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Effect of Cant Angles on the Aerodynamic Performances of an Airplane Wing with Blended Type Winglet: Numerical Analysis

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ABSTRACT

This study examined the potential of attaching winglets on wings in an airplane aiming to reduce the induced drag coefficient and increase the coefficient of lift while keeping the wing span the same. The aerodynamic characteristics of a wing having winglets have been studied numerically with the help of simulation software ANSYS-Fluent. The drag and lift coefficients have been studied for winglets having different values of cant angle, on an aircraft wing. For the work, subsonic flow of air is considered over the wing in the simulation. NACA 0012 symmetric airfoil is considered for the study. By reducing the induced drag that causes tip vortices, an enhanced winglet design with a certain cant angle can produce an aircraft's better performance significantly. Reduced fuel consumption would benefit from the overall improved aerodynamic performance. Blended winglets will increase the lift coefficient about approximately 42% to 49% and reduce the drag coefficients. These winglet designs are capable of reducing the induced drag and converting wingtip vortices to increase thrust, saving costs by reducing fuel consumption, reducing noise levels and enhancing aircraft engine performance.

Keywords: Airplane Winglet, Cant Angle, Pressure Coefficient, Drag Coefficient, Lift Coefficient

1. Introduction

Wings are the most important and vital part of an airplane which keeps it floated and steady and also helps it to move through a direction into the air stream of surroundings. Aircraft designers tried to develop the current methodologies for aircraft control more than 100 years ago. Structural enforcement methods were actively used on aircraft structures in those early years as a way of controlling the aircraft motion, with the inventive ‘wing warping’ used by the Wright brothers for rolling motion control being the most notable technique [1]. A Wing is an airfoil-shaped body which travels through air generates an aerodynamic force. The part of this force is called lift whose direction is vertical to the direction of airplane motion. Drag is considered the parallel component of the force to the freestream direction of motion. Subsonic flight airfoils with a leading edge that is rounded have a typical shape, followed by a straight trailing edge, which is often symmetrical between upper and lower surface curvature. Foils constructed with water with similar functions as the operating fluid are called hydrofoils. A winglet is an airfoil-shaped structure attached and extended at the wingtip almost perpendicularly. The upward and inward angles of a winglet are called the cant angle and the toe, respectively, are important and meaningful in any application for proper results. Winglets help to alleviate the driven drag effects. The pressure on top surface of the wing is lower than the pressure beneath the wing in flight. That is why there would be a pressure differential between the upper and lower surfaces of the wing. That would result in the desired lift which would help an aircraft to float in the air considering the required consequences. A winglet is attached inclined or vertically with the wings at the wingtips. Winglets make it easier for the wings to generate lift, which ensures the planes need fewer inputs from the engines.

Bourdin et al. [2], investigated a significant technique for the control of Morphing aircraft. At that concept, a winglet pair have consisted of an adjustable cant angle, attached at the tips of a baseline wing and actuated independently. The feasibility of the concept is shown by the estimation of a vortex lattice numerical model and followed by the wind tunnel experiments. Comparisons are made between the experimental and numerical observations in fair alignment, with the key variations believed because of aero-elastic effects of the wind tunnel.

Houghton and Carpenter [3] observed that if a winglet is attached to a wing then it would substantially decrease the flutter speed of the wing when the wings are in the region of transonic Mach number. Therefore, the slide slip’s effect on the winglets due to the angle of attack is to cause increased loads.

Analysis and development of wings and wing/ winglet configurations at low speeds are conducted by Chattot [4] who considered numerical evaluation in the Prandtl lifting – line theory for the non-linearity connected with a 2-D lift curve, where the local angle of attack is greater than the maximum lift angle of attack. The governing equation has been familiarized with an artificial viscosity term that helps the iterative method to converge to the correct solution. The effect of yaw has been calculated and weathercock stability has been found to provide the optimum wing/winglet combinations.

Theoretically and experimentally, Gall and Smith [5] investigated the most probable improvement of the aerodynamic properties of a biplane design by installing winglets. The perfect performance factor is improved by up to 13% and the lift curve slope and overall coefficient of lift are also improved. A mathematical analysis

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comparing the biplane with an upgraded winglet to a monoplane shows that the biplane has the ability to improve the $L/D_{\max}$ by 6.4% and the classical performance function, $C_{\mathrm{L}}/C_{\mathrm{D}}$ by 13%.

