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Effect of Torrential Rainfall on Aerodynamic Characteristics of MALE UAV With Two-Element Airfoil Wing Using CFD Approach

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ABSTRACT

This paper presents the effect of torrential rainfall rates on the aerodynamic characteristics of a MALE UAV (Medium Altitude Long Endurance Unmanned Aerial Vehicle) with a Two-Element High Lift Airfoil Wing (TEAW) and its performance degradation like Rate of climb, Vmax using CFD software suite CFD++. The presence of droplets in the vicinity of the gap between the primary and secondary element of TEAW is also reported. Widespread rain type with torrential rainfall rates of 100 - 2000 mm/hr. and corresponding Liquid Water Content (LWC) of 3.73 – 46.14 g/m^3 at 5000 ft (1.54 km) IRA (Indian Reference Atmosphere) conditions are considered for CFD simulations. Significant reduction is seen in lift at higher angles of attack in addition to a reduction in stall angle by 2 degrees and an increase in drag due to the effect of rain. From the study it is observed that the drag value increases with LWC and lift reduction and increase in pitching moment slope with increasing LWC is minor. The spanwise effect of rain on the TEAW with a twist is also studied. This data will be used to formulate the SOP (Standard Operating Procedure) to fly the MALE UAV in various rain conditions as required by the certification agency.

Keywords: Two element airfoil wing (TEAW); Torrential rain; Eulerian dispersed phase formulation; Liquid water content (LWC); MALE UAV

NOMENCLATURE

C_L : Coefficient of lift
C_D : Coefficient of drag
C_m : Coefficient of pitching moment
α : Angle of attack
C_p : Coefficient of pressure
R : Rainfall rate

1. INTRODUCTION

Nowadays UAVs play an important role in intelligence, surveillance, and Reconnaissance mission operations. They are required to operate in different weather scenarios. A typical MALE-UAV is capable of operating for more than 20 hrs during its mission and may have to cover a distance of more than 500 km at various altitudes depending on the requirement. Due to the long endurance requirement of the MALE UAV, it may have to fly in various adverse conditions such as turbulence, low-pressure zone, gust, rain, ice accretion, *etc.*[1]. For manned aircraft, several studies have been carried out for flight in adverse conditions and safe operating standards have been established for the same[1]. The previous study about localised pressure depression and heavy rain on aerodynamic characteristics of MALE UAV[2] with single-element airfoil wing was carried out to formulate the SOP to fly in heavy rain environment. However, due to the long endurance requirement of the MALE UAVs, they may have to fly in various types of rain environments. This has sparked an interest in the effects of torrential rainfall rates on the aerodynamic characteristics of a MALE UAV. Typically, the presence of rain imparts a downward and backward momentum, reduces visibility, decreases the accuracy of measurement instruments/sensors, erodes aircraft surfaces, and increases fuel consumption[1,3,7].

Generally, MALE UAV$_S$ are powered by IC (Internal Combustion) engines with variable-pitch propellers. Two-element airfoil wing is selected in MALE UAVs in order to improve its endurance and service ceiling by flying the UAV at lower speed and higher C_L. This is possible because the C_{Lmax} and design C_L of a Two-element airfoil is higher than that of a single-element airfoil. Due to the higher C_{Lmax} and design C_L of the two-element high lift airfoil, its stall speed as well as the operating speed (1.2 V_{stall}) is lower compared to a single-element airfoil. This helps in achieving lower drag during climb for a fixed power and flying at a lower throttle during the cruise. Two-element airfoil wing consists of primary and secondary elements. The primary element is used as the main lifting surface and the secondary element is used as either control surfaces like a flap, aileron, or fixed surfaces depending on the mission requirements as shown in Fig.1. When flying such high lift configuration in rain, the sheet of water forming on the aircraft surface can lead to clogging in the gaps between the two airfoil elements which can cause premature separation on the trailing edge and stall refer to Fig. 6. It can also interact with the air flow over the main airfoil section and alter the aerodynamic characteristics of the configuration. The span-

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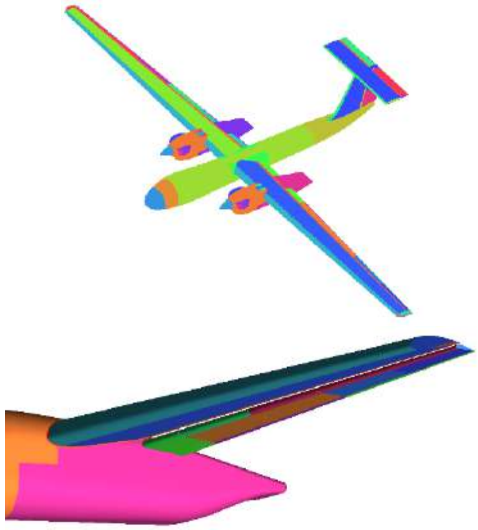

Figure 1. Surface mesh over MALE UAV and enlarged view of wing.

wise flow characteristics of water film is much more complex. Thus, determining the span-wise stall initiation is even more challenging.

