AERODYNAMIC PERFORMANCE INVESTIGATION OF A MODERN BLENDED-WING-BODY AIRCRAFT UNDER THE INFLUENCE OF HEAVY RAIN CONDITION

Tung Wan, Hei Yang
Department of Aerospace Engineering, Tamkang University
Tamsui, Taipei County, Taiwan, 251, Republic of China

Keywords: *blended-wing-body, heavy rain, two phase flow*

Abstract

Blended-Wing-Body (BWB) aircraft is the most fuel efficient flight vehicle in the future. Due to the intrinsic nature of its shape, the flight performance characteristics of BWB aircraft under severe weather conditions deserve special investigation, especially under the heavy rain condition. This paper first reviews some research findings in creating geometrical model of BWB configuration and the general aerodynamic performance degradation due to heavy rain effects. Then CFD tool is applied and the simulation of heavy rain is accomplished by using two-phase flow approaches. Results show that this work successfully simulates the BWB aerodynamic efficiency at cruise condition and the degradation effects under the heavy rain at low speed. It is expected that the quantitative information gained in this paper could be useful to the future BWB aircraft design and improve its flight performance characteristics.

1 Introduction

In order to cost down operation expenses, aviation industry always call for aircrafts that can fly more efficiently. Thus subsonic performance design of conventional large transport aircraft is in light of this way to revolutionize their aircraft shape. One of the non-conventional aircraft design concepts was proposed early as flying wing; and later on it evolves to become the Blended-Wing-Body (BWB) aircraft. BWB has a no tail design shape, whose configuration is an integration of fuselage and wing. This is a new conception distinct from classical aircraft, and compared with the customary tube-and-wing shape, its aircraft performance enhancement has long being recognized.

Generally speaking, the main aerodynamic advantage of the BWB is its lower area-to-volume ratio and the low induced drag compared with conventional aircraft. According to these reasons, the lift-to-drag (L/D) ratio of BWB aircraft can increase as much as 20% approximately then conventional aircraft [1], which can lead to millions of dollars saving in fuel cost for airline industries. Nowadays the aircrafts must fulfill with the stricter environmental requirements, and BWB seems to be the optimized transport aircraft in the future.

Currently, global warming issue has attracted public's attention. Its direct influences are the changes of weather pattern and, more important, the occurrences of severe and extreme weather. The severe weather also affects the aviation industry and flight safety, but no matter how we improve aviation safety, weather still and always will play an important role. For instance, the occurrence of thunderstorm is always accompanied by heavy rain shower and wind shear. While the hazard of wind shear has been fully investigated, and the peril factor of heavy rain effect is generally believed to be low comparing to wind shear threat, thus it is expected that heavy rain effect on aircrafts are not widely discussed in the aviation community.

Although there have been some experimental researches to analyze the aerodynamic efficiency penalties under heavy rain [2], there still have limited progress in numerical simulation. In 1994 and 1995, Valentine et al. [3, 4, 5], conducted a series numerical simulation to investigate the airfoil performance under heavy rain. Their research successfully simulates rain phenomenon on the airfoil, and the degradation of aerodynamic efficiency is achieved. In 2003, Wan at al. [6] conducted the numerical simulation of heavy rain on airfoil; the main issue of their research is to add vertical rain water flow rate and the water film artificially on the airfoil. That is, increasing the airfoil roughening effects and angle of attack. In 2009, Wan et al. [7] also extend rain physics on airfoil a step further via a two-phase-flow approach, and compare well with the experiments at different rain rates. Now current work is based on numerical simulation conducted by Wan and Pan and the experimental results by Bezos et al. [8], and the investigation of heavy rain effect is further extend to the modern three-dimensional BWB configuration.

2 Research Background

2.1 Aerodynamics of the Blended-Wing-Body Concept

In 1903, Wright Flyer designed and first flown, and then 44 years later the swept-wing Boeing B-47 took in air, it was mostly the fundamental subsonic jet transport design features at that time. The similarity is swept wing, empennage, and the engines hung beneath on pylons [9]. And after another 60 years later, Airbus A380 still appears to be essentially equivalent of B-47. On the other hand, the BWB has better lift-to-drag ratio (L/D) then conventional aircraft. The additional increment of the L/D ratio is described by the following reasons inherent in the BWB configurations: 1. the surface area of BWB is less then conventional aircraft which including body, wing, engine, and control surfaces. The total reduction of surface area could be as high as 33% with no corresponding frictional drag penalty [9]. 2. BWB has no clear fuselage, and the “fuselage” of BWB can also generate lift force. This is an obvious phenomenon distinction from classical aircraft.

It was observed that the total increase of lift-to-drag (L/D) ratio for the BWB configuration could be approximately as high as 20% compared to the conventional aircraft; and this is the reason that causes us to carry out comprehensive studying on a large-capacity BWB aircraft. BWB has been in the design arena long time ago. Early, BWB design was published by Northrop [10] who developed an all-wing aircraft shape in 1947. Later Lee had presented the possibility of cost reduction all-wing aircraft in 1965 [11]. In the late 1980s, NASA Langley developed and improved advanced technology subsonic transports for the design mission that has 800 passengers and 7000 n mile range at 0.85 Mach number cruise speed. But all these configurations are never left the design room due to various different reasons.