An optimization algorithm developed by Kroo et al. [6] for an aircraft based on their evolutionary theory discovered a 'C'-wing arrangement with a winglet and a horizontal extension which shows a reduction of drag keeping the lift, span, and height fixed. A study by evolutionary biologists has also shown the efficiency of certain slotted wings and shown how by growing wing efficiency steadily, these characteristics may have developed spontaneously in birds. The general definition of non-planar wings, which includes winglets, was presented by Kroo et al. [6]. They studied several aircraft, comprising winglets, nag wings, box wings, and basically handles the non-planar wakes. Due to their capacity for lower vortex drag without increased span, such designs are of interest, a key restriction for many aircraft. The structural advantages of biplanes were utilized by the Wright brothers. Highly cambered, thin portions at very low Reynolds numbers make the cable braced Wright biplane ideas are very appealing. Smith et al. [7] find, however, that single winglets modified to biplanes increases stability by 13%, and increase the lift-curve slope and the vehicle's maximum coefficient of lift.

In his patent on wingtip airfoils, Jonathan Santos predicted the breakthrough in the new proposal. Santos found that to maximize the performance of a single winglet, a series of winglets at the tips of the wing could take the benefit of the spiral arrangement of the tip vortices. A series of programs were carried out by Spillman and McVitie [8] to study systems similar to wing tip airfoils, that he named ‘wingtip sails’. On a Trainer aircraft named Paris MS 760, wingtip fuel tank, they examined the use of one to four sails. The wind tunnel experiments were verified by flight test studies and showed smaller takeoff rolling and decreased fuel consumption. Afterward, the reduction of wingtip vortex was established because of wingtip sails, and lower vortex energy was found 400-700 m downstream of the plane. The advantage of fitting wingtip sails was found by achieving 39 drag count reductions ($\Delta C_{\mathrm{D}} = 0.0039$). The advantage will still be about 25% of the usual zero-lift drag of the simple wing, even halving the zero-lift drag coefficient gap.

Hossain et al. [9] investigated on bird feather similar winglets in the aircraft wing model for the aerodynamic properties. NACA 653-218 airfoil is used in this regard. The experimental analysis shows that a decrease of 25-30% in the drag coefficient and a 10-20% increase in the coefficient of lift by using a winglet similar to bird feather for an incident of 8°.

Beechook and Wang [10] showed that an aircraft's efficiency is greatly affected by the induced drag caused by the vortices at the wingtip. Aircraft winglets are incorporated to decrease the production of vortices to maximize fuel efficiency. The purpose of the research was to examine the efficiency of the winglet at different cant angles of 0°, 30°, 45° and 60° at different incidence. The experimental work was carried out in a closed-loop wind tunnel under conditions at sea level and 35 m/s freestream velocity.

The study is related to the numerical analysis of the swept wing with and without winglet at different configurations depending on the changing values of angle of attack corresponding to the freestream flow surrounding the wings. The research gap is about to fill by analyzing for swept wings at a specified swept angle between the wing root and the wingtip orientations for a normal plain wing and the wings with 30º, 45º and 90º winglets. The aerodynamics characteristics of the wing have also been determined when the winglet is attached to the wing perpendicularly and the results have been analyzed with proper discussion.

This numerical study demonstrates and determines the aerodynamic characteristics of airplane wings with and without blended type winglets. The purpose is to see whether it shows better aerodynamic performance if winglets are attached to the airplane wings than the wing having no winglet. The study also covered the effect of the cant angle of the winglets on performance and determine the best angle. It may come out beneficial for the proper understanding of the aerodynamic improvements with winglet by demonstrating variations of pressure, lift, and drag coefficients for different cant angle of winglets.

2. Numerical methodology

2.1 Airfoil description and design:

An airfoil shape can be found by making a cross-section perpendicularly on a wing or blade of a wind turbine or a sail used in propeller, motor blade etc. The NACA airfoil sections considered herein are obtained by combining a thickness distribution and a mean line. An airfoil is obtained from a perpendicular plane to the corresponding wing considered as a cross-section shape. There are several types of NACA airfoils families used as cross-section shape in the construction of the wing of an airplane. In this study, NACA 4 digit series is considered. The first digit of the designated number indicates the locus of the maximum positional point of the corresponding airfoil in the number of hundreds of chord of the airfoil. The second digit indicates the horizontal position maximum camber from the leading edge of the airfoil in the number of tenths of the chord of the airfoil. And the last two numbers indicate the maximum thickness of the airfoil in hundreds of the chord of the airfoil.