Using CFD, the effect of rain on aerodynamic parameters can be estimated which can allow us to build protective features into the autopilot system of the MALE UAV. In this paper, the effect of widespread rain type with torrential rainfall rates (100 mm/hr. to 2000 mm/hr.) on the aerodynamic characteristics of MALE UAV with Two-Element Airfoil Wing (TEAW) is studied.

2. LITERATURE REVIEW

The study of adverse weather effects on aerodynamic characteristics of symmetrical, cambered high-lift airfoils and aircraft has been done by many researchers[15,7,9] in the past which shows that the loss of aerodynamic efficiency in heavy rain environments has been the primary reason for many aircraft accidents. Experimental and computational data suggest that airfoils as well as aircraft in heavy rain experience an overall degradation of performance. Two major parameters contribute to the performance degradation[4]: (1) Impact of rain droplets on airfoil/ aircraft surfaces and splash back which leads to the formation of an uneven water film that effectively increases the surface roughness of the airfoil, and (2) the droplets from rain splash back are accelerated by the airflow which in turn de-energizes the boundary layer and makes it more susceptible to separation. Heavy rainfall accounts for about 40 % of all the weather-related factors affecting flight safety, even higher than low-altitude wind shear and atmospheric turbulence (Cao, *et al.*).

Rhode[3] first investigated the effect of rainfall on a DC-3 aircraft from wind tunnel tests. He showed that there is an increase in drag by 4.7 % associated with the aircraft encountering a rain cloud with an LWC of 50 g/m^3 and thus, there will be a reduction in airspeed by 17.6 %. He also brought out that the instrument error other than the Rate of climb indicator & the air speed indicator is of small consequence.

In Haines & Luerst[4] conducted research on the frequency and intensity of rain on the aerodynamic penalties due to torrential rainfall rates (100 - 2000 mm/hr) and their effects on landing aircraft during heavy rainfall. From their research study, they estimated that the increase in the drag coefficient of an aircraft due to drop cratering and wave-induced roughness is around 5 % to 10 % at rainfall rates of 100 mm/h increasing to 30 % - 50 % at a rainfall rate of 2000 mm/h. The loss in maximum lift coefficient due to roughness associated with drop impact cratering is around 37 % at 100 mm/h rainfall to more than 30 % at higher rates. Loss in maximum lift due to film waviness is around 11 % to 30 % depending upon the rainfall rate. Reduction in stall angle of 1° to 6° and a corresponding increase in stall speed also result from these penalties to maximum lift.

To further investigate the effects of heavy rain, Hansman & Craig[5] conducted experiments and CFD simulation on Wortmann FX67-K170, and NACA 0012 and NACA 64-210 airfoils at a 1000 mm/hr rainfall rate and LWC of 30 g/m^3 for the Reynolds number of 3.1×10^5. They reported that at low angles of attack, the degradation in lift characteristics due to wet conditions varied significantly between the airfoils. Their experimental results show a lift reduction of 25 % for Wortmann FX67-K170, 15 % for NACA0012, and minimal for NACA 64-210 airfoil. The severity of the performance degradation for the airfoils varied due to the susceptibility of each airfoil to premature boundary-layer transition.

In the last two decades, Computational Fluid Dynamics (CFD) numerical simulation has been rapidly developing. Since the 1990s, many researchers have carried out CFD simulations for rain based on similarity criteria for rainfall measurement, the characteristics of the wing surface droplet splash, and therefore the aerodynamic effect analysis of the wing (Valentine & Decker 1995)[6]. In 1992, Gaudy Gaudy M Bezos[7], *et al.* carried out the wind tunnel rain system simulation for a thunderstorm-type rain ranging from 16 to 46 g/m^3 at Reynolds number of 2.6×10^6 and 3.3×10^6 and subsonic tunnel on NACA0012 symmetrical and NACA 64-210 cambered airfoil with leading edge and trailing edge high lift devices. From the test, they found that the NACA0012 symmetrical airfoil performance losses in the rain environment are not a function of LWC whereas cambered airfoil performance degradation like a decrease in the lift, increase in drag, and increase in slope of pitching moment is the function of LWC and test velocity. Their study also indicates that rain effect sensitivity to camber. Both airfoil shows a significant reduction in maximum lift and an increase in drag in a simulated rain condition. They also found out that the landing configuration as well as the rear element deflected condition were more sensitive to rain environment than the cruise configuration.