In the early 2000s, Russian designers Bolsunovsky et al. [12] combined research results on BWB, aerodynamic configuration, and structural concept to let them conforming to the FAR-25 prescription. Comparison with conventional aircraft shape confirmed the advantages of a BWB. In 2004, Liebeck et al. [9, 13] proposed their idea on the design of BWB subsonic transports, and they chronicle the technical development of BWB concept. Later Roman et al. studied aerodynamics of high subsonic BWB configurations, concluded that Mach number 0.93 has penalty performance relative to Mach number 0.85 [14]. When cruise Mach number increased, the lift-to-drag ratio (L/D) will decrease to lead the design unfeasible. In 2004, Qin et al. [15, 16] also calculated the aerodynamic performance of BWB aircraft. They carried out three-dimensional aerodynamic surface optimization of different BWB configurations and improved aerodynamic performance at cruise condition.

In this work BWB model is based on Qin’s model [15], because the aerodynamic optimization has already been achieved. Our approach refer to the geometric model with calculated L/D performance similar to the result done by Smith et al. [17], which is part of European Commission project entitled MOB—A computational design engine incorporating multidisciplinary design and optimization for BWB configuration [18]. So until now, the common consensus of flying wing and BWB has taken into the shape, but still no one investigate the heavy rain influence on BWB aircraft yet. And it is felt that because BWB's close similarity to a flat plate, its heavy rain effect deserves special attention.

2.2 Physics and Influences of an Airfoil in Rain

As for the heavy rain effect, in 1941 Rhode was the first one to do research of heavy rain on aircraft flight [19]. In the late 1980s, Hansman et al. [20] tested the performance of a small-scale wind-tunnel laminar flow for three different airfoils, Wortmann FX67-K170, NACA0012, and NACA64-210. The simulated rain rate is 1000 mm/hr at Reynolds number of 3.1×10^5. At low angles of attack, the lift degradation in wet conditions varied significantly for different airfoils. The Wortman section had the greatest lift degradation (~25%) and the NACA64-210 airfoil had the least (~5%). At high angles of attack, The NACA64-210 and NACA0012 airfoils were observed to have improved aerodynamics in rain conditions due to a reduction of boundary-layer separation. Since the dominated laminar flow on the dry airfoil was now tripped to turbulence; the original laminar flow separation behavior has been improved.

In the meantime, FAA and NASA developed a large-scale, ground-based outdoor test capability at the Langley Aircraft Landing Dynamics Facility (ALDF) in 1987 to assess the influence of rain on airfoil performance. The NACA64-210 airfoil section was choosing to be the tested wing and with a 10 ft chord and 13.1 ft span. A rain simulation system led by Bezos [8] was constructed along a 525 ft section of the track. The system produced realistic rainfall intensities of Liquid Water Content (LWC) and consistent with airborne and ground-based rain fall data measured in convective rainstorm. This outdoor, full-scale experiment is conducted due to the scaling difficulties of droplets diameters for extrapolation of subscale data to full scale conditions. In that study, the lift slope degradation has been revealed, and drag coefficient also increased with the rain rate increase. But due to wind tunnel characteristics and probably the outdoor interference effects, this test's no rain data is somewhat deviate from the classical NACA64-210 airfoil section test data.

In 1995, Valentine et al. presented the numerical simulation of heavy rain influence on NACA64-210 airfoil [3, 4, 5]. To assess the airfoil performance in rain, a two-way momentum coupled, two-phase flow scheme was deployed for the evaluation of the effect of splashed-back droplets on the airfoil. In their research, two physical phenomena had been hypothesized to be responsible for the degradation of airfoil performance in rain, the loss of boundary layer momentum to splashed back droplets and the effective roughening of the airfoil surface due to an uneven water film. The numerical results show a more severe rain induced stall but no change in airfoil performance until a stall angle is reached.

Recently Wan et al. investigated the same problem and conducted the numerical simulation of heavy rain effects on airfoil [6]. The primary objective of their study is to build up the thickness of water film on airfoil, and then to simulate the airfoil roughening effects by estimating the aerodynamics changed by rain. These properties included density, pressure, velocity, and angle of attack. In the end they combined all the factors and used the standard Navier-Stokes equation to solve the flow in heavy rain condition. In that study, there were total 7 cases investigated, with different airspeed, airfoil shape, and rain rates. The results indicated that at low Mach number with LWC=30 g/m^3, the lift coefficient decreased about 7.3% and drag coefficient increased as much as 38%.

In 2009, Wan et al. used CFD package FLUENT as the main analytical tools, the simulation of rain is accomplished by using two-phase flow approach's Discrete Phase Model (DPM) [7]. In that study, numerical computation compared well with Bezos' experimental data [8] for 25 g/m^3 and 39 g/m^3 LWC cases. Although differ from current 3-D configuration, their 2-D airfoil simulation result is still an important reference for our BWB research.

In general rainfall's intensity is measured in terms of Liquid Water Content (LWC) of the air or the mass of the water per unit volume of air. The relation between rainfall rate (R, mm/hr) to LWC (g/m^3) is determined to be [21]

$$LWC=0.054R0.84 \tag{1}$$

Subsequently, we should determine the rain droplet speed when impacting the airfoil, thus the terminal velocity of each rain droplet is necessary for our investigation. The meaning of rain droplet terminal velocity is that during free fall, the falling droplet is maintaining a constant speed and is not accelerating. The reason is that frictional drag force due to air and the gravity force are in equilibrium. It is assumed that when aircraft go through a severe thunderstorm during take-off or landing phases, the rain drops must fall at the terminal velocities at these low altitudes. Terminal velocity of a raindrop is function of droplet size and altitude, and it has been established by Marlowitz [22] as

$$V_T\left(m/s\right)=9.58\left\{1-\exp\left[-\left(\frac{D_d\left(mm\right)}{1.77}\right)^{1.147}\right]\right\} \tag{2}$$

where V_T is the terminal velocity, and the D_d is the rain droplet size in mm.