If X_u and Y_u, respectively, represent the abscissa and ordinate of a standard point on the airfoil's upper surface and y_t is the ordinate of the distribution of symmetrical thickness at chordwise position x, then $Y_u = y_t$ give the upper surface coordinates. The lower surface coordinates similarly are $X_l = x$ and $Y_l = -y_t$.

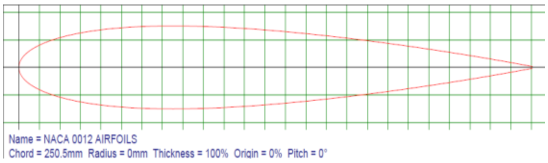

Fig.1 Generated NACA 0012 airfoil

The equation for a symmetrical 4-digit series NACA airfoil,

$$y_t = 5t\left[0.2969\sqrt{\frac{x}{c}} - 0.1260\left(\frac{x}{c}\right) - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right] \quad (1)$$

where, x denotes the local position on the chord from the leading to trailing edge, t is the maximum thickness as a fraction of the chord and c is the chord length.

The leading edge is constructed as a part of a cylindrical shape with a radius of r.

$$r = 1.1019t^2 \quad (2)$$

Table 1 Airfoil specifications at different wing sections

Parameter	Chord, C (mm)	Thickness, t (mm)	Trailing edge radius, r (mm)
Wing root	250.50	30.06	995.68
Wingtip	85.81	10.2971	116.834
Winglet root	85.81	10.2971	116.834
Winglet tip	45	5.4	32.1314

2.2 Wing model designing:

The CAD models of normal wing and wings with winglets are generated in SolidWorks 2016 software. The airfoil data for NACA 0012 is obtained from an online tool [11] which is imported to the SolidWorks software and the sketch for the airfoil is generated for wing root and also for wingtip. The span length of the wings is considered 500 mm. The maximum and minimum chord lengths are 250.50 mm and 85.81 mm, respectively, at the wing root and wingtip. Thus the Reynolds number based on chord length is relevant at subsonic flight speeds. One of the major development parameters is the model's span length, compared to the chord length.

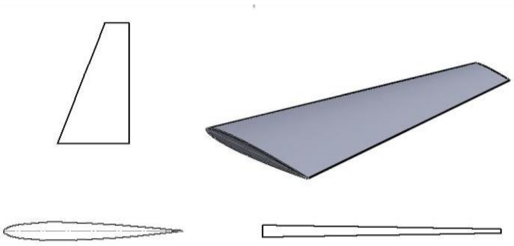

Fig.2 Designed airplane normal wing model with no winglet

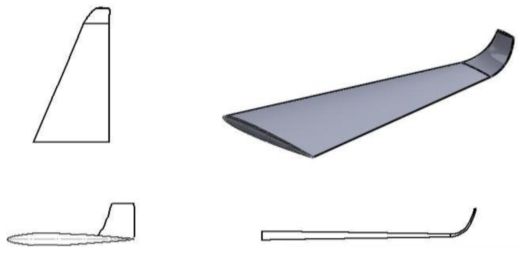

Fig.3 Designed airplane wing model with 90° winglet

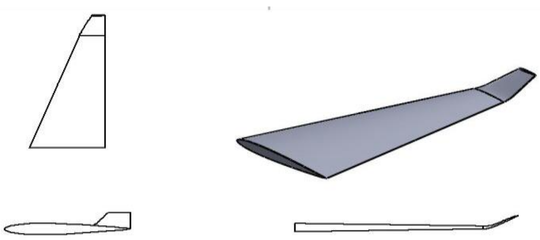

Fig.4 Designed airplane wing model with 30° winglet

Table 2 Wing specifications of the constructed model

Description	Dimension
Airfoil shape	NACA 0012
Type of wing	Swept Back
Sweep angle	18.23 degree
Span of wing	500 mm
Taper ratio	0.342
Aspect ratio	2.92
Wing planform area	0.17104 m^2
Maximum chord	250.50 mm
Minimum chord	85.81 mm

Table 3 Specifications of winglets

Description	Dimension
Type of winglet	Blended
Cant angle	30°, 45° & 90°
Height of winglet	42.88, 57.18 & 90mm
Winglet taper ratio	0.5244
Maximum chord	85.81 mm
Minimum chord	45 mm

2.3 CFD solver setup

A computational analysis usually consists of 3 stages: pre-processing, run simulation and post-processing. The pre-processing stage is involved with the geometry construction with name setup and generation of the grid (mesh). The designed wing geometry and wing with winglet geometry constructed in SolidWorks software are exported to the workspace of Design Modeler of ANSYS Workbench for further pre-processing works. A C-domain is constructed for both types of geometry, which is assigned as fluid and the previously designed geometries are assigned as solid objects. The domain is dimensioned about 6 × chord length at wing root in the downstream direction of the flow. Here, the leading edge point of the wing root and the center point of the quarter-sphere portion of the C-domain has been coincident together. The domain sketch at the YZ plane is extruded towards the downstream of the flow. As there is no need for calculation, both the wing root plane and the domain plane have been considered coplanar (XY plane). The total volume of the domain around the normal wing geometry is measured about 4.523 m^3 and for the wing with winglet geometry, it is measured about 17.401 m^3.