Valentine & Decker[8] studied the effect of splashback that occurs when rain droplets impact an airfoil. The droplet impact results in an ejecta fog of small droplets near the leading edge of the NACA 64-210 airfoil. Three rainfall rates (100, 300 & 500 mm/hr) are studied using the tracking or lagrangian scheme with a thin layer Navier-Stokes code. From the numerical results, they show a region of high droplet concentration corresponding to the ejecta fog and water bow wave observed experimentally. Also, the drag of splashed back droplets acts as a momentum sink near the leading edge of the airfoil and has the potential to de-energize the boundary layer and contribute to a degradation of airfoil performance in rain.

Wan & Wu[9] numerically simulated the effects of heavy rain on airfoils, considering the water film layer and vertical rain mass flow rate on the airfoil's upper surface, which resulted in increased airfoil roughening effects. Wu studied a transport-type airfoil, NACA 64-210, and concluded that the maximum decrease in lift (Cl) was 13.2 % and the maximum increase in drag (Cd) was 47.6 % in heavy rain conditions.

3. GEOMETRICAL AND FLOW CONDITIONS USED FOR CFD SIMULATION

A MALE UAV with a high aspect ratio tapered wing and T-Tail configuration is selected for CFD simulation. Wing has a span of 20.6 m, MAC (Mean Aerodynamic Chord) of 1.09 m, and a wing setting of 6°. It has a geometrical twist of -3°. Other parameters are not given due to confidentiality.

CFD simulation was carried out for the α sweep between -8° to 14° with β = 0.0° at M = 0.1089 (V = 42.07 m/s), and an altitude of 1.54 km (5000 ft.) for Indian atmospheric conditions (P_{ref} = 84.3 kPa, T_{ref} = 293.2 K). Torrential rainfall rate (R) of 100 mm/hr. - 2000 mm/hr. is considered. LWC is calculated and taken as 3.73 – 46.14 g/m^3. As summarized in Cao[1], *et al*., given a value of R, the liquid water content (LWC) in the rain can be taken by following Marshall and Palmer[10]. Droplet size distribution and their terminal velocity can be calculated following Joss and Waldvogel[11] and Markowitz[12]. The rain properties for R = 1000 mm/hr. is given in Table 1. Reference 13 provides the procedure to estimate the rain properties required for rain CFD simulation. Droplet evaporation to water vapour, secondary aero break-up, and wall impingement effects are taken into account[13].

4. GRID AND COMPUTATIONAL DETAILS

Figure 1 shows the surface mesh of the MALE UAV used for the CFD simulation. A hybrid mesh is prepared using ICEM CFD software. The element size on the aircraft surface is given between 1 mm to 60 mm (depending on the curvature and size of the surface) and for far-field it is given as 10000 mm. A spherical computation domain of radius 100 times the MAC of the wing is created. The surface element size of the aircraft is selected depending on location to capture the actual surface contour. A total of 24 prism layers are created between the surface and volume elements to capture the viscous and non-linear characteristics. A total of 43 million tetrahedral cells & and 66 million Penta cells are generated for discretising the computational domain. This mesh used for CFD simulation arrived after carrying out a grid independence study with varying surface element sizes and number of prism layers.

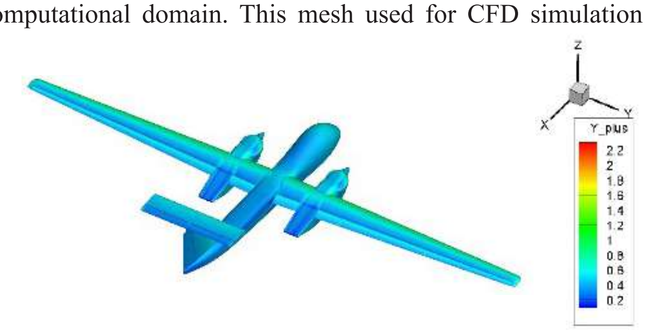

Figure 2. Yplus contour for MALE UAV without rain effect at α=4°.

CFD++ software[13] with preconditioned compressible Navier-Stokes solver and Spalart-Allmaras turbulence model is used for the rain CFD simulations. The water droplets required for rain simulation are accounted for using the Eulerian Dispersed Phase (EDP) formulation[13], which allows for two-way mass, momentum, and energy interactions across the rain droplets and atmospheric air.

Table 1. Rain properties considered for rain simulation[1] at α= 0° (Y – Vel = 0 as side slip angle (β) is 0°) and rainfall rate(R) = 1000 mm/hr.

