For a clearer view of the wingtip vortex formation, 10 degree angle of attack is given to all the wings with winglets.

## 1.3. Results And Discussions

Streamline velocity behind a conventional wingtip (on the left) and upward angled winglets (on the right) are shown in Fig.3. Angle of incidence of winglet with longitudinal wing surface changes from 45° to 135° degree. A circular pattern of rotating air is shown at the left side of wing but at the right side, wingtip vortexes varies and it directly depends on the angle of winglet with longitudinal wing surface. With the increasing angle of winglet with the surface, the vortex formation is reduced.

When the winglet comes to fully vertical position, there is no or little turbulence formation as shown in Fig.3(c). With the increasing angle from 90° to 145° turbulence seems to be weak but remarkable increase is observed when the angle increases further than 145° as shown in Fig.3(f).

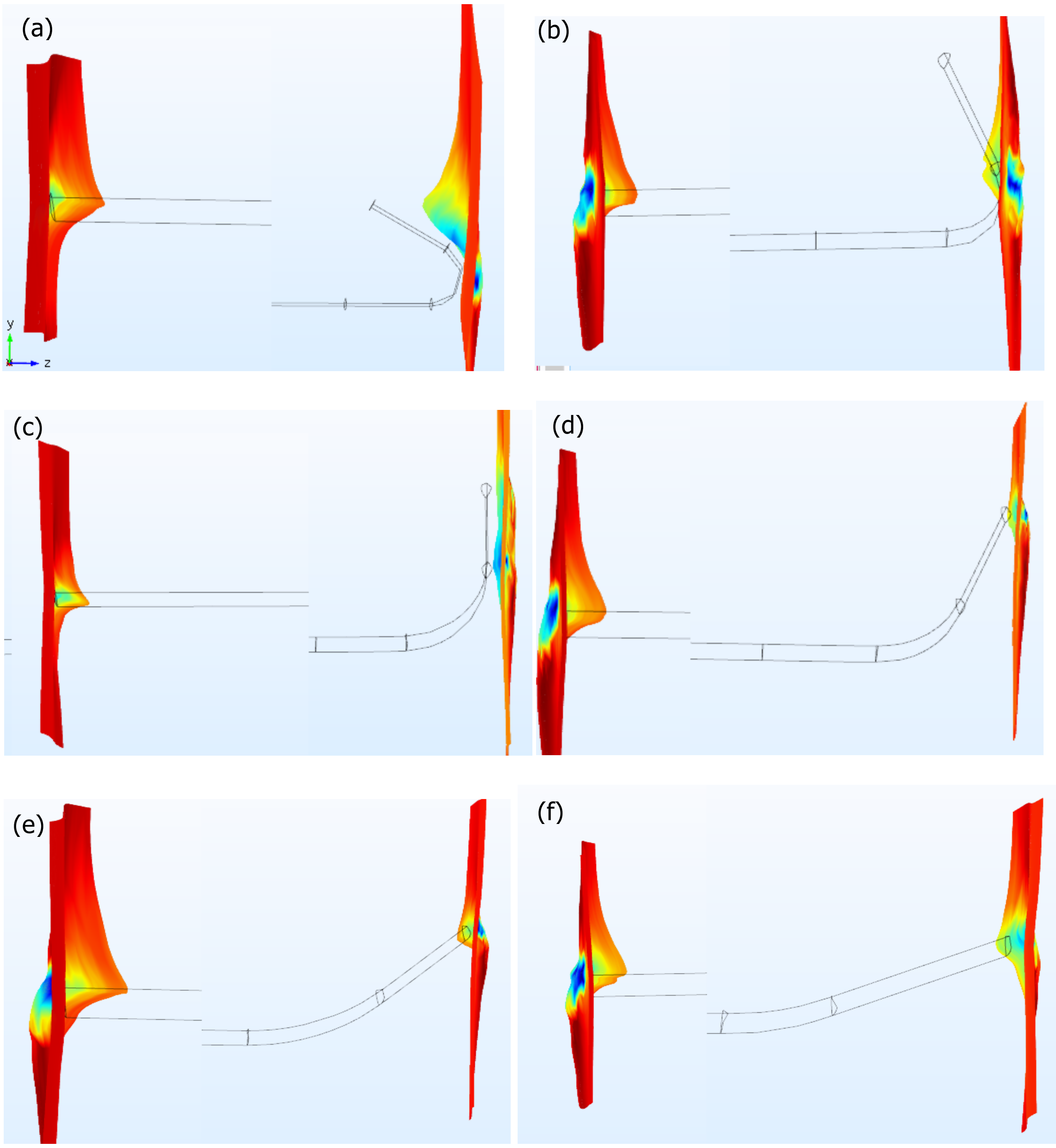



**Figure 3. Streamline velocity of wingtip vortices behind conventional wingtip (on the left) and up sloping winglet (on the right)**

Streamline velocity behind a conventional wingtip (on the left) and down sloping angled winglets (on the right) are shown in Fig. 4. In this part winglet angle with longitudinal surface increased from 45° to 160 degree. A circular pattern of vortexes formation is clear at the left side of wing but at the winglet side it depends on angle between winglet and horizontal axis. When the winglet is in exact vertical position, vortex formation is at the lowest level but it is evident at the angle between 45° and 90°. Size of the vortex is growing with the angle increases starting from 90 degrees to further. According to the numerical calculations, the optimal orientation angle is around 90 degrees as seen in

Fig.4. But these types of implementation would increase the possibility of contact wing with the ground therefore that negatively affect in terms of applicability.

