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Analysis of Airfoil Aerodynamic Performance in Heavy Rain

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Abstract: **This thesis involves in Airfoil aerodynamic performance in heavy rain conditions for particular airfoils with different Cambers. Rainfall is an environmental phenomenon that can potentially influence flight performance. Comparing the simulation results with each other thus predicting significant aerodynamic penalties for the airfoil in heavy rain conditions is going to be carried. Adhered water increases the effective mass of the wings and body and alters the wing's moment of inertia, whereas drop impact imparts downward momentum to the body. Raindrops impacting wings can also produce roughness will increase aerodynamic drag. Moreover, non-uniform distribution of drops across the body and wings may adversely influence control and maneuverability. The percentage decrease in CL and the percentage increase in CD will be going to be calculated. Airfoil Performance degradation in heavy rain at low angles of attack will be determined near the leading edge using ICEM CFD and FLUENT. Finally the major characteristics involved in the airfoil aerodynamic penalties will be indicated.**

Keywords: **Airfoil aerodynamic performance, using ICEM CFD and FLUENT, environmental phenomenon.**

1. INTRODUCTION

Rainfall is environmental phenomenon that can potentially influence flight performance. Adhered water increases the effective mass of the wings and body and alters the wing's moment of inertia, whereas drop impact imparts downward momentum to the body and elevates the power required to stay airborne. Raindrops impacting wings can also produce superficial roughness and, depending on hydrophilic surface characteristics, can increase aerodynamic drag. Moreover, non-uniform distribution of drops across the body and wings may adversely influence control and maneuverability. Potential damage to wing microstructures caused by high impact pressures of falling drops, as observed for airfoils, might also be expected. Surprisingly, some birds, bats and insects have been observed flying even during heavy rain, although the various mentioned mechanical penalties while doing so have not yet been characterized.

Heavy rainfall greatly affects the aerodynamic performance of the aircraft. Aerodynamic efficiency degradation due to the heavy rain has been the cause of many aircraft accidents. The aerodynamic penalty of aircraft flight through heavy rain has been deemed to be a critical cause in many severe aviation accidents. The Eastern Flight 066 accident at Kennedy Airport (NTSB, 1976) is a telling example, though the factor of heavy rain was not taken into consideration at that time. Three years later, another Flight named 693, a Boeing 727- 25 civil airplane, suffered from an intense rainfall associated with wind shears on its eventual routine to the Atlanta International Airport. Several severe aviation accidents in 1981 aroused people’s consciousness of the seriousness of rain influence on aircraft flight.

This study will be quite useful for the designer of the commercial aircrafts and unmanned aerial vehicles and will be helpful for training of the pilots to control the airplanes better in heavy rain environment. NACA airfoils are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). The shape of the NACA airfoils is described using a series of digits following the word "NACA". The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

2. LITERATURE SURVEY

Investigation of rain effect on aircraft flight was begun with the wind tunnel test, and the earliest was conducted by Rhode in 1941. It dealt with the situation of an aircraft encountering heavy rain at moderate cruising altitude of about 5000 ft and concluded that, the heavy rain exposure time is not sufficient to force the aircraft to the ground. In 1982, Haines and Luers did a research concerning the frequency and intensity of very heavy rains and their effects on a landing aircraft. In 1987, Hansman and Criag compared the aerodynamic performance degradation of NACA 64-210, NACA 0012, and Wortman FX 67-K170 airfoils under the low Reynolds numbers in heavy rain conditions and explored the various mechanisms underlying by forcing boundary layer to transition. In other similar wind tunnel experiments, laminar flow airfoils were also found to experience performance degradation approximately equivalent to that caused by tripping the boundary layer to turbulence. In 1992, Bezos et al. determined the severity of rain effect, the aerodynamic penalty over a range of rain intensities, and the importance of surface tension interactions of water as a scaling parameter. Thompson and his team examined another NACA 4412 airfoil in moderate rain in wind tunnel. They primarily placed emphasis on the correlation of surface film behavior including rivulet formation. Subsequently, they went on a further examination on the aerodynamic efficiency of the same airfoil in moderate rain. Comparisons with different flow patterns showed the aerodynamic degradation depended on the location of rivulet formation and the diameter of these rivulets. The latter factor was found to be more important to aerodynamic performance.