Rain droplet size (mm)	Fluidised density (kg/m$^{3)}$	Number of droplets/m^3 volume	X-Vel (m/s)	Z-Vel (m/s)
1	0.0015	2781	42.07	-3.88
2	0.0046	1104	42. 07	-6.55
3	0.0062	438	42. 07	-8.05
4	0.0058	174	42. 07	-8.83
5	0.0045	69	42. 07	-9.22
6	0.0031	27	42. 07	-9.41

5. RESULTS AND DISCUSSION

To bring out the effect of rain on MALE UAV with TEAW, CFD simulations are carried out in the absence and presence of torrential rainfall with various rates (100 mm/hr. to 2000 mm/hr.). Figures 2 show the surface Yplus contour for MALE UAV without rain effect at α= 4 º.

The sectional, surface (top) streamlines pattern of the wing at 25 %, 50 % & 75 % span, and the corresponding sectional C_p plot at α=10° and R=1000 mm/hr are shown in Fig. 3 and Fig. 4 respectively. A comparison of the sectional C_p plot and streamline pattern shows that there is a reduction in flow acceleration on the top surface of the wing in the presence of rain as shown in Fig. 3 and Fig. 4. Also, there is an advancement in the point of flow separation on the top surface of the wing. These effects are due to the accumulation of rain droplets on the surface of the wing which forms a wavy and uneven water film on the surface that leads to an increase in the surface roughness and hence an increase in skin friction[6-8]. The sectional and surface streamline pattern and C_p plot comparison also shows the flow deceleration due to rain is higher near to root region compared with the tip region of the wing. It is due to a delay in the tip stall because of the wing geometrical twist. A change in the pressure distribution can also be induced as seen in Fig. 4. The spanwise lift coefficient distribution comparison for port wing with and without rain effect for the (non-linear α range) α=8º to 12º, β=0º shows that the wing lift starts reducing after α=10º for wing with rain effect and after α=12 º for wing without rain effect at R = 1000 mm/hr. as shown in Fig. 5.

Figure 6 shows the sectional contour of the number density for 3 mm droplet size in the vicinity of the gap between the primary and secondary elements α=4° and R = 1500 mm/hr.