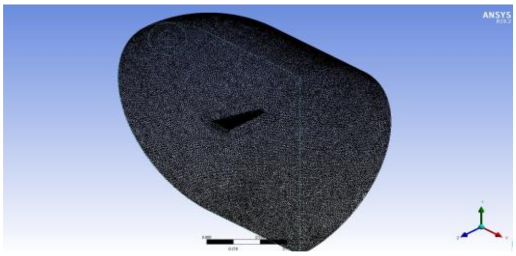

Fig.5 Mesh generation for plain wing without winglet

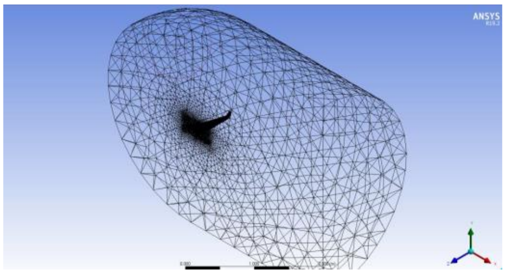

Fig.6 Mesh generation for wing with winglet

Near the wing and winglet geometry, the mesh element size is smaller and progressively growing towards the boundary walls of the domain. Fine layers of structured mesh (inflation layers) were generated around the geometry surfaces to catch the boundary layer clearly which followed by the 3-D unstructured tetrahedral mesh were produced. Mesh independence is checked thoroughly in the study. As to discuss it, i.e. the value of C_L is fixed at 0.057 while the mesh elements were increased up to 4.1 million for 10º angle of attack for the normal plain wing. The independence of results from the number of mesh elements is checked for the various winglet orientations of the wing at different cant angles which showed the range of mesh elements of the whole model geometries from 4 to 6 million. The number of mesh elements is considered about 4.2 to 4.9 million numbers of mesh elements for better accuracy of results. Inflation layers with a first layer height are more capable of processing the sub-layer of viscous flow, which typically happens in a turbulent layer where viscous stresses are prevailing.

Table 4 Boundary conditions and solver parameters for the numerical model

Factors	Considerations
Fluid type	Ideal gas
Simulation type	Steady state solution
Inlet boundary	Velocity inlet at 100 m/s
Angle of attack	2 to 20 degrees
Outflow boundary	Pressure outflow
Fairfield boundary	Wall
Top and bottom walls	No slip condition wall
Convergence factor	0.001
Solver type	Pressure based solver
Viscous model	k-epsilon (2 equations)

3. Results and discussion

When the free stream strikes the wing at a specified angle of incidence on the wing, aerodynamic forces (lift and drag) are generated due to the pressure differences between the upper and lower surfaces of the wing. The distributions of pressure at the upper and lower surfaces are observed at different angles of attaching keeping the same flow conditions and the Reynolds number. After that, the pressure coefficient curves with the positional line as well as the chord line are studied to see the differences it would exhibit at different flow directions. The lift and drag coefficient values are directly extracted from the numerical simulations following the procedures suggested by Hasan and Al-Faruk [12]. Due to the low Mach number consideration, the flow will be attached at most of the cases of the flow directions until the stall of airfoils occurs where the lift coefficient sharply falls after reaching the maximum value. At this point, the flow separation may occur.

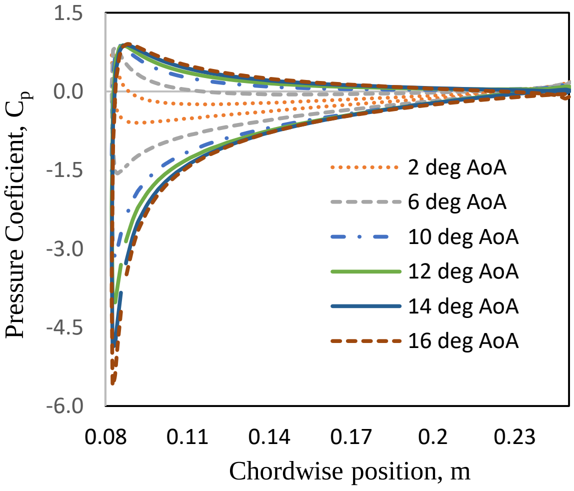

Fig.7 Pressure coefficient vs. chordwise position for 90° cant angled winglet at mid-span (z=250mm) of the wing

From the above figure, it can be observed that for the angle of attack 16°, C_p at the upper surface will be larger at negative value causing the largest pressure difference between the wing surfaces.