Numerical simulation approach was introduced and developed with the development of computer technology. In 1995, Valentine and Decker studied the NACA 64-210 airfoil aerodynamic performance and the track of raindrops in flow over the airfoil by numerical simulation. In 1999, Thompson and Marrochello calculated the location of the one set of rivulet formation in the surface-water flow over a wing with a NACA 4412 airfoil and compared the results with wind-tunnel experiments. In 2003, Wan and Wu also conducted the numerical simulation of heavy rain effect on airfoil. The water film layer and vertical rain mass flow rate on the airfoil upper surface were added, thus increasing the airfoil roughening effects. In 2010, Wan and Pan studied the cruise and high-lift NACA 64-210 airfoil aerodynamic efficiency in heavy rain via a two-phase flow approach. Later, he reinvestigated the high-lift NACA 64-210 with the consideration of proper modeling of discrete water droplets, shear flow between air oil elements, and studied aerodynamic performance of a 3D blended-wing body aircraft under severe rain through a two-phase flow approach. Zhang and Cao and Ismail et al. studied aerodynamic characteristics of the NACA64-210 and NACA 0012 airfoils in rain and preliminarily explored the mechanism.

The present study uses the discrete phase model (DPM) in Fluent to study the typical commercial transport airfoils NACA0015, NACA2412 aerodynamic performance in heavy rain, but mainly it places emphasis on the mechanism exploration. The raindrops in present study are assumed to be non-evaporating, non-deforming spheres.

3. NUMERICAL APPROACH

The computational domain consists of an extruded O-type grid around the NACA 0015 and 2412 airfoils. The first step in computational fluid dynamics is to examine the grid dependency on numerical results. Generally, the more nodes are distributed, the more accurate solution will be acquired, and however the more expensive computational memory and time will be required. The aerodynamic penalties due to rain are not greatly affected by the number of grid cells.

The incompressible air flow field is solved by FLUENT, a common commercial flow field solver, the details of which can be referred to in the help literature and will not be repeated here. For a Reynolds number of 2.6×10^6, the flow characteristic is considered as turbulent, so turbulence model is added to solve the Navier-Stokes equations. During the calculation of the original and tripped airfoils in dry condition, the steady pressure-based solver is chosen, of which the segregated SIMPLE algorithm is adopted to discretize the pressure-velocity coupling term. The pressure term uses second-order scheme, and the QUICK scheme is used in the momentum term discretization.

Airfoil aerodynamic performance is measured by lift and drag coefficients in this research, which are defined, respectively as follows:

$$C_L = \frac{L}{(0.5 * \rho_a v_\infty^2 * c)}$$

$$C_D = \frac{D}{(0.5 * \rho_a v_\infty^2 * c)}$$

Where C_L is the lift coefficient and C_D is the drag coefficient, L is the lift, D is the drag, ρ_a is the density of air, and $V\infty$ is the air free-stream velocity, and c is the chord length of the airfoil of interest.

3.1 PARTICULATE PHASE:

3.1.1 Scaling Of Rain Model:

To study the heavy rain effect, first of all, it is necessary to measure the intensity and frequency of heavy rain. To study the heavy rain effect, first of all, it's necessary to measure the intensity and frequency of heavy rain. Usually the rainfall rate, R in millimeter per hour or the Liquid Water Content, LWC in gram per cubic meter is chosen to categorize different intensities of rain. A rainfall of 100 mm/h or greater is often deemed as heavy.

The LWC can be written as a function of N (D) as follows:

$$LWC = \int_0^\infty \rho_w \frac{\pi}{6} D^3 N(D) dD$$

Where ρ_w is the Density of Water, Integrating the above formula, we may attain the correlation of LWC and R by

$LWC=0.054R^{0.84}$

Subsequently, it is necessary to establish the size distribution of water droplets under different rain rates. Many researchers like Best, Ulbrich, and so on have established various raindrop size distribution formulas for various situations. Marshall and Palmer developed the classic formula of drop size distribution in 1948 based on massive experimental data. It is shown as follows:

$N(D) = N_0 Exp(-ID)$

Where N (D) ($m^{-3}mm^{-1}$) is the number density of spherical raindrops of diameter D (mm) per cubic meter of air, D_{max} is the maximum drop diameter, and N_0 and I (mm^{-1}) are parameters of N (D) and have different values for different types of rain. For Storm-type heavy rainfall, I varies with rainfall rate R as $I = 3R^{-0.21}$ and N_0 has the constant value:

$N_0 = 1400m^{-3}mm^{-1}$

Correspondingly, here, it is assumed that raindrops have been with uniform velocity before hitting the aircraft surface, that is, without acceleration.

$$V(D) = 9.58\left\{1 - Exp\left[-(\frac{D}{1.77})^{1.147}\right]\right\}$$

Where D is the terminal velocity, a correction for it aloft is given by Markowitz as

$V(D) = V_0(D)(\rho_0/\rho_a)$ ^0.4

Where V_0 (D) is the terminal velocity consistent with the density of air aloft ρ_0.

3.1.2 Wall-Film Model:

In our study, the wall-film model in Fluent is mainly adopted to model the interaction of particle and wall surface. It allows a single-component liquid drop to impinge upon a boundary surface of arbitrary configuration and forma thin liquid film. The major physical processes that affect the liquid film include mass and momentum contributions to the film thanks to drop impingement, droplet splashing effects, evaporation, shear forces on the film, dynamic pressure effects, gravity driven flow, convective heat and mass transfer, flow separation, and sheet breakup, as shown in Fig 3.2(a). In present study, we ignore the film evaporation to simplify our solution, so it is unnecessary to consider the effects of the thin liquid film on the air flow.

The main assumptions for the film model are as follows.

i. The layer is thin, less than 500 microns in thickness due to the assumption of a linear velocity profile in the film.

ii. The temperature in the film particles changes relatively slow due to the use of an analytical integration scheme.

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iii. The film temperature is always below the boiling temperature for the liquid.

iv. Film particles are assumed to be in direct contact with the wall surface and the heat transfer from the wall to the film occurs through conduction.

The wall interaction regimes are calculated for a drop wall interaction based on local information. The four regimes including stick, rebound, spread, and splash are based on the impact energy and wall temperature, as shown in Figs 3.2(b) and 3.2(c) (Tb is the liquid boiling temperature and Tw is the wall face temperature). Below the liquid boiling temperature, the impinging droplet can stick, spread, or splash, while above the boiling temperature, the particle can either rebound or splash. As to our case of which the temperature is below the boiling point, particles stick, spread, and splash, resulting in aerodynamic efficiency degradation of an aircraft. The criteria by which the regimes are partitioned are based on the impact energy and the boiling temperature of the liquid. The impact energy E is defined by

$$E^2 = \frac{\rho_w V_r^2 D}{\sigma_w} * \left(\frac{1}{min(h_0|D, 1) + \frac{\delta_{bl}}{D}} \right)$$

Where ρ_w is the water density, V_r is the particle relative velocity in the frame of the wall (i.e., $V_r = V_p - V_{\mathrm{wall}}$), σ_w is the water surface tension, and h_0 is the total height of the wall film.

δ_{bl} denotes the thickness of the boundary layer and is defined by:

$$\delta_{bl} = \sqrt{\frac{\mu D}{\rho_w V_r}}$$

The sticking regime is applied when the dimensionless energy E is less than 16 and the particle velocity is set equal to the wall velocity. In the spreading regime, the probability of the drop having a particular direction along the surface is given by an analogy of an in viscid liquid jet with an empirically defined radial dependence for the momentum flux. If the wall temperature is above the boiling temperature of the liquid, impingement events below critical impact energy (E) result in the particles rebounding from the wall. Splashing occurs when the impingement energy is above a critical energy threshold, defined as Ecr = 57.7. Besides, in our study, we sample a cumulative probability distribution function (CPDF), which is acquired from the Weibull distribution function and fitted to the data from Mundo et al., to determine the different diameter of each splashed parcel. The equation of the cumulative probability distribution function can be expressed as:

$$pdf\left(\frac{d_i}{D_p}\right) = 2\frac{d_i}{D_p^2} Exp\left[-\left(\frac{d_i}{D_p}\right)^2\right]$$

And it represents the probability of finding drops of diameter d_i in a sample of splashed raindrops.