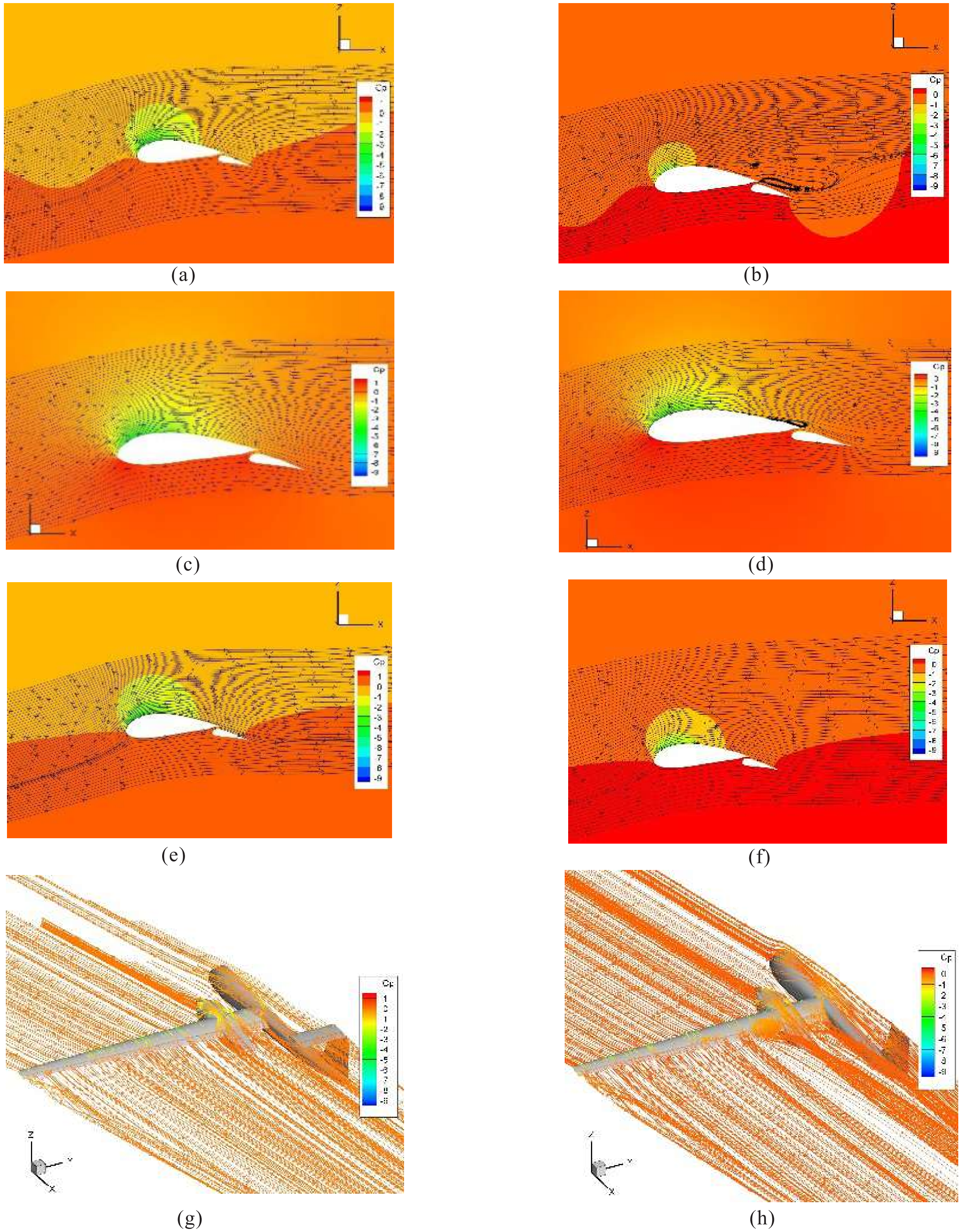

Figure 3. Sectional and top surface streamlines pattern of the wing at 25 %, 50 % & 75 % span at α = 10° and R = 1000 mm/hr. (a) Without rain at 25% of the wing span; (b) With rain at 25% of the wing span; (c) Without rain at 50 % of the wing span; (d) With rain at 50 % of the wing span; (e) Without rain at 75 % of the wing span; (f) With rain at 75 % of the wing span; (g) Without rain; and (h) With rain.

Comparison plots C_L, C_D, C_m vs α for MALE UAV with and without rain effect and its delta effects due to rain are shown in Fig. 7 to Fig. 9. The comparison of C_D *vs* α plot shows the drag value increases with rainfall rate as well as LWC. The comparison of C_L *vs* α plot shows lift value starts decreasing after α= 4º and the stall alpha decreases by 2 degrees due to torrential rainfall[6-8]. The comparison of C_m *vs* α plot shows pitching

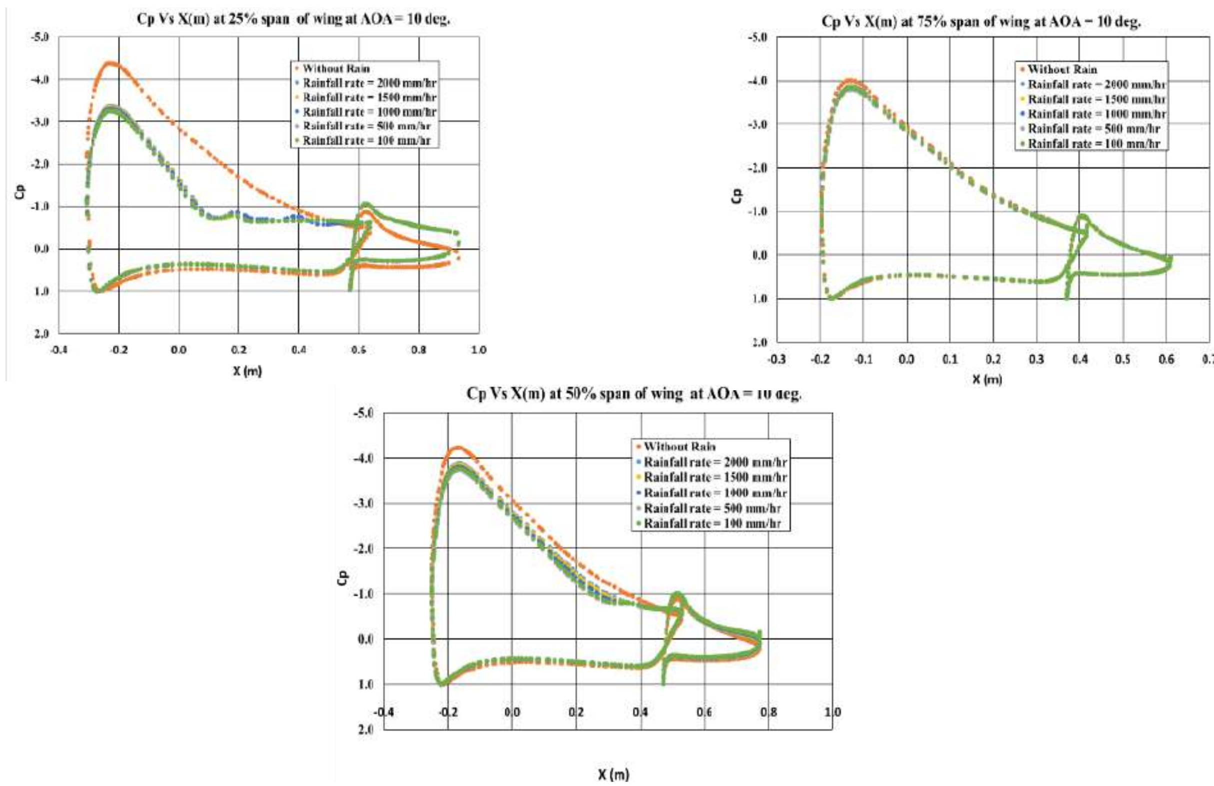

Figure 4. Sectional C_p plot at 25 %, 50 % & 75 % span of the wing α = 10° and R = 1000 mm/hr.

