The stall of different ice accretion airfoil

Yupeng Feng*
Technical Center, Chengdu Aircraft Industrial (Group) Co., Ltd, Chengdu, China

*Corresponding author e-mail: feng948837675@163.com

Abstract. Ice along the leading edge of upper surfaces have detrimental effects on performance and control of an aircraft. Various icing shapes airfoil have various influence on aerodynamic characteristics and stall phenomenon. The mechanics model, of which ice accretion zone is on the leading edge, is produced by the assembly of various ice shapes (rime ice and mixed ice) and NACA0012 airfoil, In order to analyse the cause of stall phenomenon. The Reynolds averaged Navier-Stokes (N-S) equations are solved using Spalart-Allmaras (S-A) turbulence models the entire flow field. The results show: 1) the stalling angle of attack is various in case of various ice shapes on the leading edge. The stalling angle of attack is 15.5° in case of none ice, about 9° in case of rime ice and about 7.8° in case of mixed ice. 2) The way of airflow separation is different in case of various ice shapes on the leading edge. The vortex zone is expanded from the trailing edge to the leading edge in case of rime ice. Both vortex zones at the leading edge and the trailing edge are expanding meanwhile into one vortex zone in case of mixed ice.

1. Introduction
Aircraft accidents continue to occur due to the formation of ice on aircraft in flight [1]. Ice along the leading edge of upper surfaces have detrimental effects on performance and control of an aircraft [2-3]. However, commercial aircraft continue to be in flight due to their revenue and schedules of must be maintained except the most severe icing conditions [1]. Ice condition bring the risk of flight and threaten the property security. So many experts paid their attention to the relevant icing questions and made relevant study in icing airfoil.

Addy [4] modified the airfoil model of icing leading edge considering the altitude, surface roughness and heat transfer law. William [5] analyze the detrimental effects on drag increase in case of various icing shapes airfoil. Broeren [6] obtain the aerodynamic characteristics considering the ice accretion on the leading edge of airfoil.

The study mentioned above do not explain how the stall phenomenon is brought forward and the range of attack angle is narrowed. In order to analyze the cause of stall phenomenon, the icing-NACA0012 airfoil are established based on the N-S equation and S-A turbulence model to calculate the flow field around airfoil and aerodynamic characteristic.
2. Numerical method

2.1. Mechanical Model
In this paper, the mechanics model, of which ice accretion zone is on the leading edge, is produced by the assembly of various ice shapes (rime ice and mixed ice [7]) and NACA0012 airfoil.

![Shapes of the leading edge with ice.](image)

2.2. Governing Equations
The governing equations considering the different icing-airfoil is be written in Cartesian coordinates as follows:

\[
\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \frac{\partial \mathbf{s}_x}{\partial x} + \frac{\partial \mathbf{s}_y}{\partial y}
\]

Where \( \mathbf{u} \) indicates flow vector; \( \mathbf{f} \) and \( \mathbf{g} \) are the components of flow flux in the x and y directions, respectively; \( \mathbf{s}_x \) and \( \mathbf{s}_y \) are the sum of viscous stresses and heat exchange flux in the x and y directions, respectively.

2.3. Numerical model
The finite volume model is showed in Fig. 2. The chord of airfoil, L, is 1 m. The far-field boundary is established to circular by the leading edge as center and 15 times characteristic length as radius. The grid is an O type and the mesh is all quadrilateral. This domain is meshed with 19683 elements and 19440 nodes. The boundary layer around airfoil is local grid refinement. The boundary conditions (BCs) is listed in the Table 1. Reynolds number is 2.88×10^6.

![Finite element volume model.](image)

| Type               | Operating pressure(pa) | Ma  | Temperature (K) |
|--------------------|------------------------|-----|-----------------|
| pressure-far-field | 101832                 | 0.162 | 288             |
The Reynolds averaged N-S equations are solved using S-A turbulence models the entire flow area. Turbulent viscosity ratio is 2, the explicit relaxation factor of force and moment 0.3, the convergence condition 0.001. No-slip boundary is imposed at the surfaces of airfoil.

2.4. Verification of Algorithm
Fig. 3 illustrates the calculated pressure distribution around airfoil at the attack angle, $\alpha = 10^\circ$. To compare with the experiment test \[8\], so that we also put the data of the wind tunnel in Fig. 3. The results show that numerical data calculated by S-A model is in excellent agreement with the wind tunnel data. It is verified that the numerical method can solve entire flow area well at the big attack angle.

![Figure 3. Pressure distribution on NACA0012 airfoil.](image)

3. Numerical Result
Various icing airfoil model are calculated by the numerical method mentioned above. Fig. 4 and Fig. 5 illustrate the lift/drag characteristics in conditions of ice accretion (none, rime and mixed ice) on the leading edge.

The result shows that the stalling angle of attack is various in case of different ice shapes on the leading edge. The stalling angle of attack is $15.5^\circ$ in case of none ice, about $9^\circ$ in case of rime ice and about $7.8^\circ$ in case of mixed ice.

![Figure 4. Lift coefficient.](image) ![Figure 5. Drag coefficient.](image)

4. Discussion
Ice accretion have the effect on the flow field around airfoil and contribute to the stalling angle of attack decreased. Additionally, how the stall phenomenon is produced is also various.