Several mechanisms have been hypothesized as contributing to the degradation of airfoil (or aircraft) performance in heavy rain. They can be categories as follows:

(a) The loss of aircraft momentum due to collisions with raindrops, but this effect is found to be negligible for 2-D airfoil,

(b) The effective roughening of the airfoil surface due to the presence of an uneven water layer,

(c) The loss of boundary layer air momentum due to splash back of droplets into the airflow field as raindrops strike the airfoil surface.

From the above literature review and physical phenomenon discussion, we can have a preliminary understanding on how heavy rain causes threat to aviation safety. But heavy rain's aerodynamic effects seem depend on Reynolds number, flight speed, angle of attack, and particularly the configuration. If BWB shaped aircraft is a thing for the future, then now is the time to design its configuration and examine its performance and efficiency. Obvious the BWB aircraft is more resemble to a flat plate, thus their heavy rain effect might be more relentless than conventional-shaped aircraft.

3 Numerical Modeling

Creating a geometry model from references is the first step in this work. Our geometry model is similar to Qin's baseline geometry model [15] which is a three-dimensional aerodynamic surface optimization. The software we choose in built up a 3-D configuration is Pro/ENGINEER. Our BWB consists of three parts, center body, inner wing, and outer wing. The center body is from 0 to 13 m span, and the payload is accommodation of passengers and cargo in it. The inner wing is from 13 to 23.5 m and this part of wing will host fuel tanks. Outer wing is from 23.5 to 38.75 m and then joins to winglet at the wingtip. For complex shapes like BWB, structure grid will somehow take more efforts than unstructured grid; thus we choose unstructured grid as the first attempt. Fig. 1 shown below is the final geometry model.

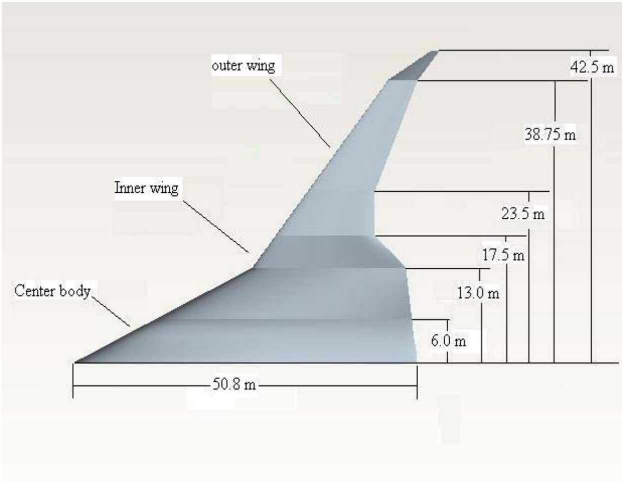

Fig. 1 Blended-Wing-Body geometry model

In this work the simulations are divided into two Reynolds number cases, 3.0×10^6 and 6.0×10^7; and flow behavior under these values are characterized as turbulent flows. In order to simulate realistic aircraft behavior under high Reynolds number flow condition, it is important to add turbulence model to the governing equation of our simulation. Reynolds-averaged approach to turbulence modeling requires that the Reynolds stresses be appropriately modeled. A common method is to employ the Boussinesq hypothesis in order to relate the Reynolds stresses to the mean velocity gradients. In current work the Spalart-Allmaras model is chosen for its widely aeronautical application and implemented as our tools.

Two different finite volume solvers were provided: pressure-based solver and density-based solver; and two pressure-based solver algorithms are also available: a segregated algorithm, and a coupled algorithm. In the segregated algorithm, the individual governing equations for the solution variables are solved one after another. However, the solution convergence is relatively slow, in as much as the equations are solved in a decoupled manner. Still, it is the method that most suitable for our two-phase flow computation. Thus, the segregated algorithm with standard SIMPLE scheme on the conservation, finite volume form of governing equations becomes our candidate flow solver.

Advances in CFD in last two decades have provided the basis for further insight into the dynamics of multiphase flows. Currently there are two approaches for the numerical calculation of multiphase flows: the Eulerian-Eulerian approach and the Eulerian- Lagrangian approach. The first approach is immediately discarded due to its strict limitation on the volume flow rate ratio. In Eulerian-Lagrangian approach, the fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, or droplets. In addition to solving transport equations for the continuous phase, it can simulate a second discrete phase in a Lagrangian reference frame. This model is called DPM (Discrete Phase Model). This second phase consists of spherical droplets dispersed in the continuous phase. Thus we can predict the trajectory of a discrete phase droplet by integrating the force balance on the particle, which is written in Lagrangian reference frame. As the trajectory of a particle is computed, it keeps track of the heat, mass, and momentum changed by the particle stream that follows the trajectory and these quantities can be incorporated in the subsequent continuous phase calculations. For heavy rain condition, we assume the rain rate is at LWC=39 g/m^3 and 25 g/m^3. In order to simulate the heavy rain phenomenon with the DPM model, the wall film model is also activated to model the water film on the airfoil, that is, the roughening effect. Finally, the two-way coupling between discrete phase and continuous phase is used. It is expected to simulate realistic rain behavior on the airfoil surface, so that more accurate aerodynamic efficiency degradation under heavy rain can be revealed.