Bilanin has investigated the evaporation of the particles near the surface and found that evaporation does not affect the airfoil aerodynamic efficiency, so in our study we ignore the vaporization of water film. Since the film particle vaporization is ignored, only the momentum and energy conservation equations remain in the conservation equations for wall-film particles.

4. PROBLEM DESCRIPTION

4.1 PROBLEM STATEMENT:

The present study uses the discrete phase model (DPM) in Fluent to study the typical commercial transport airfoils NACA0015, NACA2412 aerodynamic performance in heavy rain, but mainly it places emphasis on the mechanism exploration. The raindrops in present study are assumed to be non-evaporating, non-deforming spheres. The objective of present study is fourfold: first, to determine the aerodynamic performance of the airfoil over a wider range of attack angle; second, to calculate decrease in C_L and increase in C_D.

4.2 GEOMETRY MODELING:

ICEM CFD chosen for the modeling of airfoil. In present study NACA 0015 and NACA 2412 airfoils selected. To do this NACA 0015 and NACA 2412 point data given in following steps. Geometry of the airfoil is created in by selecting the point data and creating curves by joining those points. Below figure shows the geometry of the airfoil.

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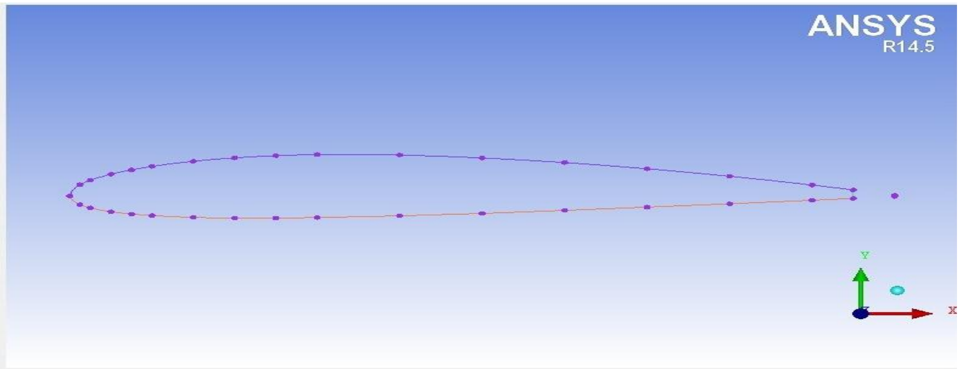

Fig 4.1: Airfoil geometry in ICEM CFD

Meshing is an integral part of the computer-aided engineering simulation process. Typical uses are for rendering to a computer screen or for physical simulation such as finite element analysis or computational fluid dynamics. An unstructured mesh is generated as shown in the below figure.

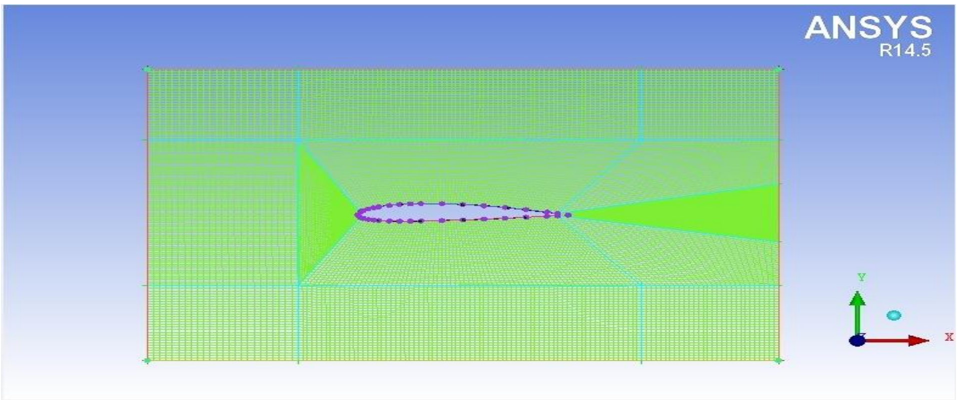

Fig 4.2: Mesh generated airfoil in ICEM CFD

5. RESULTS AND DISCUSSION

CFD Post is used to display results of the problem. For this project we need to show the pressure and velocity contours of the airfoil being undergone solution.