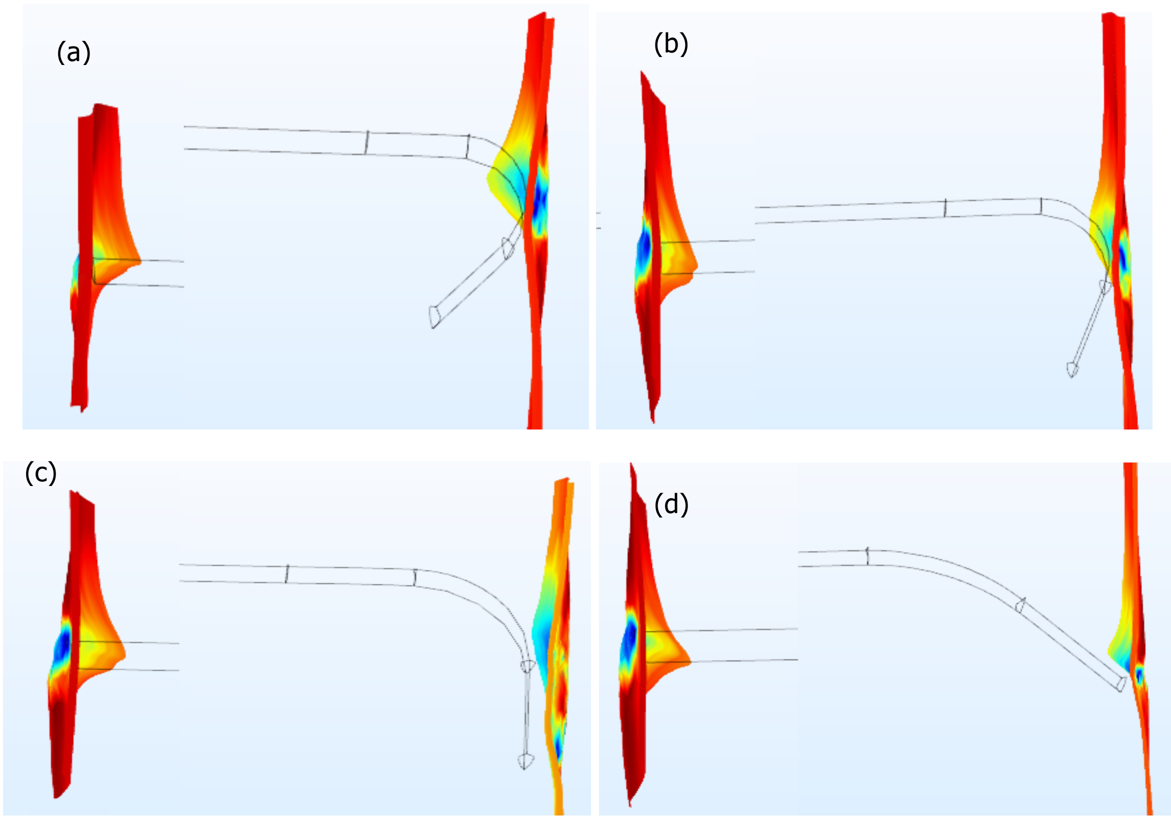
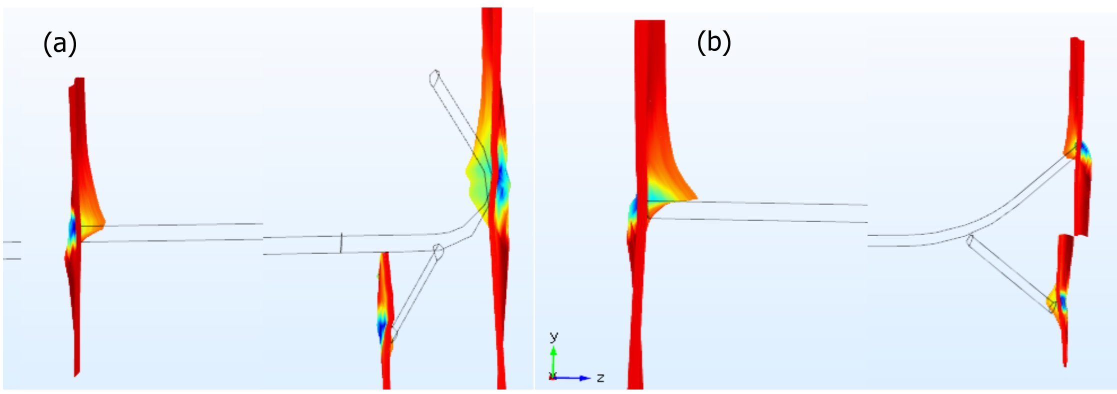



**Figure 4. Streamline velocity of wingtip vortices behind conventional wingtip (on the left) and down sloping winglet (on the right)**

Split winglets with up and down sloping are given in Fig.5. In this section different split winglet such as one side inclined upwards and long, the other side tilted in downward but short, are designed and numerical calculations are conducted to understand aerodynamic property for wingtip vortexes formation. Conventional wingtip is on the left side where the vortex formation is visible but at the split winglet side, the intensity of turbulence varies according to the design. Turbulence formation is not disappeared completely, but it appears to be extremely weak except for Fig.5(a). Winglet with narrow angle with wing surface increases the vortex formation as seen in other figure in this paper.