Before we proceed to the numerical simulation of BWB, the accuracy of computational results should be validated. To achieve this is to choose ONERA M6 wing and through the comparison between experimental data, WIND simulation, and our numerical results. The verification of ONERA M6 wing is the three-dimensional, transonic, turbulent flow problem, with Mach number 0.8395, which is close to our BWB cruise condition. After numerous simulations, the hybrid type of grids seems achieve our purpose the most. In this case, total cells number is about 1.77 million and the Reynolds number is 11.72E+6.

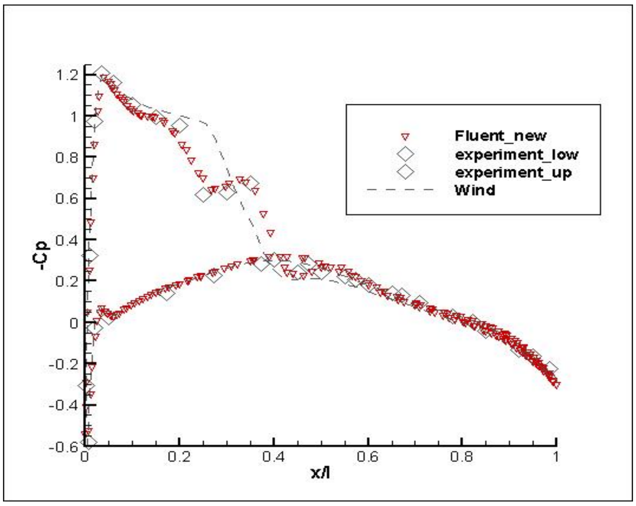

Fig. 2 Pressure coefficients on the wing surface at section (y/b)=0.80

With angle-of-attack (AOA) of 3.06 degree, the turbulence model used is Spalart-Allmaras model. This turbulence model might cause some unsatisfactory result at high AOA, which is mainly due to the unstable shear stress prediction at wall boundaries. However, the major issue we investigate here is at low AOA, and the same command will perform in the BWB case. The verification results are shown above as in Fig. 2 and our wall Yplus is all below 12, and obvious ours is slightly better than the bench mark computation work done by Wind, representing the expediency of our tool.

4. Results and Discussion

4.1 Blended-Wing-Body Simulation

Before the simulating calculation of the heavy rain, the geometry model of the BWB has to build up first. The main wing body consists of six wing section positions respectively at span stations: y=0.0, 1.0, 3.0, 6.0, 10.0, 13.0 m. The airfoil section at y=10.0, 13.0 m is symmetric. The airfoil of the outer wing at y=17.5, 23.5, 38.75 m is composed of supercritical airfoil. The winglet is making up linear interpolation of NACA0012 airfoil joining to outer wing. The average airfoil thickness to chord ratio distribution at different span location is approximate 17% in the center body, and reach to a maximum of 18% at 6 m span location. The twist distribution of the airfoil/wing profile is that near center body and outer wing twisted downward, and at the inner wing twists the opposite angle upward about the leading edge. The twist angle distribution of the BWB airfoil/wing is shown in Fig. 3

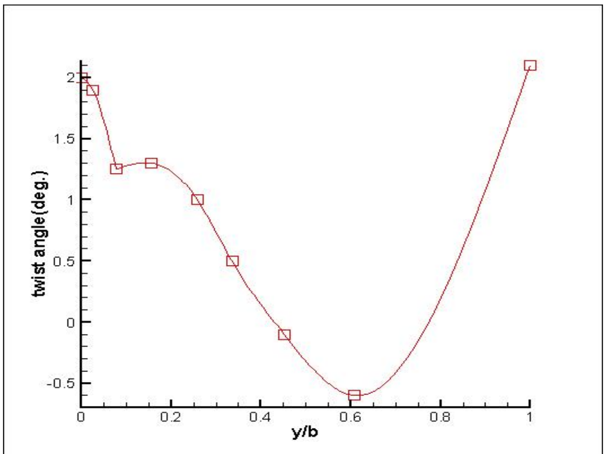

Fig. 3 BWB twist angle distribution

The leading edge sweep angle swept back 63.8 degree in the center body and swept back 38 degree at outer wing. This BWB possess a projection area of 756.24 m^2 for aerodynamic coefficient reference area consideration, and the mean aerodynamic chord (mac) length is 17.71 m. After building up the BWB geometry, we shall validate that the performance of our BWB design is indeed close to Qin's optimized shape. Our created geometry is as shown below and the resemblance is confirmed:

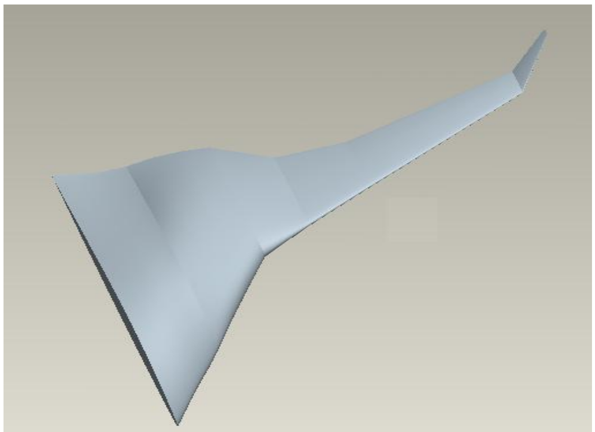

Fig. 4 Blended-Wing-Body

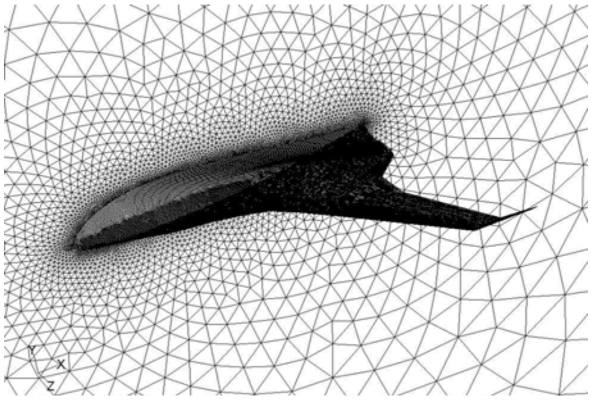

Figure 5 Near mesh of the Blended-Wing-Body

The simulated BWB with both twist angles and winglets that achieve our purpose is in Fig. 4. After the tedious process of the calculation and re-simulation, we have gained the best lift-to-drag (L/D) of 14.30 at 0.85 cruising Mach number, and wall Yplus value is approximate to be below 90. With the same Spalart-Allmaras turbulence model implemented, the total grid points are close to 3.45 millions in order to realize the above efficiency goal. Table 1 is the aerodynamic performance efficiency compared with the value achieved by Qin [15]. Although it cruises at a lower but more reasonable attitude, still we can attain a lift-to-drag ratio within 0.5% of the optimized objective.

Table 1 Aerodynamic efficiency of BWB

	AOA(deg)	C_L	C_D	L/D
Qin	3	0.4101	0.02855	14.37
Current	2	0.2468	0.01725	14.30

4.2 Heavy Rain Simulation

After designed the BWB at cruise condition, in this work we mainly concern about the worst heavy rain situation during take-off and landing, or for Liquid Water Content (LWC) of 39 g/m^3 at Reynolds number 3E+6 and 6E+7. First, considering the BWB fly at Reynolds number 3E+6 under the heavy rain condition is to make exact comparison with Bezos' experimental data [8]. Although the experimental data is at Reynolds number 2.6E+6, slightly differ from 3.0E+6. But the difference is negligible. The corresponding velocity of the BWB aircraft is now at an unrealistic value of 2.475 m/s, and the lift and drag coefficient change with respect to angle of attack diagrams are show below in Figs. 6 and 7.

In these two diagrams Bezos' experimental data represents a simulated 2-D airfoil section under LWC=39 g/m^3 heavy rain, and the two numerical data are for BWB simulations, with no rain and LWC=39 g/m^3 rain rate conditions. From Figs. 6 and 7, we observe first that there are significant difference between our BWB results and experimental data. The difference in lift curve slope and C_L value at zero angle of attack is due to the dissimilarities in geometry (2-D vs. BWB) and camber, just as expected. Also, the difference in drag can be entirely explained by geometric shape, 3-D BWB has more exposed wet area, thus lead to larger skin frictional drag. Beyond 12 degree angle of attack, our simulation becomes hard to converge. A fact either representing the intrinsic nature of BWB, or the discrepancy of our CFD tool, or both.

As for the BWB simulation, obviously the heavy rain rate will lead to a noticeable increase in drag, but contrary to our expectation, the decrease in lift is rather small. This disparity is again due to the different mechanism in lift and drag generation. Lift generated through an uneven distribution in pressure and velocity at upper and lower surfaces. For a swept 3-D configuration like BWB, the influence of tip vortex and cross flow is much stronger than the impact of rain droplet, thus the lift coefficient only degrade a little in heavy rain situation. This is a finding quite contrary to our expectation, differ from our 2-D simulation for NACA 64-210 airfoil and with high lift devices [7], and even differ from a no swept UAV wing results [23]. It is believed that the stronger cross flow on BWB's upper surface leads to lift's resistance to heavy rain, again a triumph for BWB design. As for the increase in drag, then obvious the mixture of air and rain droplet will have a somewhat larger shear stress value, so heavy rain will lead to larger skin frictional drag, and thus the larger total drag, just as expected.

