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A Review on Aerodynamics of Flight in Adverse Condition

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Abstract—*There are different adverse meteorological conditions which affect the flight safety. Those factors are like heavy rainfall, ice accretion, crosswind, low level wind shear, heavy rain, runway incursion, runway accumulated water or ice, bird-strike etc. This review paper symmetrically overviews different effects of rainfall and ice accretion on aircraft aerodynamic. This overview includes a list of research techniques which include the current research achievement by considering all rainfall and ice-foil simulations. This study includes different whether condition for different aerofoil as per the past reasearch.This lesson describes briefly about the flight safety considering different aspects like how raindrop impingement, spalashback and flow of the water film on lifting surface and different types of ice-shaped accretion, roughness including the flow field separation and reattachment degrade the aerodynamic performance. This review is necessary in any hazardous weather conditions that are fatal to any aircraft especially during takeoff and landing for operating it in low altitude and low speed. The current study describes all the possible past studies for the commercially used aerofoil thatsuccessfully simulates the performance degradation under ice accumulation and heavy rain. The degradation rate increases with the rain rain and ice formation and the premature stall phenomena is also reported .it is expected that the information gained in this review will be helpful for the next reasearch in airline industry for the improve aviation safety.*

Keywords*: Aerodynamics, Airfoils, Aircrafticing, Perfor-mance, Degradation, mach number, reynoldsnumber, SLD, Roughness, LWC, MVD, Navierstoke equation, ice accretion, Surface roughness, water rivulet, Discrete Phase Model(DPM)*

1. INTRODUCTION

As a function of aircraft for its widespread use in various sectors such as aerobatic flight, exploration, rescue and private flight, So it is necessary that the aircrafts should fly in all type of situations and weather.From last few decades it has been observed that 50% above chances of flight threat is related to adverse weather condition. Like low altitude wind shear, heavy rain, storms, thundering, ice foilsformation. Among them rain fall and ice accretion are playing the prominent problems in aviation. This review describes the articles involving the effect of rain fall and ice accretion on aviation .This text includes both traditional techniques like Wind-tunnel experiments, icetunneltest and the emerging technique i.e. CFD(Computational Fluid Dynamics).This paper contains the overview of rain fall effect and ice accretion effect. The overview regarding rainfall effect includes the ongoing research for evaluating rain fall effects including some analytic and experimental methods to evaluate some scaling consideration to find out the effect on aerodynamic efficiency numerically and computationally .The overview regarding ice accretion includes the effect of ice on performance parameter like drag, lift using different analytic test result. This paper also includes some experimental methods and results addressed to ice roughness effect, SLD, relation in between both ice foil and aerofoil geometry. The main goal of this overview is to describe all sorts of research and discussion that are going on the aerodynamic effect on flight aviation in adverse condition.