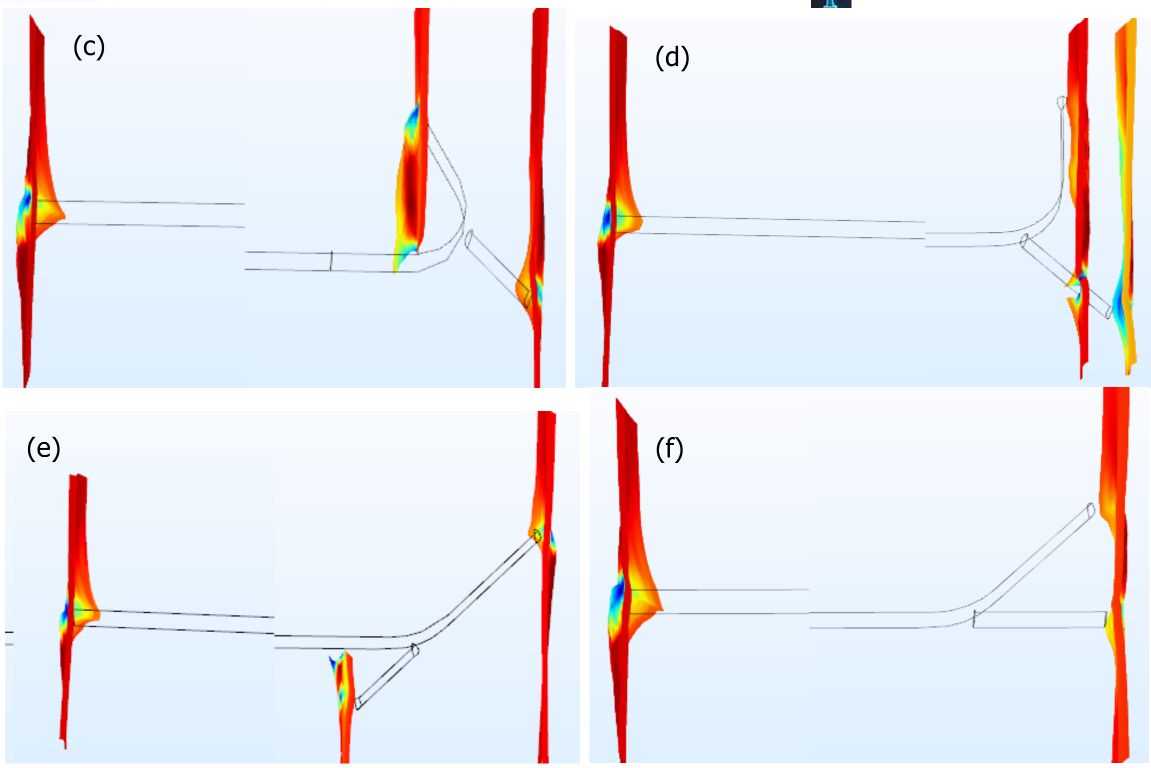
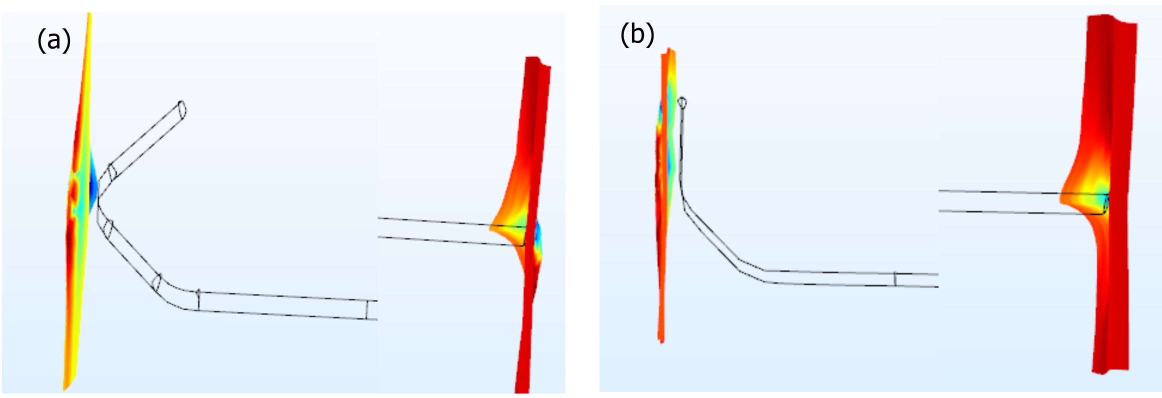



**Figure 5. Streamline velocity of wingtip vortices behind conventional wingtip (on the left) and split winglets with up and down sloping (on the right)**