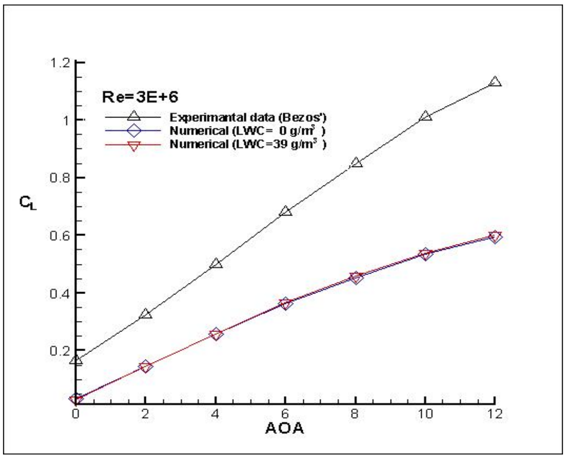

Fig. 6 Lift coefficients for 2 numerical results comparing to experiment data

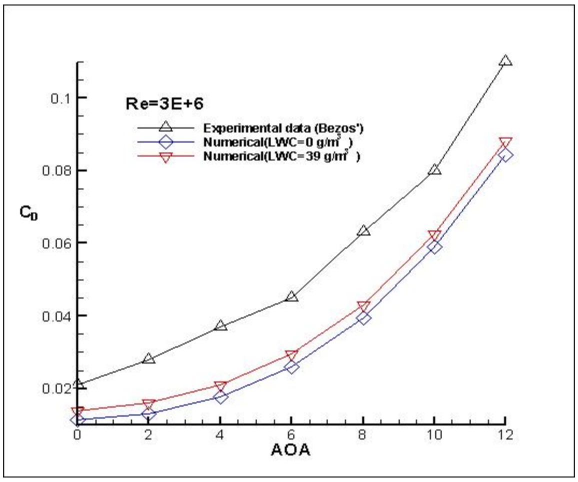

Fig. 7 Drag coefficients for 2 numerical results comparing to experiment data

Next, we need to further consider the real landing or take off situations. The take off/landing velocity is chosen to be 49.48 m/s (with Mach number 0.149), and it will lead to a more realistic Reynolds number 6.0E+7. Now the numerical simulation of BWB aircraft flies at Reynolds number 6.0E+7. Two heavy rain cases of LWC=25 g/m^3 and LWC=39 g/m^3 are both compared with Reynolds number 3.0E+6 data, lift and drag coefficients are as shown below in Figs. 8 and 9. Basically the lift curve show only slight variation with respect to Reynolds number or rain fall rate during take-off/landing phase, and the explanation is same as before, i.e. stronger cross flow effect.

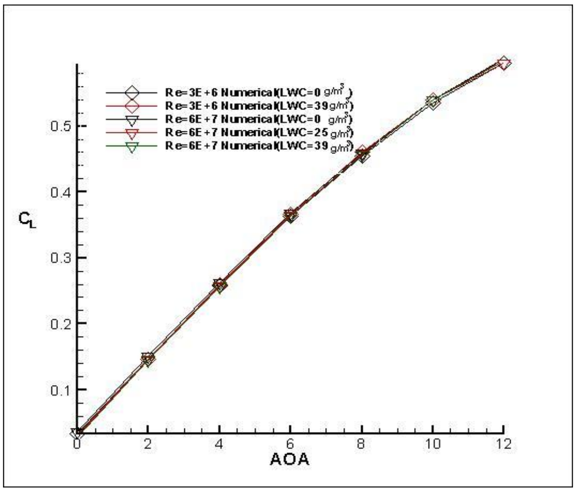

Fig. 8 BWB lift coefficients comparison for different rain rate

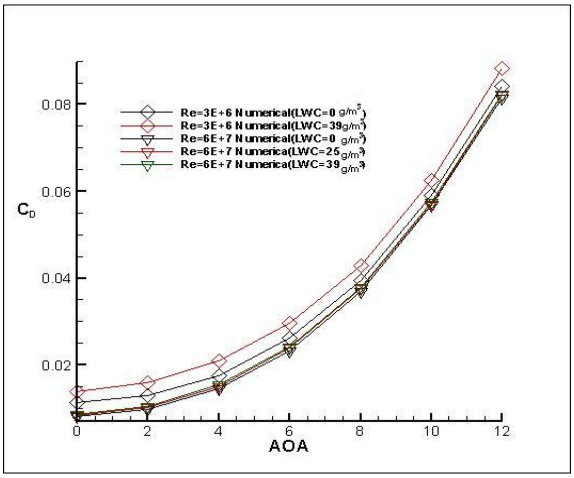

Fig. 9 BWB drag coefficients comparison for different rain rates

For drag coefficient then it will increase with a lesser amount at Reynolds number 6.0E+7, and its percentage increase is now varies from 4.83% to 22.8% at Re=3.0E+6 to 0.87% to 6.99% at Re=6.0E+7. It is observed that higher Reynolds number (higher relative air speed) actually help to increase the mixing effect of air-water mixture, and lead to a lesser water film layer, thus the drag increasing effect become diminishing. Also, the minimum drag increasing effect occurs at high angle of attack.

Degradation comparison of BWB lift and drag with NACA64-210 airfoil numerical and Bezos' experimental data with LWC=39g/m^3 and low speed condition are as shown in Figs. 10 and 11. There are large difference between the 2-D cases and 3-D BWB. At high angle-of-attack, the BWB lift or drag coefficient degradation percentage is always becoming less. This is mainly due to the larger absolute values at higher angle of attack. Results show that if the shape of airfoil is resemble to a flat surface, i.e. 2-D airfoil, then the rain droplet impact the area will cause larger degradation, just as we might expected. Fig. 12 also shows the BWB lift-to-drag ratio vs. angle of attack under the heavy rain during take-off/landing, and the L/D ratio could reach a maximum decrease of 1.60 or close to 10% decrease at 4 degree angle of attack. This represents a large amount of performance loss, is a simulation result that all future BWB aircraft designer or operational personnel should be warmed of. On the other hand, the maximum lift-to-drag ratio still occurred at 4 degree angle of attack, even during heavy rain situation.

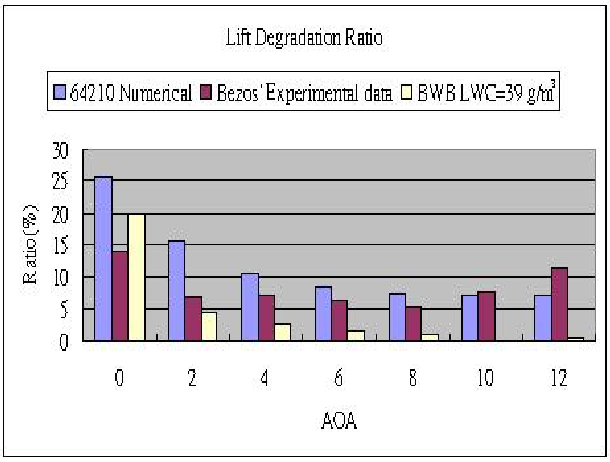

Fig. 10 Lift degradation comparison of BWB with NACA64-210 numerical and Bezos' data (LWC=39g/m^3)