2. LITERATURE REVIEW

Yihua Cao et al.[1] investigated three parts to identify current state-of-the-art research achievements of rain effects on aircraft aerodynamics. The first part was the aerodynamic penalties caused by rain for various types of airfoils. In this part, he described how rain influenced different aerodynamic property like decreasing in lift, slope of lift curve, lift-to-drag-ratio, and increase in drag, which affects the safety issues of aircraft. He also described here all the flight characteristics and conditions i.e. intensities of rain fall , angle of attack, Reynolds numbers, stall characteristics of wings, change in airflow field around an aircraft in rain by analytic estimation, wind-tunnel experiment, or CFD numerical simulation approaches. The second part was about the characteristics of raindrop impact, splash-back and formed water film flow. In this section, he explained that the surface water flow depended upon many factors like wettability of the airfoil surface, the type and configuration of the airfoils (single-element or multi-element), flow location on the airfoil surface. It was explained that how a smooth continuous film formed on the forward section of the airfoil surface and the film broken into many rivulets afterwards at low angle of attack and at high angle of attack a large region of separated flow appeared between the breakdown of the continuous sheet and the trailing edge. The third part presented the current research achievements on the potential mechanisms of rainfall effects on aircraft aerodynamics. Some experiment conclusions about the rain-influenced mechanics were also drawn by CFD numerical simulation. Ismail et al.[2] studied the heavy rain effect the heavy rain effects on the aerodynamic efficiency of cambered NACA 64-210 and symmetric NACA 0012 airfoils by taking griden as prepossessing software for creating geometry and mesh, fluent as solver and tech-plot as post-processor Discrete phase modeling called DPM was used to model the rain particles using two-phase flow approach. The rain particles were considered inert. He found that aerodynamic efficiency of NACA 64210 was the function of LWC, but in case of NACA 0012, LWC value did not have much effect on aerodynamic efficiency in heavy rain condition.Zhenlong Wu et al.[3] studied the flow around NACA 0012 airfoil in heavy rain having a low Reynolds number of 3.1 × 105 and a liquid water content of 30 g/m3.A two-way momentum coupled Eulerian–Lagrangian model was introduced for two-phase flows.Lagrangian particle tracking algorithm for a general body-fitted coordinate system was developed and linked with a steady-state in-compressible Reynolds-averaged Naiver-Stokes code. Scaling laws of raindrop particles were implemented. A random walk dispersion model was incorporated to model the dispersion of raindrop particles due to turbulence in the continuous phase. A thin liquid film model was used to model the raindrop-wall interactions such as raindrop impacts, splash-back, and the resulting water film on the airfoil surface. This was concluded with two physical phenomena, one was the loss of boundary momentum by raindrop splash-back and the effective roughening of the airfoil surface due to an uneven water film and the second one was , regarding the low-Reynolds-number simulation results which would be considered for low Reynolds number vehicles such as mini-RPVs and sailplanes. Dr. Bruce Moylan et al.[4]investigated that the droplets were distorted in the post-shock flow field environment . So he studied that the impacting force, and subsequent vehicle damage were a function of the drop state at the moment of impact. This research studied about the time sequence of a droplet demise event in a shock tunnel flow. The focus of this research is to understand both the impact event, and the associated material damage mechanisms. An analytical model were used for both the vehicle flow field and the time accurate embedded flow field surrounding the droplets as they changed shape prior to impact. The data presented here were collected at the ballistics range for Mach numbers ranging from 2 to 7 for various shapes. The analytical method was developed by extensive modifications of the Smoothed Particle Hydrodynamics Code (SPHC) with better water equation of state that included the super-cooled regime to develop the fidelity of the impact physics for raindrops at high altitudes. The analytical model demonstrated that the temporal distortion of water in a post-shock environment and the impact with reasonable accuracy. This research has demonstrated that the droplets as large as 2-mm in diameter or greater had sufficient time to both alter their initial spherical shape and to also lose mass due to shear induced stripping and the State-of-the-art hydro codes had been employed in order to better understand the associated physics of droplet/flow field interactions instead of e shock tube and tunnel data, as it was insufficient to properly characterize the droplet demise event in a vehicle induced flow. Tung Wan et al[5] did an analysis on the aerodynamic performance degradation due to the heavy rain .He used modified computational model to enumerate the 2D heavy rain effect droplet catering, liquid water content, droplet terminal velocity, air density. In this CFD model, A modified Bowyer's grid generator and Nervier- Stokes finite volume flow solver (Roe's scheme) were used. In this analysis some modification were taken against Bowyer scheme like Boundary vertex check, Laplacian smoothing, Local refinement by adding points or regenerating grids within a locally confined region, and adding local points to the convex region to avoid inherent nature of Delaurey-type unstructured grid generator. The 4thorder Runge-Kutta time stepping is also implemented for more converging rate .This analysis revealed the conclusions and future scopes as follows

I. water film and the cratering effects were the main reason for decreasing in aerodynamic performance

II. 3D Dimensional wings model could developed to simulate the real local situation mainly the gust wind factors.

III. PC Cluster system should be used to enhance our computational efficiency and save computer time.

IV. Richard V. Rhode[7] did an analysis on the air flight performance reduction due to the heavy rain and they changes of the air density in a stormy weather for a typical transport airplane .Here maximum rain density was taken into account some calculations were done according to the reference [6] by taking into account the various data like average falling velocity of rain relative to air and it was considered that the falling velocity of rain relative to earth is immaterial as airplane flies through a descending air current moves except the turbulence based disturbances caused by the sudden transition from one current to another. It was found that throughout the studies that the rain-accumulated water on the wings was having the negligible effect on the increase of the weight of airplane more around 1% to 5% due to the vertical pressure and change in vertical momentum. It was analyzed that the forward motion of the flight was immensely affected by heavy rain effect due to the drag resulting effect as rain speed varies with the square of the speed and we know that the airplane speed is much more high , so in this consideration the drag effect was not neglected .Some assumptions were made here like the fine droplets with an inertia was small enough as compared to the viscous force exerted by the air, and the large droplets would not flow with the airflow , but accelerated the speed of the airplane. Some calculations were made here to show the final conclusion that the power absorbed by the rains is less than the reverse power available, and the several effects like the effect of rain and atmospheric phenomena on airplane instruments appeared to be small consequence except rate-of-climb indicator which was heavily affected during the convective situation. This analyzed also pointed out that under the simulated rain condition , the leak in the pressure lines gave the serious error to the air speed indication due to the accumulation of water in the line which was not recognized by the pilot quickly .So this analysis gave a scope to take some initiative to flight safety issues in adverse situation. Carroll et. Al.[8] studied the ice formation in airplane(VE-7)under NACA.In his study, he discussed the , how ice was more hazardous than the additional weight along with the ice protection method .In this method he analyzed different avoidable conditions under which ice were formed. after that a lot of research were made on the aerodynamic effects due to surface roughness.Gulick[9] did his research of simulation on the roughness factor of the wing having aspect ratio 6 in the in the Langley Full-Scale Tunnel and found that due to the ice formation , drag was increased to 90% and lift was decreased to 25% .Research started for changing in aerodynamic performance due to the ice growth by measuring the changes in the drag, pitch and moment coefficient.. Bowden [10] did his research on a complete aerodynamic evaluation on NACA 0011 airfoil. In his analysis, he used six component force balance system to determine the clear change in lift, drag and pitch moment. Then research started regarding the work on aerodynamic penalties by considering some other factors like droplet size, LWC (liquid water content), angle of attack and icing time and some research were about ice deposition growth with and without flaps and slats. The Swedish-soviet working group on their sixth meeting [11] reported regarding the flight safety and reported some issues regarding the ice gathering effect. This report analyzed a number of wind tunnel tests to simulate ice and frost accretion on aircraft. Then after the earlier days CFD analysis came into picture which performed a great role for experimental analysis for different glaze ice horns .Calculations were done based on the available data for different airfoils by using different different methods as following

