Research on Numerical Simulation of Three-dimensional Icing for Aircraft and Aero-engine

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Abstract. Based on the idea of modularization, the three-dimensional icing calculation research code for aircraft and aero-engine is developed by using the secondary development features (UDF) of FLUENT. By analyzing the physical process of aircraft and engine inlet parts icing, two-phase flow field calculation, water droplets collect calculation, thermodynamic calculation of icing, wall mesh calculation program is compiled, four calculation modules of icing calculation program were realized. By solving the key problem of data exchange and control solution process between the secondary development program and the four calculation modules, the module integration is completed and the three-dimensional icing numerical simulation of icing components of aircraft and aero-engine was realized. The calculation of icing on NACA0012 3D airfoil is carried out, and compared with the experimental results in literature. The results show that the maximum icing thickness is in good agreement with the experimental results, and the predicted ice shape is consistent with the experimental ice shape development trend. The calculation results show that the proposed three-dimensional icing calculation method is effective and reliable. On the basis of this, numerical simulation of icing was carried out on the trailing adjusted strut of aero-engine inlet with a tail angle of 0°, and the water collection coefficient of the strut wall and the icing area of the strut at different time were obtained. It provides a new method for pre-researching aircraft and aero-engine icing.

Introduction

Ice accretions may occur on certain exposed parts of an airplane, such as the airfoil and an aero-engine when the airplane flies in clouds which contain supercooled water droplets. What is worse is that ice accretion on the aero-engine entry components (such as the struts and the centre conical body) would occur at some special meteoric conditions under which there would not be ice accretion on the airfoil of aircraft. Once the ice becomes thicker and thicker, the mass flow rate of airflow would reduce, that would lead to engine performance deterioration. If the ice accretes severely, the engine couldn’t work normally and even endanger the aircraft [1, 2]. It is one of the main hazards to flying. So the research on aircraft icing has been an important part in aircraft design [3].

With the continuous development of computational fluid dynamics, numerical simulation of the icing phenomenon of aircraft and aero-engine has become one of the most important methods for icing pre-research [4]. The earliest studies were mainly two-dimensional icing calculation. The researchers found that the three-dimensional characteristics of the aircraft and aero-engine parts of the icing problem, dealing with two-dimensional calculation, there have a large error, it is difficult to accurately simulate the icing phenomenon [5-7]. Therefore, it is necessary to study the three-dimensional icing numerical simulation of aircraft and aero-engine components.

In this paper, a complete set of three-dimensional ice calculation method is established through the study of the icing phenomenon of aircraft and aero-engine components. On this basis, a three dimensional icing calculation research code is developed. The numerical simulation of NACA0012 airfoil icing is carried out. Compared with the literature results, the reliability of icing calculation method is verified. The software was used to simulate the icing of trailing adjusted strut. Strut of adjusting angle of 0° were computed, and distribution of liquid water, icing area under different time were obtained.
Software Development

According to the actual physical process of icing, the icing calculation research code has designed four calculation module:

1. Two-phase flow calculation module;
2. Water droplets collect calculation modules;
3. Icing calculation module;
4. Dynamic mesh calculation module.

The three-dimensional icing calculation research code designed in this paper is developed on the platform of FLUENT. Use FLUENT secondary development features—User-Defined Function (UDF). According to the needs of software design prepared two-phase flow field calculation, water droplets collect calculation, thermodynamic calculation of icing, wall mesh calculation program. Four key technologies for numerical simulation of three-dimensional icing of aircraft and aero-engine are realized.

The main problems that need to be solved in the three-dimensional icing calculation research code are the data exchange and control solution between the secondary development program and the four key technologies, as shown in Figure 1.