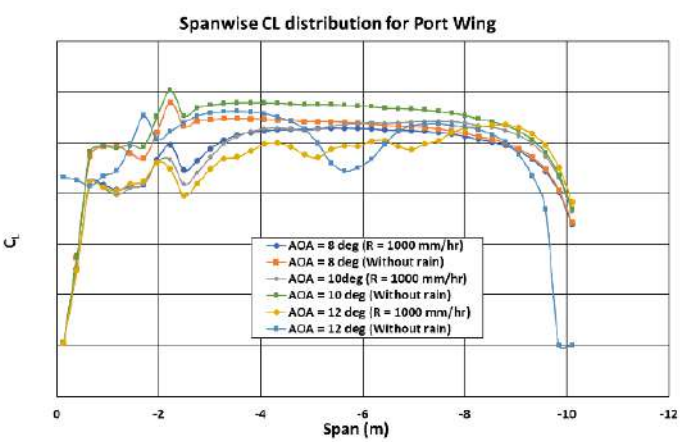

Figure 5. Spanwise C_L distribution with and without rain effect for MALE UAV with TEAW at α=8° - 12° R = 1000 mm/hr. V= 42.07 m/s & Alt = 1.54 km.

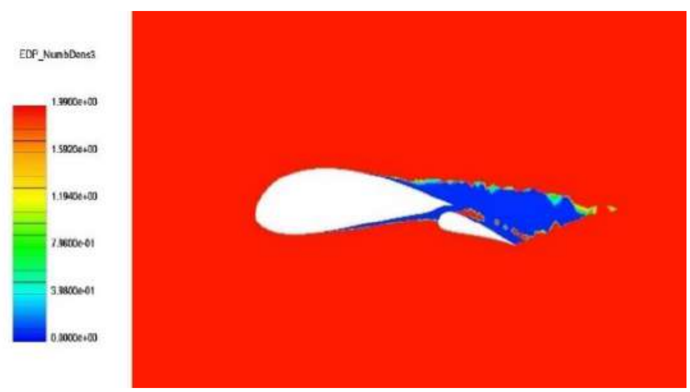

Figure 6. EDP number Density contour with droplet size of 3mm at wing Mid-span section α = 4°, V=42.07m/s & R = 1500 mm/hr.

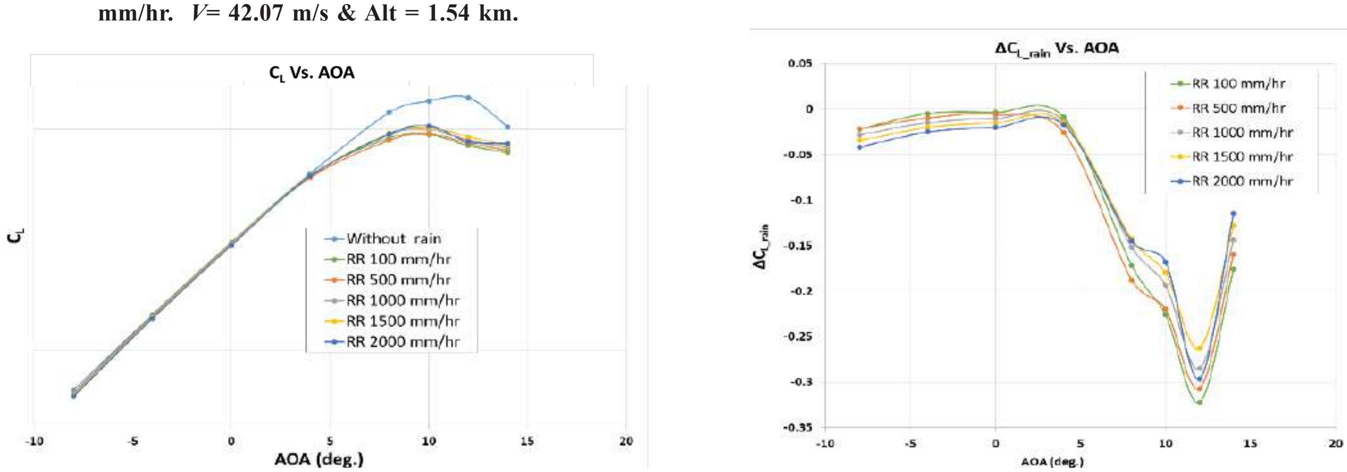

Figure 7. C_L vs α with & without rain Effect and ΔC_{L_rain} vs α for MALE UAV with TEAW.