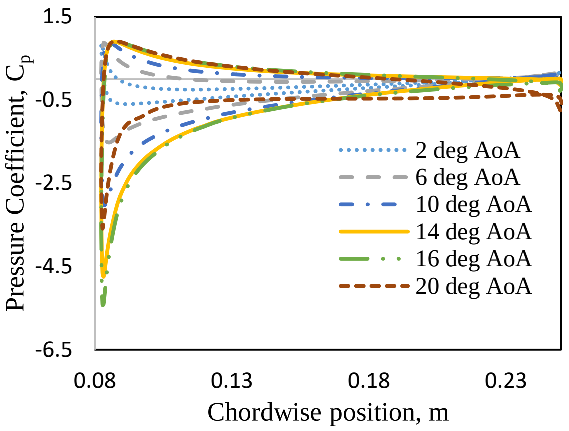

Fig.8 Coefficient of pressure against the chordwise position (X coordinate) for 45° cant angled winglet at mid-span (z = 250mm) of the wing

From Fig.8, the value of the pressure coefficient at both ranges is largest for 16° angle of attack. But for 20° incidence, the C_p values at wing surfaces change than before as stall occurs. This figure indicates the C_p values improvements as the value of angle of attack changes incrementally.

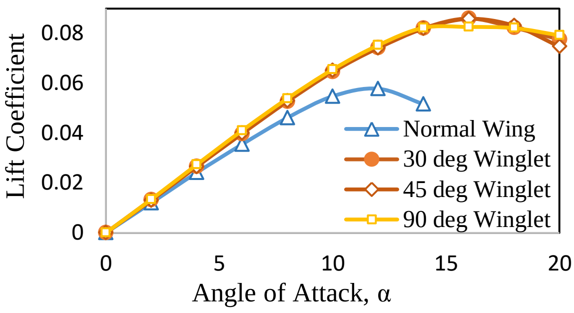

Fig.9 Lift coefficient values comparison with incidence between plain wing and wing with winglets

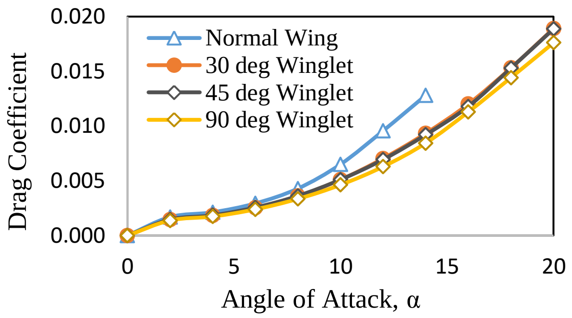

Fig.10 Drag coefficient values comparison with incidence of wing between the normal plain wing and wing with winglets of different cant angles

The values of C_{D} exhibits smaller values as compared to lift coefficients. From these figures, the value of C_{L} reaches a maximum peak point; $C_{\mathrm{L,max}}$ corresponding to the related value of angle of attack. As the incidence values increases, the lift coefficient increases until the stall occurs. The value of incidence at which the stall of the lift coefficient occurs is known as α_{stall}. From Fig.9, it can be observed that the values of α_{stall} is 12° and 14° for normal wing and 90° winglet, respectively. The value of α_{stall} is 16° for both wings with 45° winglet and 30° winglet, respectively. The drag coefficient values gradually increase with the increase of incidence values for all cases.