First, the three-dimensional icing calculation software uses FLUENT to solve the three-dimensional compressible N-S equation of the air field to obtain the velocity and temperature fields of the air. Secondly, DPM (DEFINE_DPM_EROSION) based on Lagrangian method is used to calculate the water droplets impingement, to obtain the parameters such as the impact position and impact amount of water droplets, and to obtain the distribution of water droplets in the air field. The dynamic mesh macro function DEFINE_GRID_MOTION calculation program contains two parts: In the first part, the icing thermodynamic model is used to calculate the amount of ice and the runback water on the surface of solid units. In the second part, the amount of movement and the direction of movement of each node on the icing surface are calculated based on the amount of icing on the surface of each unit. Finally, the DPM macro function DEFINE_DPM_OUTPUT is a post-processing program in the post processing module, and the function is the distribution of water droplets at the outlet.
Simulation Case

Icing airfoil with three-dimensional characteristics such as NACA0012 airfoil [8-10], are numerical simulated. Ice shapes from computation agree with experimental results, which indicate the validity of a three-dimensional ice research code in this paper [11]. On this basis, ice accretion on trailing adjusted strut were simulated.

Verification Case—Three-dimensional Icing Numerical Simulation of NACA0012 Airfoil

Airfoil chord length 0.5334m, wing span 2m.
Table 1. Calculation conditions.

<table>
<thead>
<tr>
<th>Condition No.</th>
<th>Airvelocity [m/s]</th>
<th>LWC [g/m³]</th>
<th>Temperature [℃]</th>
<th>attack Angle[°]</th>
<th>Computation time [min]</th>
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</thead>
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<td>6</td>
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<td>1.0</td>
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</table>

The calculation condition is shown in table 1, and the airfoil profile of the center section after icing is compared with the experimental data.

As shown in Figure 2, the upper icing limit and maximum icing thickness, are in good agreement with the experiment, the lower limit is basically consistent with the experiment. The maximum icing thickness appears in the moving stagnation point region. The thickness of the ice layer on the lower surface of the airfoil is slightly smaller than the experimental value. As shown in Figure 3, the upper and lower icing limits are in good agreement with the experimental data, the maximum icing thickness is slightly different from the experimental value. Through this example, the rationality and accuracy of the three-dimensional ice research code developed in this paper is verified.

**Icing Calculation Case—Three-dimensional Icing Numerical Simulation of Trailing Adjusted Strut**

The tail angle of the tail adjustable aero-engine inlet strut is adjusted to 0°, and its icing is numerically simulated. The airfoil of the Adjusted strut is shown in Figure 4. The boundary
conditions for this example are shown in Figure 5, it includes pressure inlet, pressure outlet, inner and outer casing wall and the two sides are periodic boundary. The calculation condition is shown in Table 2.

![Strut airfoil structure](image)

![Computational boundary conditions](image)

Table 2. Calculation conditions.

<table>
<thead>
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</tbody>
</table>

Results 1: Water collection coefficient

Results 2: Icing shape

As shown in Figure 6, the range of water drop collection of the struts is roughly between x=0 and x=0.12, and the maximum value of the collection coefficient is about 0.94. Due to the larger inlet velocity, the trajectory of water droplets is less deflected by the air field, resulting in a larger Water droplets collection efficiency at the stagnation point.

As shown in Figure 7, icing only occurs near the stagnation point. Although the total inlet temperature of the inlet is higher in the calculation conditions (268K), but because of the high speed, the static temperature of the flow is lower, about 260K, so the ice type is frost ice. As the air flow is larger, and water droplets collection efficiency is higher, the collection rate of the strut is higher and the amount of ice is larger in unit time.
Conclusion

1. The three-dimensional ice research code based on the secondary development of FLUENT can simulate the three-dimensional icing of aircraft and engine components, its modular design idea is conducive to the development of further on the three-dimensional icing program.

2. The three-dimensional icing of NACA0012 airfoil is numerically simulated, the calculated results generally reflect the characteristics of the experimental results, the maximum ice thickness is in good agreement with the experiment, the growth trend of ice is consistent with the experiment.

3. The icing problem of the tail adjustable aero-engine inlet strut is qualitatively studied, and the quantitative study still needs the support of the subsequent experimental research.

4. The research results provide an alternative way for the calculation of three-dimensional icing formation for aircraft and aero-engine, and can be used to improve the design technology of anti-icing system.

Reference