moment coefficient slope starts increasing after $\alpha = 4^o$. It is due to the downward and backward moment imparted by the raindrops striking the UAV[7]. From the study, it is observed that there is an increase in drag by 10 % to 20 % and decrease in a lift by 0.29 % to 8 % at rainfall rate of 100 mm/hr, increase in drag by 30 % to 34 %, decrease in lift by 0.48 to 8.9 % at rainfall rate of 500 mm/hr, increase in drag by 37 % to 61 %, decrease in lift by 0.75 % to 7 % at rainfall rate of 1000 mm/hr, increase in drag by 42 % to 86 %, decrease in lift by 1 % to 7 % at rainfall rate of 1500 mm/hr and increase in drag by 52 % to 110 %, decrease in lift by 1 % to 7 % at rainfall rate of 2000 mm/hr in linear operating α region of -4° to +8°. A summary of the delta changes in aerodynamic force and moment coefficients due to R = 1000 mm/hr. is provided in Table 2. Table 3 provides the inviscid, viscous, and EDP components of C_L and C_D in percentage because of R = 1000 mm/hr. A comparison of viscous and inviscid components of C_L and C_D and its percentage due to rain shows that the inviscid component of lift reduction is greater than the viscous component, whereas the increase in the viscous component of drag is greater than the inviscid component.

From the study, there is an increase in drag by 40 % – 60 % in linear flight operating alpha (α = -4° to 8°), Rate of climb reduction of 0.6 m/s, V_{max} reduction of 8 m/s and C_{Lmax} reduction of 9.5 % at 5000 feet altitude were observed due to

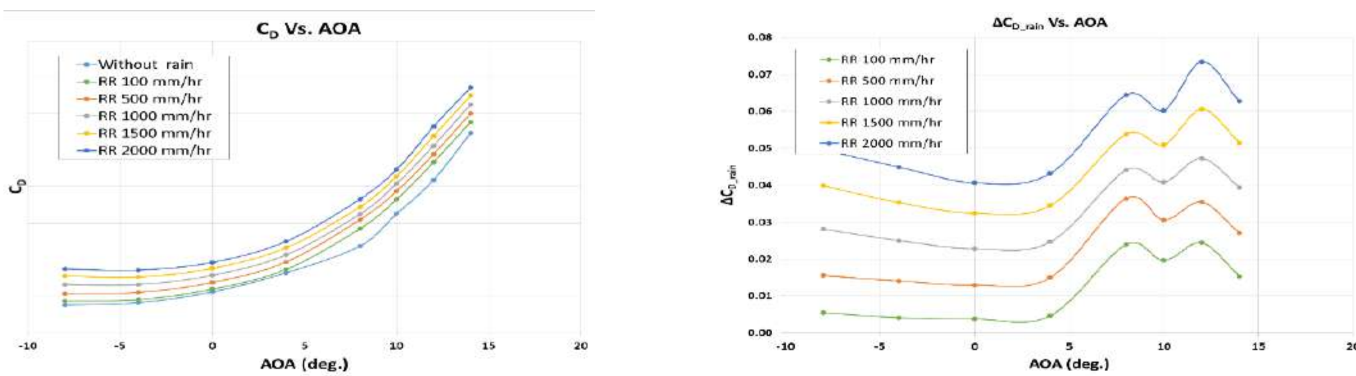

Figure 8. C_D *vs* α **with & without rain effect and** ΔC_{D_rain} *vs* α **for MALE UAV with TEAW.**