A study similar to this one is performed by increasing the number of winglet only for up sloping or up and down sloping and effect of the number of winglets on the aerodynamic performance was investigated and their performances was compared with baseline wing section [15]. According to the investigation, it was always calculated that aerodynamic performance increased as the number of winglet increased, the lift coefficient increases and the drag coefficient decreases. But here aerodynamic performance is not directly depending on the number of winglet but reduction in vorticity is dependent on the angle between the winglet and the lateral surface. For the single or split winglet, as the angle between the winglet and the wing surface approaches 90 degrees, the turbulence density decreases considerably and as the angle narrows or expands from 90°, the turbulence increases. Two-step inclined winglets up sloping with lateral surface are given in Fig.6. Conventional wing tip is at right hand side where vortex formation is evident but at the winglet side the vortex formation seems to be quite weak for the Fig.6(a) and Fig.6(b) but in the other two Fig.6(c) and Fig.6(d), the turbulence intensity is less than the conventional wing tip but more than the first two configuration.



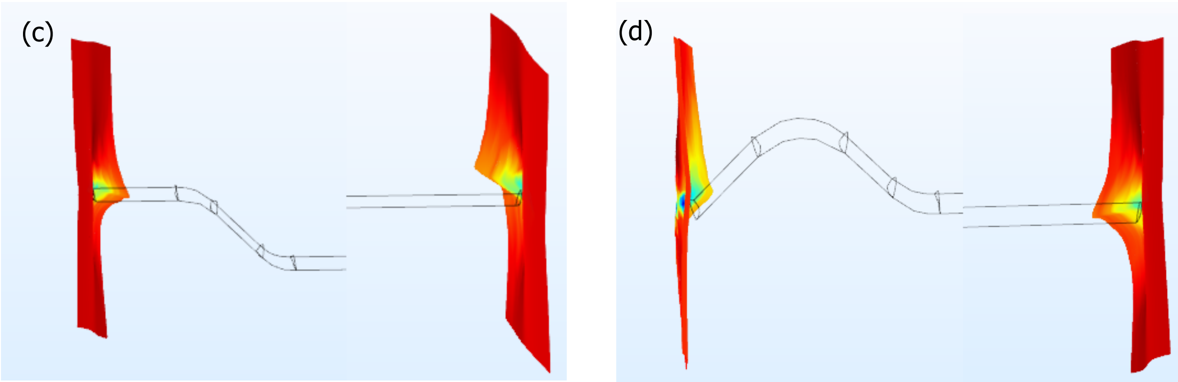



**Figure 6. Streamline velocity of wingtip vortices behind conventional wingtip (on the left) and winglet with up gradual angle.**

Numerical calculations are performed for two steps down curved winglets and are given in Fig.7. In this part, the weakest vortex is formed for the winglet which is designed by first sloping down 45° and then 90 degrees with lateral surface as seen in Fig.7(b) but in other designs vortex formation is observed on a scale comparable to traditional wing tip. Also, the designs are shown in Fig.7 and Fig.6 is mirror symmetry relative to the wing surface and it seems that vortex formation is weaker near the winglet for the upward sloping. A better flow is simulated for up sloping winglet compared to the down sloped one.