The stalling angle of attack of rime ice airfoil, $\alpha_{\text{stall}}$, is $9^\circ$. The angle of attack, $\alpha_{\text{stall}} + 0^\circ$, $\alpha_{\text{stall}} + 0.5^\circ$
and $\alpha_{\text{stall}} + 1.0^\circ$, are chosen to analyze the cause to stall by the contour plot of pressure and contour plot of Ma and flow field.

Fig. 6, Fig. 7 and Fig. 8 illustrate that the pressure coefficient distribute, the contour plot of pressure and contour plot of Ma and flow field around rime ice airfoil, respectively. From Fig. 6, Fig. 7 and Fig. 8, we can observe: 1) with the angle of attack increasing by, the pressure gradient where $x/L$ is at 0%, the leading edge is decreasing which is not good for the air flow accelerated around the leading edge of upper surface. Ma is decreasing and pressure is increasing on the leading edge; 2) the flow separation is not produced where $x/L$ is at the range of 0~45%, due to the pressure coefficient on upper surface is increasing and Ma is decreasing with the angle of attack increasing by; 3) the flow separation is produced where $x/L$ is at the range of 45~100%, due to the pressure coefficient on upper surface and Ma are decreasing with the angle of attack increasing by, respectively. What’s more, the vortex zone is expanded from the trailing edge to the leading edge. The vortex zone expand to 80% of chord where the angle of attack is $\alpha_{\text{stall}} + 0.5^\circ$ and 45% of chord where the angle of attack is $\alpha_{\text{stall}} + 1.0^\circ$.

![Figure 6. Pressure distribution on the rime ice airfoil.](image)

![Figure 7. Contour plot of pressure on the rime ice airfoil.](image)

![Figure 8. Contour plot of Ma and flow field on the rime ice airfoil.](image)
The stalling angle of attack of mixed ice airfoil, $\alpha_{stall}$, is 7.8°. The angle of attack, $\alpha_{stall} +0^\circ$, $\alpha_{stall} +0.1^\circ$ and $\alpha_{stall} +0.2^\circ$, are chosen to analyze the cause to stall by the contour plot of pressure and contour plot of Ma and flow field.

Fig. 9, Fig. 10 and Fig. 11 illustrate that the pressure coefficient distribute, the contour plot of pressure and contour plot of Ma and flow field around mixed ice airfoil, respectively. From Fig. 9, Fig. 10 and Fig. 11, we can observe: 1) the pressure peak is on leading edge of upper surface, the airflow is accelerated due to the pressure gradient at front of the peak and the airflow slowdown due to the adverse pressure gradient at below of the peak; 2) as the angle of attack increases by, the pressure peak is decreasing. The airflow accelerated weaken due to the pressure gradient decreases at front of peak and the vortex flow is produced. The pressure sustain unchanged at the vortex zone, so airflow separation is produced; 3) both the pressure coefficient and Ma are decreasing at the trailing edge of airfoil, vortex and airflow separation are exist; 4) with the angle of attack increasing by, both vortex zones at the leading edge and the trailing edge are expanding and finally they become into one vortex zone.

**Figure 9.** Pressure distribution on the mixed ice airfoil.

**Figure 10.** Contour plot of pressure on the mixed ice airfoil.

**Figure 11.** Contour plot of Ma and flow field on the mixed ice airfoil.
5. Conclusion
From the study mentioned above, the conclusions can be made:

1) The stalling angle of attack is various in case of various ice shapes on the leading edge. The stalling angle of attack is 15.5° in case of none ice, about 9° in case of rime ice and about 7.8° in case of mixed ice.

2) The way of airflow separation is different in case of various ice shapes on the leading edge. The vortex zone is expanded from the trailing edge to the leading edge in case of rime ice. Both vortex zones at the leading edge and the trailing edge are expanding meanwhile into one vortex zone in case of mixed ice.

References
[1] M. B. Bragg, T. Hutchison, J. Merret, R. Oltman and D. Pokhariyal, Effect of Ice Accretion on Aircraft Flight Dynamics. 38th AIAA Aerospace Sciences Meeting & Exhibit. AIAA 2000-0360.
[2] A. Lampton, J. Valasek, Prediction of icing effects on the lateral/directional stability and control of light airplanes. Aerospace Science and Technology (2011), doi:10.1016/j.ast.2011.08.005.
[3] A. Lampton, J. Valasek, Prediction of Icing Effects on the Coupled Dynamic Response of Light Airplanes. Journal of Guidance, Control, and Dynamics. 31(2008) 656-673.
[4] H. E. Jr. Addy, D. Orchard, W. B. Wright, M. Oleskiw, Altitude Effects on Thermal Ice Protection System Performance; a Study of an Alternative Approach. NASA, TM-219081.(2016)
[5] W. Olsen, R. Shaw, J. Newton, Ice Shapes and the Resulting Drag Increase for a NACA 0012 Airfoil. NASA TM-83556.
[6] A. P. Broeren, M. G. Potapczuk, J. T. Riley, P. Villedieu, F. Moens, M. B. Bragg, Swept-Wing Ice Accretion Characterization and Aerodynamics. NASA TM-216555. (2013)
[7] W. J. Chen, D. L. Zhang, Numerical Simulation of Ice Accretion on Airfoils. Journal of Aerospace Power. 20 (2005) 1010-1017.
[8] N. Gregory, C. L. O’Reilly, Low-speed aerodynamics of NACA0012 airfoil section, including the effects of upper-surface roughness simulation hoar frost. National Physical Laboratory, NPL Aero Report 1308. (1970)