Lift/Drag Characteristics of Different Ice Accretion Airfoil

Yupeng Feng*, Bin Zhang#, Bin Chen$	extsuperscript{b}$

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

*Corresponding author e-mail: feng948837675@163.com, #710657546@qq.com, bcbin54321@163.com

Abstract. Aircraft icing has influence on the preliminary safety and performance evaluation of airplane. In this paper, based on different ice shapes (none, rime, mixed), the aerodynamic models of airfoil are established to analyze. Various lift/drag characteristics are obtained by numerical simulation using computational fluid dynamics (CFD) under different icing conditions. Navier-Stokes (N-S) equation and Spalart-Allmaras (S-A) turbulence model are adopted. The results show: 1. It’s obvious that lift-drag characteristics are different under various ice shapes. The lift coefficient ($\alpha=0^\circ \sim 7^\circ$): $CL_{\text{none}} > CL_{\text{rime}} > CL_{\text{mixed}}$, the drag coefficient ($\alpha=0^\circ \sim 7^\circ$): $CD_{\text{none}} < CD_{\text{rime}} < CD_{\text{mixed}}$. 2. At the same angle of attack ($\alpha=6^\circ$), lift/drag characteristics in the condition of different ice shapes are different. The pressure gradient at the leading edge is $\nabla p_{\text{none}} > \nabla p_{\text{rime}} > \nabla p_{\text{mixed}}$, which has important effect on the speed of airstream flow and the flow separation at the front zone of airfoil.

1. Introduction
Aircraft icing is a phenomenon that accumulation of ice is on the surface of airplane in different positions: the leading edge, engine inlet, windshield and so on [1]. Aircraft icing has influence on the preliminary safety and performance evaluation of airplane, including climb performance, stability characteristics, and dynamical response. Icing conditions accounted for 2.9% of general aviation accidents in 1997, 2.4% in 1998, 3.6% in 1999, and 2.7% in 2000 [2-3]. Therefore, aircraft icing is paid high attention on, especially icing in the leading edge. A lot of researchers have some relevant study about icing in the leading edge.

Broeren [4] discussed the formation of icing on the leading edge of the wing by means of both experiments and numerical simulations, then compare wind tunnel data with simulation result and analyze the reasons of differences between the experiments and numerical simulations. Addy [5] modified the airfoil model of icing leading edge considering the altitude, surface roughness and heat transfer law. Chung [6] taken the flow field and aerodynamic characteristics around the wing with different icing shapes into consideration.

From the study mentioned above, we can observe the process of icing and the change of aerodynamic characteristics after icing. However, the study on the reasons of change in aerodynamic characteristics after icing is not in a deep-going way. Based on different ice shapes (none, rime, mixed) [7], the airfoil models of icing leading edge are established. Through N-S equation and S-A turbulence model, the aerodynamic characteristics of icing airfoil are analyzed and the factors cause the difference after icing is also pointed out.
2. Numerical Method

2.1. Mechanical Model

The different ice shapes are produced in the different meteorological condition. In this paper, NACA 0012 airfoil is chosen to make a study how the ice shapes on the leading edge have influence on aerodynamic characteristics of airfoil. The icing airfoil models are established in Fig. 1.

![Figure 1. Shapes of the leading edge with ice.](image)

2.2. Governing Equations

Considering different ice shapes on the leading edge, the governing equations can be written in Cartesian coordinates as follows:

\[
\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} = \frac{\partial s_x}{\partial x} + \frac{\partial s_y}{\partial y}
\]

(1)

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

A steady-state pressure-based implicit solver with second-order upwind discretization and Coupled pressure-velocity coupling was chosen. The S-A model is used to describe the turbulent flow process.

2.3. Verification of Algorithm

The icing airfoil in this study is established. The chord length, \( L \), is 1 m. The grid is an O type and the mesh is all quadrilateral, Fig. 2. This domain is meshed with 19683 elements and 19440 nodes. Boundary conditions (BCs): \( \text{Ma}=0.162, \text{Re}=2.88 \times 10^6 \), the pressure in far-field, \( \text{p}=101832 \text{Pa} \), static temperature, \( \text{T}= 288 \text{K} \). Turbulent viscosity ratio is 2, the explicit relaxation factor of force and moment is 0.3, the convergence condition is 0.001, and no-slip boundary is imposed at the surfaces of airfoil.

![Figure 2. Finite element volume model.](image)

![Figure 3. Pressure distribution on NACA0012 airfoil at attack angle 0°.](image)
It is given that the calculated pressure distribution of upper surface and below surface of airfoil at the attack angle, $\alpha=0^\circ$, in Fig. 3. $x/L$ is the location along the chord. To compare with the experiment test [8], 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 experiment data. So, the numerical method can solve icing-airfoil model effectively.

3. Numerical Result
The different icing airfoil models are calculated by the numerical method mentioned above, then aerodynamic characteristics of airfoil with ice shapes on the leading edge are obtained. Fig. 4 and Fig. 5 illustrate lift coefficient and drag coefficient of airfoil in the conditions of no icing on the lead edge, rime icing on the lead edge and mixed icing on the lead edge. From the results mentioned in the figure, we can observe that the aerodynamic characteristics are different in the case of different ice shapes. The lift coefficient and drag coefficient of rime icing airfoil and mixed icing airfoil are different from no icing airfoil. At the range of attack angles, $\alpha=0^\circ$--$7^\circ$, lift coefficient is $C_{L_{none}}>C_{L_{rime}}>C_{L_{mixed}}$ and drag coefficient is $C_{D_{none}}<C_{D_{rime}}<C_{D_{mixed}}$.