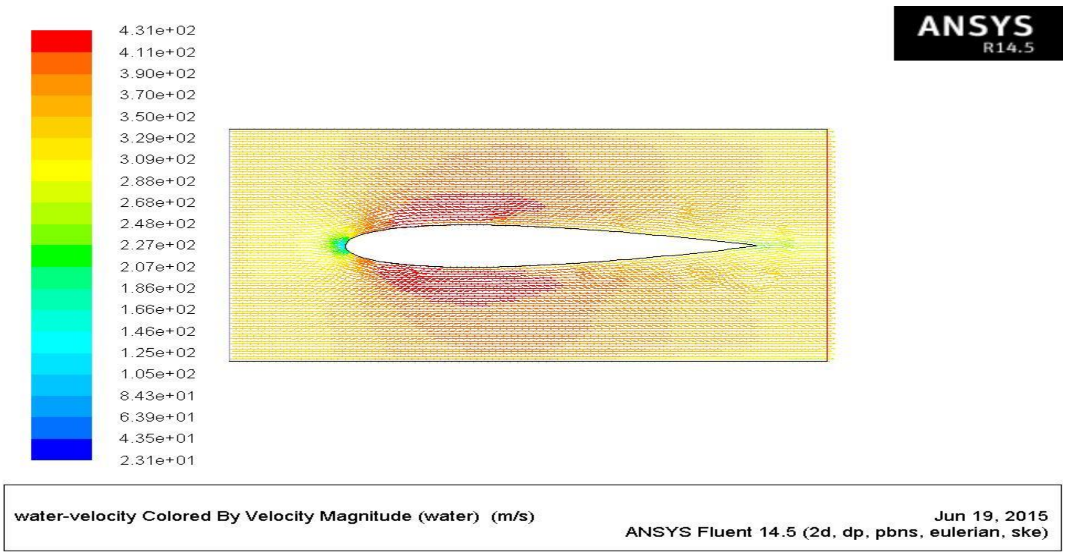

Fig 5.1: Velocity contours of NACA 0015 airfoil in CFD

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The above figure shows the velocity magnitude contours on the NACA 0015 airfoil when we choose water-liquid as a material flows on the airfoil. From the figure the water particles are injecting on the airfoil, some particles splashing back from the airfoil wall. Below figure shows the pressure contours on the airfoil. From the figure pressure is more at the trailing edge of the airfoil.