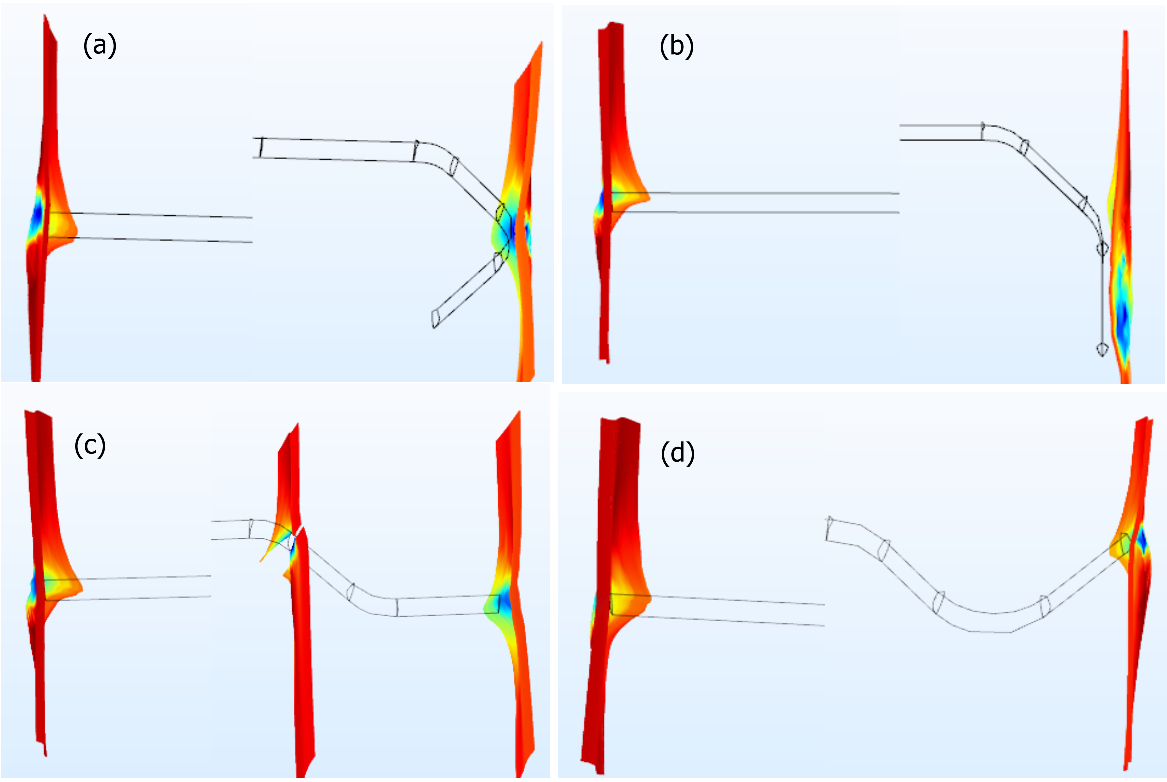



**Figure 7. Streamline velocity of wingtip vortices behind conventional wingtip (on the left) and winglet with down gradual angle.**

### 1.4. Conclusion

The work performed in this paper interest the efforts of conducting a computational fluid dynamics (CFD) simulation of airflow past a fixed 3D NACA0012 wing with winglet at Reynolds numbers of $0.5x10^6$ to $1x10^6$ using a finite element methodology. Details of the wing tip vortexes fields are investigated around single and split winglet design with COMSOL 5.2 commercial software by using SST turbulence model. Numerical methods are performed for slightly varying highest mesh configuration at the angle of attack 10° for each case. To see normal wing tip vortexes, conventional wingtip are simulated together with winglet in all case. There are several types of wing tip devices such as up and down sloping, split winglet with varying length and slope are designed and numerical investigation conducted to understand implementation of different wingtip device on wingtip vortex formation. Although they function in different manners, the intended effect is always to reduce the aircraft's drag by partial recovery of the tip vortex energy. Initially, up sloping winglets with varying angle are designed and obtained results are compared with those obtained for conventional wing tip vortex and varying angled winglet. The comparison shows that vertical or wider-angled designs with the lateral surface, decreases the amount of vortex vorticity considerably but as the angle increases further than 145 degrees, the vortex formation increases again. Next, down sloping winglets are investigated numerically and results indicates that less turbulence is observed at vertical or wider-angle winglet with lateral surface. Then split winglets with up and down sloping are investigated and less vortex formation is observed compared to other designs. Finally, two-step inclined single winglet are designed and investigated, less turbulence is observed in the right angled configurations. Aerodynamic device attached to the wing tip generally reduce the wingtip vortex but which design is more useful depends on other parameters needed for flight safety.

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