Potapczuk [12] did his calculation using thin layer , RAN(Reynolds Average Nervier Stroke) method. In this method..He discussed the significant behavior of ice accretion on the leading edge. For the evaluation nervier stroke equation was used in a body fitted curvilinear coordinate system. Codes were written on computational space (xi-eta coordinate) to predict the overall effort analysis for ice accumulation resulting for the presentation for rime, glaze and iced aerofoil shapes. Colleagues [13] calculated ice-foiled geometry by using IBL(Interactive Boundary Layer) method with both inviscid and viscous boundary layer iteration scheme resulting in the increased computational power , developed turbulence modeling and improved grid generation. Some new technologies were evolved in the area of CFD like 3D Navier-Stokes calculations of an iced wing and unsteady RANS to calculate the ice-induced separation bubble on iced-wings. Brumby [14] performed his experiment on wings surface roughness for maximum lift and stall angle for NACA.In this experiment, frost characteristics was simulated by 2D wings-tunnel tests at flight Reynolds numbers to determine the effect of under wings frosts on transport airfoil takeoff performance. He prepared different graphs like the effect of Reynolds number on lift and drag for large frost, frost starting location on drag and lift, maximum lift coefficient for upper surface roughness and localized span wise disturbances versus the roughness height .Jeff M. Diebold et. al.[15]did research on simulating of nominally 3D ice frost. In his study he focused on the ice swept wings aerodynamics in the basis of classification methods which included different criteria like roughness, horn ice, and spanwise ridge ice. Effect of ice on the flow field and performance were discussed here so also the mechanism of how ice forms..LEWICE was used to describe the span-wise location on a GLC 305 wing model for a 2D ice shape .So performance result was described after comparing the actual ice shape and the simulated LEWICE-generated results. Addy et al. [16] did his research on the ice tunnel test under supercooled Large Droplet Icing (SLD)Condition .For this test he had taken the droplets having Median volumetric diameter (MVD) 99 and 160 μm and analyzed the effect of temperature , droplet-size, flap setting and angle of attack on ice accumulation. NACA 23012 aerofoil was taken, which was having the taper section with a mean chord length of 68.65 inches. A crucial conclusion was derived, thatwas theicing ridge formed due to the operation of the deicing boot , which could be varying with the change in the factors like temperature, angle of attack and others. Scot E. Campbell, et. al [17] did his analysis in low turbulence, open-return wind tunnel. Aluminum NACA 0012 airfoil having 18 inch.Chord, 33 inch in span and a removable leading edge, was installed to facilitate the simulation of ice assertion . Testing was performed with Reynolds number of 1.8 million and a Mach number of 0.18.The result of the aerodynamic test was based on two factors like, icing parameter variations, and derived aircraft performance to icing parameter variations. This analysis gave a valid conclusion that the sensitivity was only valid for the above aerofoil in the baseline condition of LWC 0:827 gm and MVD 28:7 μm.