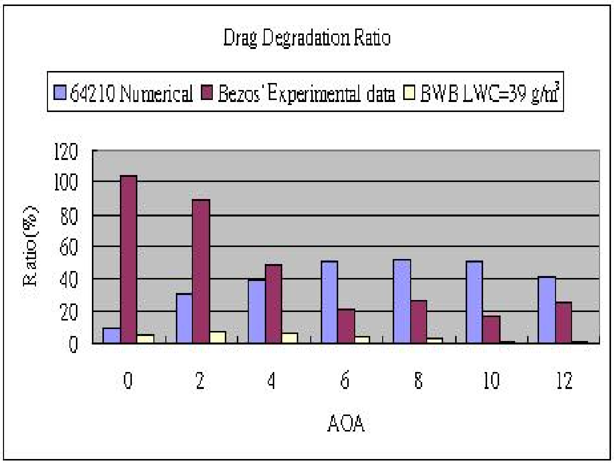

Fig. 11 Drag degradation comparison of BWB with NACA64-210 numerical and Bezos' data (LWC=39g/m^3)

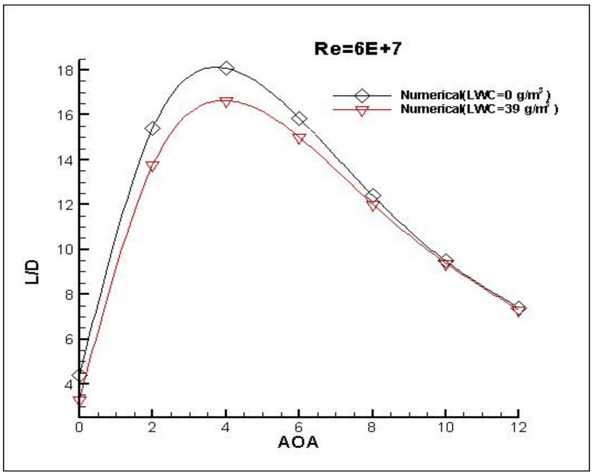

Fig. 12 Lift-to-Drag ratio change due to rain

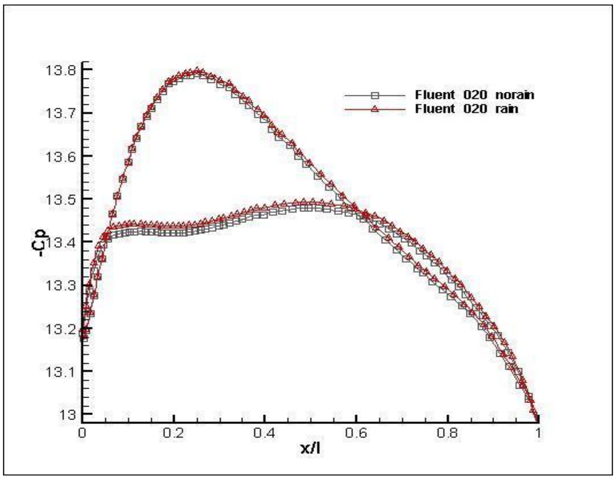

Fig. 13 Pressure coefficients on the wing surface at section (y/b)=0.20

In three-dimension numerical calculation, it is hard to display the mechanism of the two-phase flow simulation. Therefore, we must display pressure coefficient on the aircraft section profile. For conditions under the heavy rain, the numerical simulation data at angle of attack of 2 degree and the pressure coefficient on the wing surface at section y/b=0.20 is shown above in Fig. 13. Once again the validity of current method is being justified.

5. Conclusions

In this work, we first create the airfoil section profile at each span station, prove the importance of twist angle of Blended-Wing-Body wing and its winglet, and confirm that the geometrical model of the Blended-Wing-Body has the best lift-to-drag (L/D) ratio of 14.30 during cruise condition. For each heavy rain case we successfully simulate the aerodynamic performance degradation rate of a complete 3-D BWB aircraft by using a novel but realistic two-phase flow approach. The degree of degradation for our numerical calculation is smaller than the Bezos' experimental data for both the 25 g/m^3 and 39 g/m^3 rain rates. Considering the differences in geometrical model between the BWB shape of our design and Bezos' experimental data of a rectangular wing/airfoil, the simulation done in this work seems reasonable.

As for aerodynamic performance consideration, although the change of lift coefficient is somewhat hard to comprehend at very low velocity, but overall the computed lift-to-drag ratio degradation is conforming to the real physical phenomenon. For the low speed situation of take-off/landing phases under heavy rain, the lift coefficient is decreased, and the drag coefficient is increased. Finally, we verify that the BWB aerodynamic efficiency degradation under severe weather is slightly better than expected, but the numerical simulation of BWB under heavy rain is always an important parameter to consider for civil aviation company to design the next generation transport aircraft.

In the future, the geometrical model of our Blended-Wing-Body could still going through a deeper profile optimization for three-dimensional aerodynamic performance, and aircraft engine could also be added. Furthermore, the influence of different rain rate, cross wind, and the flow control will be the next focus of such topic in our Blended-Wing-Body related numerical simulation project.

Acknowledgement

The authors would like to express their sincere appreciation for the support of the National Science Council of the Republic of China for this project under the Contract No. NSC 98-2212-E-032-027.

References

[1] Eelman, S., D. Schmitt, A. Becker, and W. Granzeier, "Future Requirements and Concepts for Cabins of Blended Wing Body Configurations–A Scenario-Based Approach," *Journal of Air Transportation*, May 1, 2004.