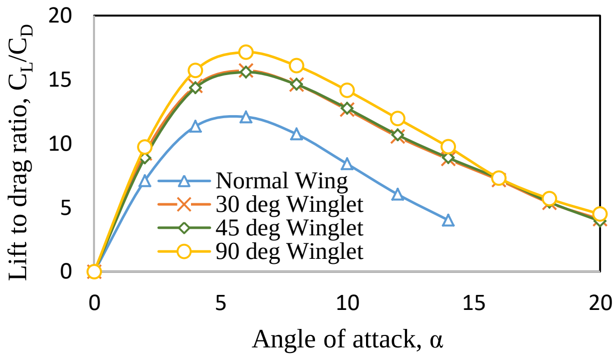

Fig.11 Lift to drag ratio values versus the incidence between the plain wing and wings with winglet of different cant angle

From Fig.11, it is observed that the ratio of lift to drag coefficients exhibits maximum values for wing with a 90° winglet. The values of C_L/C_D shows the lowest values for the normal wing. In the case of the wings with 30° and 45° winglets, the values or curves seem similar to each other. So it can be said that the variations of results are negligible for wings with 30° and 45° winglets.

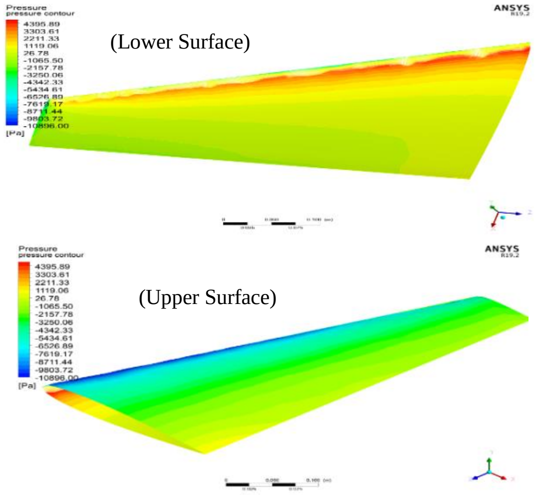

Fig.12 Pressure distribution contours for $\alpha_{\mathrm{stall}} = 12°$ of the normal plain wing without winglet

From the above results and discussions, it is proved that the wing with a 90° blended type winglet shows better results regarding the requirements of aerodynamics characteristics when both low drag force and better lift force on the specified swept type wings are required; considering the flow is subsonic.

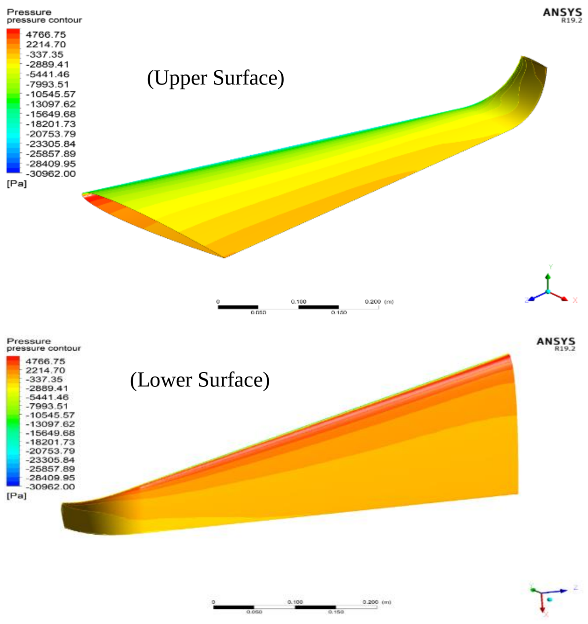

Fig.13 Pressure distribution contours for $\alpha_{\text{stall}} = 14°$ of 90° cant angled winglet

From Fig.13, the pressure distribution at the lower surface is increased at a higher rate with the increase of the value of angle of attack. Also the pressure distribution on the lower surface is increased higher with the winglet than for the plain wing. This ensures greater lift for wing with the blended winglet as compared to the plain wing without winglet for the same value of angle of attack.

4. Conclusions

This study involves with numerical analysis of the performance of aerodynamics characteristics of airplane wing with and without winglets. The results are summarized hereby at α_{stall}

Wing Type / Parameters	Normal wing	90° Winglet	Comment
Lift coefficient	0.058	0.082	42.11% increase
Drag coefficient	0.095	0.014	85.26% decrease

Also, in case of 30° cant angled or 45° cant angled winglet, the lift and drag coefficients resulted in an increased lift coefficient of about 48.5% and the decrease in drag coefficient about 87.7%. The winglets transform some of the energy that goes wasted into an apparent thrust in the wingtip vortex. This modest contribution will be significant if the gain offsets the expense of fitting and repairing the winglets throughout the lifespan of the aircraft. These winglet designs are capable of reducing the induced drag and achieving better lift force which results in additional thrust force, saving costs by reducing fuel consumption, minimizing noise levels and enhancing aircraft engine performance. Reduced fuel consumption would profit from the overall increased aerodynamic performance.

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