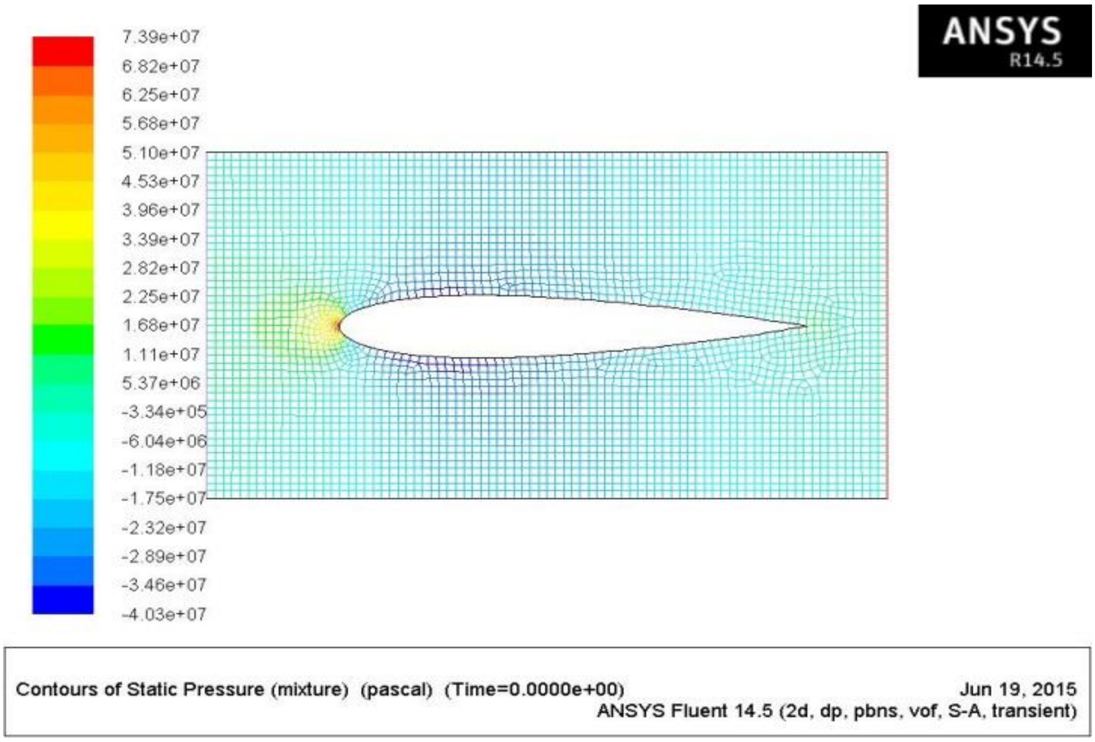

Fig 5.2: Pressure contours of NACA0015 airfoil in CFD

Below figure shows the coefficient of lift for NACA 0015 airfoil. It is observed that the C_L value reduced by 30%.

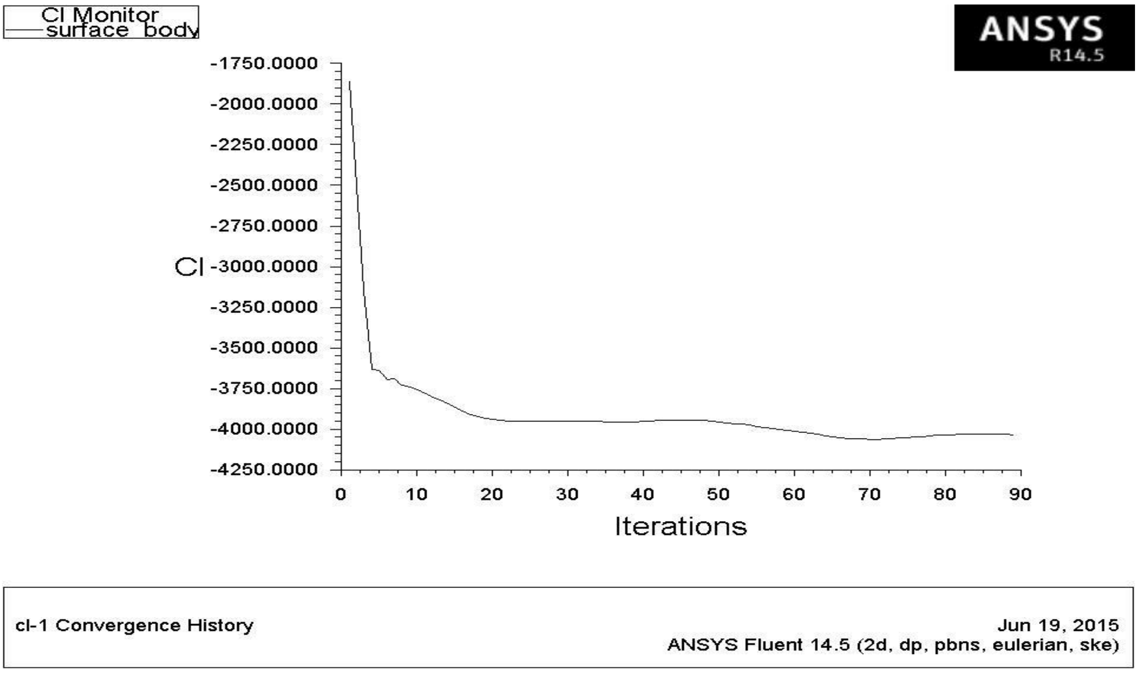

Fig 5.3: Coefficient of Lift curve

Below figure shows the C_D graph. From the figure it is observed that the C_d increased by 25%.