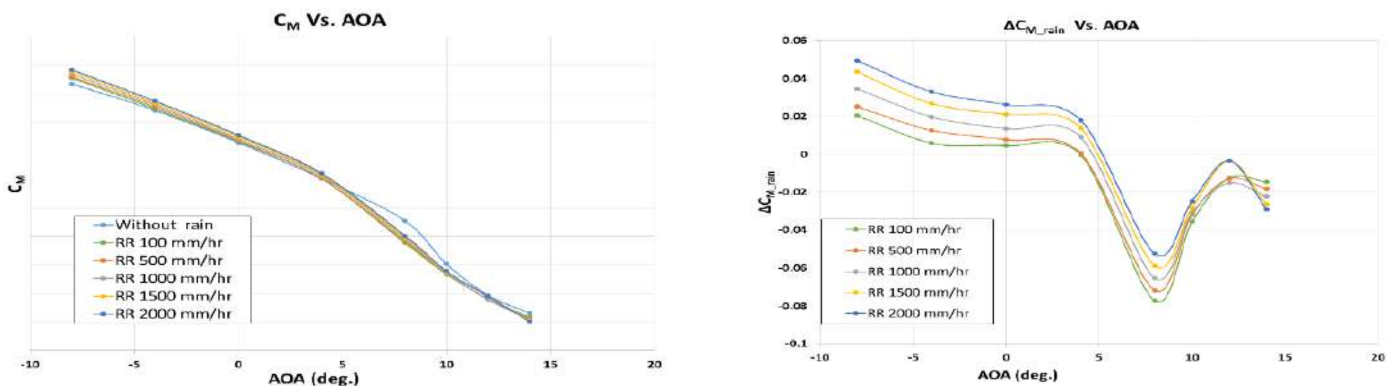

Figure 9. C_m *vs* α **with & without rain effect and** ΔC_{M_rain} *vs* α **for MALE UAV with TEAW.**

Table 2. Change in Aerodynamic characteristics of TEAW MALE UAV due to rain at R = 1000 mm/hr

α (deg)	ΔC_L	ΔC_D	ΔC_M	ΔC_L(%)	ΔC_D(%)
-8	-0.0282	0.0281	0.0345	-12.03	74.90
-4	-0.0150	0.0250	0.0197	-2.02	61.33
0	-0.0102	0.0228	0.0134	-0.83	41.11
4	-0.0127	0.0246	0.0089	-0.75	30.10
8	-0.1513	0.0440	-0.0654	-7.17	37.16
10	-0.1934	0.0408	-0.0307	-8.85	25.05
12	-0.2851	0.0472	-0.0152	-12.91	22.62
14	-0.1439	0.0394	-0.0224	-7.14	14.41

Table 3. Inviscid (inv), viscous(vis) & EDP component of C_L & C_D in % due to rain at R = 1000 mm/hr

α (deg)	$\Delta C_{L\,inv}$ (%)	$\Delta C_{L\,vis}$ (%)	$\Delta C_{L\,EDP}$ (%)	$\Delta C_{D\,inv}$ (%)	$\Delta C_{D\,vis}$ (%)	$\Delta C_{D\,EDP}$ (%)
-8	-11.59	1.22	-1.66	20.96	47.08	6.86
-4	-1.90	0.28	-0.40	19.69	36.04	5.60
0	-0.87	0.12	-0.07	14.26	22.80	4.05
4	-0.89	0.03	0.10	10.30	16.87	2.93
8	-7.46	-0.03	0.31	21.48	13.07	2.61
10	-9.11	-0.06	0.42	9.73	10.12	2.23
2	-13.30	-0.09	0.48	11.89	8.81	1.92
4	-7.52	-0.13	0.51	5.55	7.38	1.48

heavy rainfall rate of 1000 mm/hr. for the MALE UAV with TEAW.

6. CONCLUSION

CFD simulations have been carried out to study the effects of torrential rain on the aerodynamic characteristics of MALE UAV with TEAW using CFD++ software.

From the torrential rainfall rate study, an increase in drag along with a reduction in lift and a decrease in stall angle of 2 degrees is observed for the MALE UAV with TEAW due to the presence of rain droplets on the surface of the wing which leads to the formation of a wavy and uneven water film that effectively increases the surface roughness of the wing. This effect also includes the droplet presence in this region of the gap between the primary and secondary element[7] of TEAW which decelerates/de-energizes the boundary layer of the secondary element.

From the torrential rain effect study carried out for MALE UAV with TEAW using CFD methodology, there is an increase in drag by 40 % – 60 % in linear flight operating alpha (α = -4° to 8°), Rate of climb reduction of 0.6 m/s, V_{max} reduction of 8 m/s and C_{Lmax} reduction of 9.5 % were observed at 5000 feet altitude due to rainfall rate of 1000 mm/hr. Finally, this rain effect data will be used to formulate a Standard Operating Procedure (SOP) to fly MALE UAVs in torrential rainfall rates environments.

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CONTRIBUTORS

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In the current study, he has studied the effect of torrential rainfall on the aerodynamic characteristics of MALE UAV with two-element airfoil wing configuration.

Dr K.M. Parammasivam is a Professor and Head of the Aerospace Engineering Department of MIT, Anna University, Chennai. His areas of research are computational aerodynamics, combustion, wind energy, and vehicle aerodynamics.

In the current study, he has guided the adverse weather effect on the aerodynamic characteristics of MALE UAVs using CFD methodology.

Dr. S. Rajagopal obtained PhD in the area of multidisciplinary optimisation for UAV design from the Indian Institute of Science, Bengaluru. is a Scientist and presently the PGD (UAV) at DRDO-ADE, Bengaluru.
In the current study, he has guided the adverse weather on the Aerodynamic characteristics of MALE UAVs.