[2] Luers, J. K. and P. A. Haines, "Heavy Rain Influence on Airplane Accidents," *Journal of Aircraft*, Vol. 20, No. 2, Feb. 1983, pp. 187-191.

[3] Valentine, J. R., "Airfoil Performance in Heavy Rain," *Transportation Research Record*, No. 1428, Jan. 1994, pp. 26-35.

[4] Valentine, J. R. and R. A. Decker, "Tracking of Raindrops in Flow over an Airfoil," *Journal of Aircraft*, Vol. 32, No. 1, Jan-Feb. 1995, pp. 100-105.

[5] Valentine, J. R. and R. A. Decker, "A Lagrangian-Eulerian Scheme for Flow around an Airfoil in Rain," *International Journal of Multiphase Flow*, Vol. 32, No. 1, 1995, pp. 639-648.

[6] Wan, T. and Wu S. W., "Aerodynamic Analysis under Influence of Heavy Rain," *Journal of Aeronautics, Astronautics, and Aviation*, Nol. 41, No.3, September 2009, pp.173-180.

[7] Wan, T. and Pan S. P., "Aerodynamic Efficiency Study under the Influence of Heavy Rain via Two-phase Flow Approach," *Proceedings of the 27th International Congress of Aeronautical Sciences (ICAS)*, Nice, France, September 19-24, 2010.

[8] Bezos, G. M. and B. A. Campbell, "Development of a Large-Scale, Outdoor, Ground-Based Test Capability for Evaluating the Effect of Rain on Airfoil Lift," NASA TM-4420, April 1993.

[9] Liebeck, R. H., "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, Vol. 41, No. 1, 2004, pp. 10-25.

[10] Northrop, J. K., "The Development of All-Wing Aircraft," *Journal of Royal Aeronautical Society*, Vol. 51, 1947, pp. 481-510.

[11] Lee, G. H., "The Possibilities of Cost Reduction with All-Wing Aircraft," *Journal of Royal Aeronautical Society*, Vol. 69, 1965, pp. 744-749.

[12] Bolsunovsky, A. L., N. P. Buzoverya, B. I. Gurevich, V. E. Denisov, A. I. Dunaevsky, L. M. Shkadov, O. V. Sonin, A. J. Udzhuhuand, and J. P. Zhurihin, "Flying Wing- Problems and Decisions," *Aircraft Design*, Vol. 4, Issue 4, December 2001, pp. 193-219.

[13] Liebeck, R. H., M. A. Page, and B. K. Rawdon, "Blended Wing Body Subsonic Commercial Transport," AIAA Paper 98-0438, 1998.

[14] Roman, D, R. Gilmore, and S. Wakayama, "Aerodynamics of High Subsonic Blended-Wing-Body Configurations," AIAA Paper 2003-0554, 2003.

[15] Qin, N., A. Vavalle, A. Le Moigne, M. Laban, K. Hackett, and P. Weinerfelt, "Aerodynamic Considerations of Blended Wing Body Aircraft," *Progress in Aerospace Sciences*, Vol. 40, 2004, pp. 321-343.

[16] Qin, N, A. Vavalle, A. Le Moigne, M. Laban, K. Huckett, and P. Weinerfelt, "Aerodynamic Studies of Blended Wing Body Aircraft," AIAA Paper 2002-5448, 2002.

[17] Smith, H. and A. Yarf-Abbasi, The MOB Blended Body Reference Aircraft, MOB Project Technical Report: MOB/4/CU/Treport/No4.

[18] Morris, A. J., MOB, "A European Distributed Multi-Disciplinary Design and Optimization Project," AIAA Paper 2002-5444, 2002.

[19] Rhode, R. V., "Some Effects of Rainfall on Flight of Airplanes and on Instrument Indications," NACA TN903, April 1941.

[20] Hansman, R. J. and A. P. Craig, "Low Reynolds Number Tests of NACA 64-210, NACA 0012, and Wortmann FX67-K170 Airfoil in Rain," *Journal of Aircraft*, Vol. 24, No. 8, 1987, pp. 269-276.

[21] Thompson, B. E., J. Jang, and J. L. Dion, "Wing Performance in Moderate Rain," *Journal of Aircraft*, Vol. 32, No. 5, Sept.-Oct. 1995, pp. 1034-1039.

[22] Markowitz, A. M., "Raindrop Size Distribution Expression," *Journal of Applied Meteorology*, Vol. 15, 1976, pp. 1029-1031.

[23] Tsai, P. C., C. H. Lin, and T. Wan, "A Two-phase Flow Approach for UAV Aerodynamic Study under Heavy Rain," *2009 AASRC/CSCA Joint Conference*, Taipei, Dec. 12, 2009.

[24] Dunham, R. E., Jr., "The Potential Influence of Rain on Airfoil Performance," von Karman Institute for Fluid Dynamics, 1987.

[25] Hasting, E. C., Jr. and G. S. Manuel, "Scale-Model Tests of Airfoils in Simulated Heavy Rain," *Journal of Aircraft*, Vol. 22, No. 6, June 1985, pp. 536-540.

[26] Haines, P. A. and J. K. Luers, "Aerodynamic Penalties of Heavy Rain on Landing Aircraft," *Journal of Aircraft*, Vol. 20, No. 2, Feb. 1983, pp. 111-119.

[27] Fluent's User Guide

[28] The ONERA M6 Wing, available on-line; URL: http://www.grc.nasa.gov/WWW/wind/valid/m6wing/m6wing01/m6wing01.html