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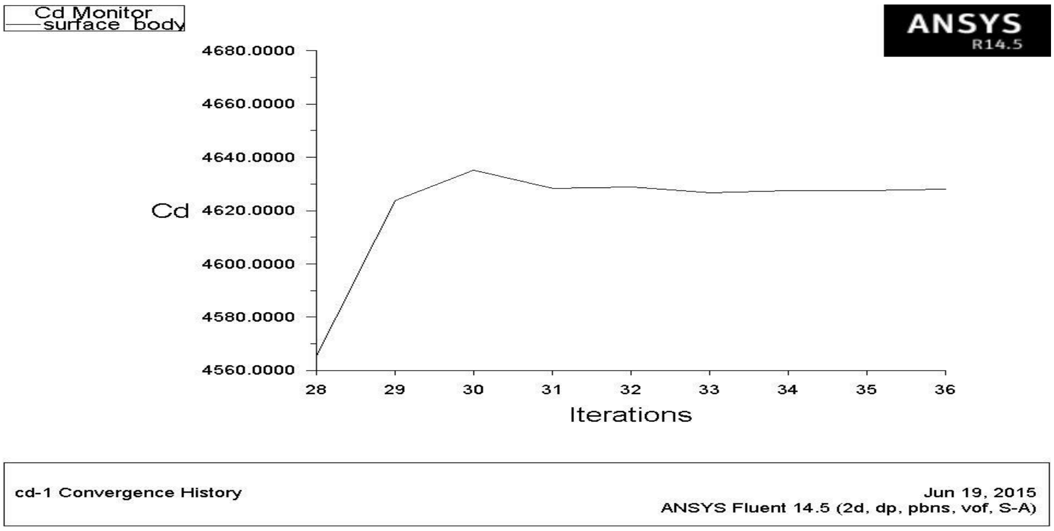

Fig 5.4: Coefficient of Drag curve

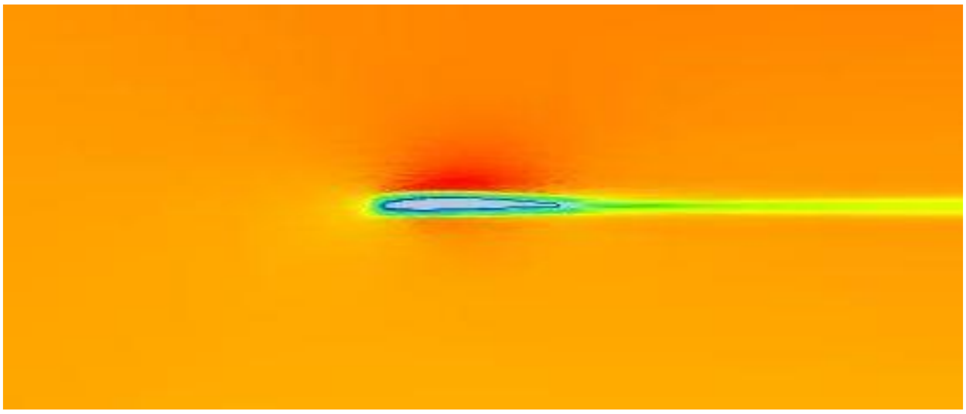

Fig 5.5: Velocity contours of NACA 2412 airfoil

Below figures shows the C_l and C_d curves for NACA 2412 airfoil.