Ide, Robert F. Et. Al.[18] did a research necessitating re-calibration of the icing clouds .This report described the methods used in re-calibration to establish a uniform icing cloud . One standard icing blade technique was used to measure LWC .This study encompassed different description about droplet size calibration methods, a comparison details of a LWC and droplet size for a range of air speed with the FAA icing certification criteria and the capabilities of the IRT to produce large droplet icing clouds .A Report from Office of Aviation Research Washington, D.C. [19] gave a report on the effect of aerofoil geometry on performance with simulated ice accretion. This report explained the relationship between the airfoil geometry, ice shape geometry and the resulting degradation in aerodynamic performance. Three airfoils like NACA 23012, NLF 0414, and NACA 3415, were tested with three different types of simulated ice accretions like super-cooled, large droplet (SLD)ridge-type ice, inter-cycle ice, and the glaze horn type ice. This test was performed at Re = 1.0×106, Ma = 0.10 and Re = 1.8×106, Ma = 0.18. The major conclusion of this study was that the chord-wise location of an ice accretion feature was equally important as its size in determining the airfoil performance degradation in terms of maximum lift and the area close to the leading edge was not the most sensitive in ice accretion performance degradation, but airfoil load distribution played a great load in performance degradation.Koji Shimoi et. Al[20] did his experiment on Ice shedding analysis tools.WSU 7-ft x 10-ft wind tunnel facility was engaged to trace the trajectories of simulated ice fragments during shedding.LEWICE code was engaged to simulate the glaze ice shape with a airspeed 160 k mph.The trajectory tested was recorded by a high speed video cameras at 500-1000 frames per second .Trajectory simulations were done by the code developed by Wichita State University. The experiment and simulation concluded a marginal co-relation between the experimental and analytical results for the flat plate with significant rotation during the trajectory.Chankyu Son et al[21] presented a code for rime and glaze ice condition .This code used Messinger's model and an aerodynamic solver that used the panel method and boundary layer theory with some parameter like icing area, maximumthickness, ice distribution etc.The code was verified by the quantitative analysis of the selected parameters under ambient condition. Some of the important conclusions he made with his experiment like LWC would not alter any thermodynamic parameter in aerodynamics like heat transfer, free stream velocity was a prominent factor for establishing the characteristic of kinetic energy, convection and evaporation and the increase in ambient temperature change the rime ice condition to glaze ice condition.S. K. Jung et al[22]did his analysis on 3D droplet impingement and ice accretion by employing the eucleadian model for biphasic airflow and the computational simulation for KC-100 aircraft by using FENSAP-ICE simulation code.Mid section of the main wing was considered for analysis of lift and drag for the effect of ice accretion and the compressible Nervier-Stokes equations were engaged to derive the computational model for the water impingement. As per the result, some graphs were plotted between collector efficiency, lift and drag coefficients with MVD, LWC and temperature variation. During this time period researches are going on about the SLD accretion andAppendix C icingwhile previous research was about different aerofoil geometries in understanding different ice shapes.The previous study of the aerodynamic performance degradation due to rain has been performed by Rhode [23], who founded 18% decrease in performance for the DC-3 aircrafts for LWC 50 g/m3. Haines and Luers [24]did a research in the field of frequency and intensity of very heavy rains and their effects on a landing aircraft. In 1987, Hansman and Criag [25]compared the aerodynamic performance degradation of NACA 64-210, NACA 0012, and Wortman[26] FX 67-K170 airfoils under the low Reynolds numbers in heavy rain conditions. 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 Bezo[27] et al. founded an aerodynamic degradation by analysis heavy rain intensities and its surface tension interaction of the water.Thomsons et.al[28] studied NACA 4412 airfoils in moderate rain condition and founded that the aerodynamic performance degradation depended on the location and diameter of the rivulet formation and rivulets. In 1995, Valetine and Decker studied the performance parameter of the NACA 64210 airfoil by tracking the particles .In 2003, Wan and Wu [29]performed a simulation by taking heavy rain effect on aerofoil, in which water film layer and vertical mass flow rate of the rain were added to enhance the effect of the airdroplets.In 2010, Wan and Pan studied the behavior of the high lift airfoil NACA 64210 under heavy rain with two phase approach .He considered the proper 3D modelling of aircraft by taking discrete water droplets with its shearing action with air in two phase modelling.Calarese and hankey used two way coupled Euclerianscheme to model rain for NACA 0012 for fine and coarse rain. In fine rain condition , he founded the increase in drag and lift was a discretization. Airfoil

3. FUTURE SCOPE OF RESEARCH

This review is giving a comprehensive description about the experimental and computational researches that has been taken place in the field of aerodynamic of flight. This paper tells about all the research about the rainfall penalties, numerical study of the aerofoil performance characteristic, the flow simulation in heavy rain, simulated ice formation, its shape regime, sensitivityparameter, performance parameter of the ice accretion by taking into account different types of aerofoil geometry for different mach number and different reynolds number. This paper might give a future scope to expand the research further in the field of aerodynamics. This research can further analyzed by taking gust wind with swirl flow under heavy rain .

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