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

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

In the conditions of different $\alpha$, $2^\circ$, $4^\circ$ and $6^\circ$, the aerodynamic characteristics of different icing airfoil are different. In the Table 1, we can observe that $C_{L}$ and $C_{D}$ of icing airfoil are decreasing and increasing compared with no icing airfoil, respectively. At $\alpha=4^\circ$, $C_{L}$ of rime icing airfoil and mixed icing airfoil decreases 2.3% and 11.2% and $C_{D}$ increases 15.3% and 83.5%, respectively. In the same case of icing airfoil, with the attack angle increasing by, the lift/drag coefficient are also changed. $C_{L}$ of rime icing airfoil decreases 1.0% and 5.4% at $\alpha=4^\circ$ and $\alpha=6^\circ$, respectively. $C_{D}$ of rime icing airfoil increases 4.9% and 37.3% at $\alpha=4^\circ$ and $\alpha=6^\circ$, respectively.

| $\alpha$ | Ice shapes | $C_{L}$ | $\Delta C_{L}/C_{L}$ (%) | $C_{D}$ | $\Delta C_{D}/C_{D}$ (%) |
|---------|------------|--------|-----------------|--------|-----------------|
| None ice | 0.221      | 0.0    | 0.009           | 0.0    | 0.0             |
| 2 Rime ice | 0.219     | -1.0   | 0.010           | 4.9    |                 |
| Mixed ice | 0.202     | -8.6   | 0.013           | 37.1   |                 |
| None ice | 0.439      | 0.0    | 0.010           | 0.0    | 0.0             |
| 4 Rime ice | 0.429     | -2.3   | 0.012           | 15.3   |                 |
| Mixed ice | 0.390     | -11.2  | 0.019           | 83.5   |                 |
| None ice | 0.651      | 0.0    | 0.012           | 0.0    | 0.0             |
| 6 Rime ice | 0.616     | -5.4   | 0.016           | 37.3   |                 |
| Mixed ice | 0.538     | -17.3  | 0.032           | 168.8  |                 |

Table 1. Lift/drag characteristic in conditions of different icing airfoil.
4. Discussion

Ice shapes on the leading edge have important influence on the lift/drag characteristics of airfoil, which are simulated to analyze by the different icing airfoil models. Fig. 6 illustrate the pressure distribution of the icing airfoil at the attack angle $\theta$. In Fig. 6, we can observe that the pressure coefficient on the lower surface of different icing airfoil is almost same and the pressure coefficient on the upper surface have obvious change. At the leading edge, the pressure coefficient of icing airfoil is almost same and greater than no icing airfoil at $x/L=0.4\% \sim 3.6\%$; the pressure coefficient of no icing airfoil and rime icing airfoil is almost same at $x/L=3.6\% \sim 10\%$; the pressure coefficient at $x/L>10\%$ is $C_{p\text{ none}}<C_{p\text{ rime}}<C_{p\text{ mixed}}$. In general, icing airfoil make the pressure coefficient gradient of upper and lower surface changed at $x/L>10\%$, $\Delta C_{p\text{ none}}<\Delta C_{p\text{ rime}}<\Delta C_{p\text{ mixed}}$.

![Figure 6. Pressure distribution of the icing airfoil.](image)

Contour plot of pressure and Ma on the leading edge of airfoil are described in Fig. 7 and Fig. 8, respectively. In Fig. 7, we can observe that the pressure distribution around icing airfoil is changed. The pressure of upper surface is decreasing firstly and then increasing, the pressure of lower surface is increasing firstly and then decreasing. However, the pressure gradient at the leading edge is $\nabla p_{\text{none}}<\nabla p_{\text{rime}}<\nabla p_{\text{mixed}}$ in Fig. 6. In Fig. 8, Ma at the upper surface near icing zone are various, no icing airfoil is bigger than icing airfoil. What’s more, vortex is produced at the back of icing zone on the upper surface and vortex of the mixed icing airfoil is broader than rime icing airfoil.

![Figure 7. Contour plot of pressure and flow field on the leading edge of airfoil.](image)
In Fig. 7 and Fig. 8, we can observe that the pressure gradient at the front zone of icing airfoil is decreasing. Due to decreased pressure gradient, the flow acceleration around the leading edge is not well, which contribute to the airstream flow difficulty from the leading edge to the trailing edge and then the flow separation is appeared at the back of icing zone. As the flow field zone is increasing by, the flow reattaches to the upper surface of airfoil. The vortex and the bubble are produced. The vortex of mixed icing airfoil is wider than rime icing airfoil, because the flow speed around the leading edge of mixed icing airfoil is slower than rime icing airfoil. So, the pressure gradient at the front zone of icing airfoil has important effect on the speed of airstream flow and the flow separation.

5. Conclusion

From the study mentioned above, the conclusions can be made:

1. The lift/drag characteristics of different icing airfoil are different. At the range of attack angles, $\alpha = 0^\circ$~$7^\circ$, lift coefficient is $C_{L\text{ none}} > C_{L\text{ rime}} > C_{L\text{ mixed}}$, and drag coefficient is $C_{D\text{ none}} < C_{D\text{ rime}} < C_{D\text{ mixed}}$.

2. The pressure gradient at the leading edge is $\nabla p_{\text{none}} > \nabla p_{\text{ rime}} > \nabla p_{\text{ mixed}}$, which has important effect on the speed of airstream flow and the flow separation at the front zone of airfoil.

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