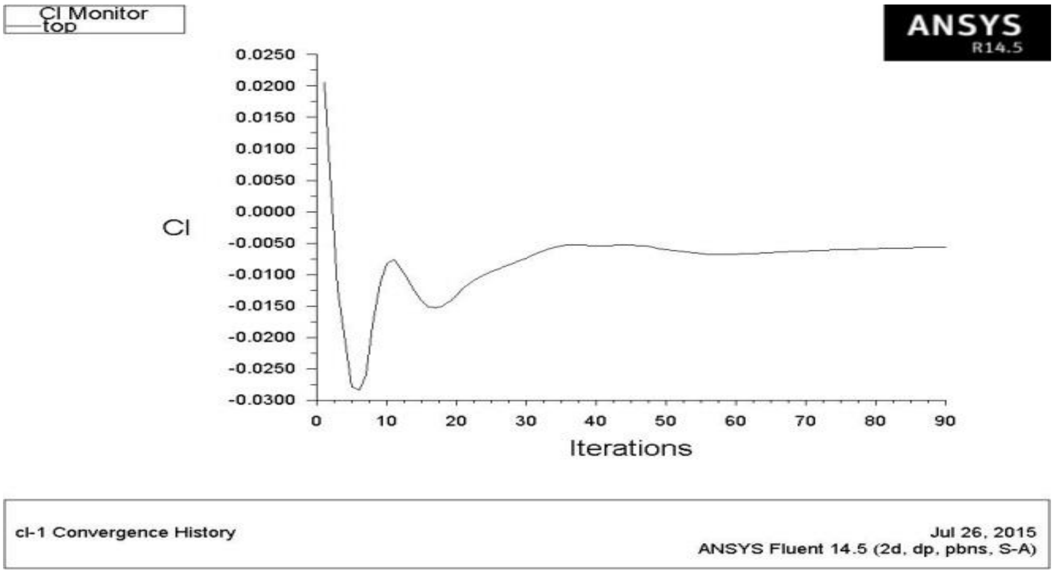

Fig 5.6 Coefficient of Lift curve of NACA 2412 airfoil

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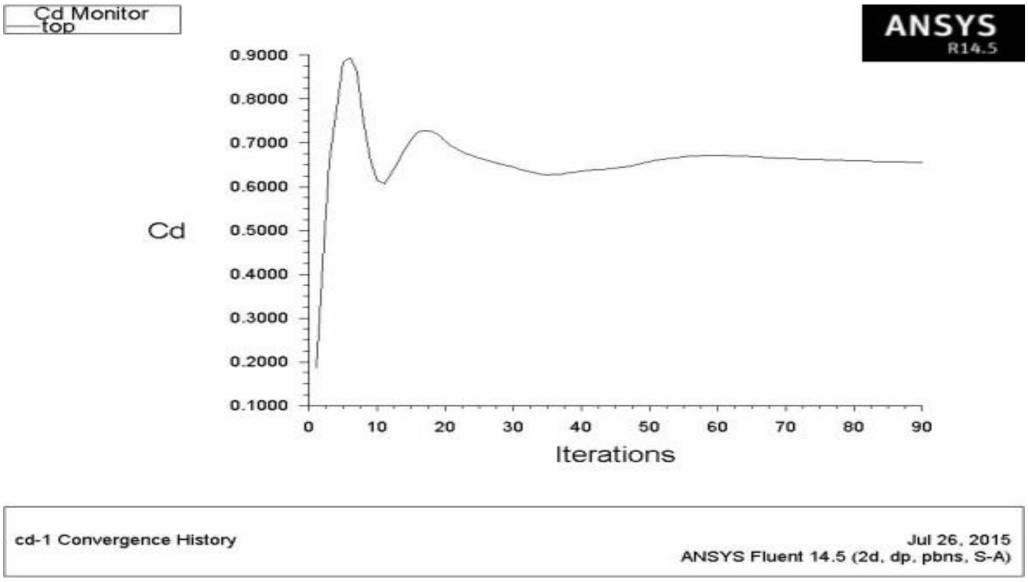

Fig 5.7 Coefficient of Drag curve of NACA 2412 airfoil

6. CONCLUSIONS

The degradation in the aerodynamic efficiency has been predicted in our simulation results. For our case we selected cambered NACA 2412 (relatively high Reynolds number) and symmetric NACA 0015 (Low Reynolds number case). For scaled models of our airfoil we employed discrete phase model (DPM). Our numerical results show aerodynamic efficiency loss for both the airfoil and also consistent with the experimental work done before stall angle. The experimental data of the heavy rain effect on aircraft is not much available, because the experimentation to include rain effects is very difficult, and expensive to conduct, so it is easy and better to simulate numerically the rain effects on different kinds of airfoil and wings.

For NACA 2412 for Reynolds number 3×10^6, the L/D degradation reaches up to 30% for AOA 4^0.This is a big loss in aerodynamic efficiency, so in future the designer of airplanes must consider these facts while designing their airplanes. For NACA 2412 airfoil the lift and drag coefficients of numerical simulation agrees well with the experimental results. The L/D degradation in average shows more consistency with the experiment.

For NACA 0015 for Reynolds number 3.1×10^5, the effect of heavy rain is less than NACA 2412 Reynolds number 3×10^6. But results are still important when considering low Reynolds number vehicles such as sailplanes. It is also seen from simulation and experimental results that for NACA 2412 the aerodynamic efficiency in rain environment is function of LWC while for NACA 0015 LWC value does not have much effect on aerodynamic efficiency in heavy rain environment. Finally the numerical results are very good in agreement with the experimental results and can be important for future airplane and UAVs designs to fly in severe weather conditions and for aviation pilots to control and manoeuvre the airplanes better.

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