Ice Growth Velocity on Civil Aircraft in Natural Icing Flight Test

Yi Wang, Wei-liang Kong, Jing-cai Ju

Abstract—Natural icing flight test, as one of the most difficult subjects in large civil aircraft certification test, was used to assess aircraft's performance and handling quality after freezing. This work aims to review the phenomenon and the law of ice accretion on civil aircraft. Meanwhile, it provide a reference for civil aircraft natural icing flight test. In this paper, computer simulation method based on ANSYS-FLUENT 19.0 software with UDF was used to simulate the ice accretion process. The result shows that the ice height mainly depends on the water droplet collection rate and surface overflow strength. Under the condition of the same diameter and liquid water content, the growth rate of streamline ice is the largest, and nearly linear with time. The average growth rate of horn ice will decrease with time, and the decreasing rate is positively related to the ice angle.

Keywords： Natural icing flight test; growth rate of ice; icing numerical simulation; evolution of collection.

I. Introduction

NATURAL icing flight test is a special meteorological subject in civil aircraft certification flight test, which is very important for civil aircraft airworthiness certification. According to the requirements of appendix O of FAR part 25, the aircraft needs to complete the icing flight test under natural icing conditions, which is a high-risk subject and needs a lot of complex preparation and coordination work. Relevant data show that the success rate of natural icing flight test is very low, and accurate icing prediction is the main reason for the success of the test. The research and development of natural ice test flight assessment method is a crucial step in the development of large passenger aircraft.

At present, there are few public reports of natural icing flight test assessment methods. The existing ICEPOT (ice probability calculation method) can only provide the probability of aircraft icing probability, and cannot predict the thickness of ice. The studies that have been carried out mainly focus on the shape of ice accretion under certain conditions.

Theoretically, the thickness of ice on the surface of an aircraft depends on the amount of water droplets in the air and the time of ice accumulation. However, the icing process is affected by several physical processes, mainly water droplet collection and flow heat transmission. The former is determined by the flight trajectory of water droplets in the flow field and the dynamic processes, such as fragmentation and splashing, while the latter is related to the surface water flow-ice coupling process. As ice accumulates, surface water droplet collection rates and surface flow/heat transmission states change. Therefore, the ice accumulation is the coupling of these two physical processes. In the actual aircraft icing process, the accumulation of ice has also been found to have obvious evolutionary characteristics. In some aircraft icing accidents, there are reports of rapid ice growth before the accident. The wind tunnel experiments show that the characteristics of ice evolve with time. Ice develops from rough ice to horn ice and lobster tail ice. In this process, the main ice structure gradually grows out of the small rough shape, but the ice angle is basically unchanged in this process [2]. This is an important entry point for the study of ice thickness accumulation. According to this feature, the law of water droplet collection and icing can be further analyzed.

The flight trajectory of the water droplets under the aircraft flow field determines its collision and collection characteristics on the wall. This process mainly depends on the Re number and We number of the droplets. It is generally believed that when the water droplet size is less than 100 μm, the droplet follows the flow better, and its deformation may not be considered. When the particle size is more than 100 μm, it is not easy to change the trajectory due to the large inertia, but dynamic processes such as deformation and crushing will occur under the action of the flow field [3 4] . The splash behavior will also occurs on the wall [5]. Water droplet collision also affects heat transfer and icing velocity [6 7]. It can be seen from the ice wind tunnel experiment that the collection rate of the surface with ice horn is obviously larger than that of the smooth icing surface, but the collection area is smaller [3]. Therefore, during the formation of ice, the collection of water droplets on the surface will undergo an evolutionary process.

Theoretical and numerical studies of aircraft icing also show that with the accumulation of ice on the aircraft surface, the surface heat transfer and overflow state also change. Myers believes that with the increase of ice layer, the decrease of heat flow on the aircraft surface will lead to the change of ice shape and the decrease of icing speed [8]. Yi Xian developed a new time-dependent icing test similar parameter for the difference between dry and wet surface phase transitions that were not considered by the Messinger model [9]. Janjua et al proposed that the aircraft icing process is a four stage evolution process from frost ice, mixed ice to

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glaze ice [10]. Kong and Liu found that the wall icing is a deceleration-acceleration process from ice layer to ice Branch [11], which was confirmed by the mechanism study of schremb et al [12]. These studies indicate that the initial icing state of aircraft surface will also undergo the evolution of velocity and shape.

In actual flight condition, the relationships between icing velocity and icing conditions are special concerns for aircraft natural icing flight test. Due to the high cost of experimental research on aircraft surface icing process, and continuous measurement of ice shape growth process are still difficult [13]. The numerical simulation method of aircraft icing can study the change of collection rate and icing rate in the process of icing, which are helpful to analyze the law of icing rate. In this paper, the variation of ice height on aircraft surface under different conditions is studied by two-dimensional icing numerical algorithm. At the same time, the mechanism of ice accretion rate was analyzed based on the collection rate of surface water droplets and the evolution process of ice shape. Finally, the environmental conditions suitable for aircraft natural icing flight test are given based on the simulation results.

II. Calculation Methodology

A. Algorithm Composition

The icing algorithm used in this paper was developed based on the ANSYS-FLUENT 19.0 software. Particle trajectory and collection of the droplets are calculated by the function of discrete phase simulation. The icing calculations are carried out through the UDF (user defined function), which was developed by using the c program. In every cell, the mass of ice is calculated by solving the equations of dendritic ice growth and heat transfer. The unfrozen water flowing into the next cell is solved by the mass balance equation of the film. These calculations are applied from the stagnation to the downstream cells in turn. Between two steps of calculation, the shape of icing surface is renewed according to the volume of accreted ice, and the dynamic mesh is used to renew the meshes in every time step.

The ice accretion rate should be defined as the mass of water taken into the ice matrix in unit time

$$\dot{M}_{ice} = \rho_w v_t = \rho_w a \Delta T^b \tag{1}$$

Where $a = 1.72\times10^{-4}, b = 1.988$ are parameters measured in experiment 错误!未找到引用源。 , $\rho_w = 1000 kg\cdot m^{-3}$ is the density of water, $\dot{M}_{ice}$ is the ice mass growth rate in supercooled model. $\Delta T = T_0 - T_1$ is the supercooling on ice dendrite tip, v_t is the velocity of ice dendrite tip.

The ice fraction in spongy ice F is (when $F<1$)

$$F = \frac{\dot{Q}}{\dot{M}_{ice} L_f} \tag{2}$$

Where L_f is the latent heat of water.

The dendrite tip supercooling is determined by the heat balance of dendritic layer.

$$\Delta T = \frac{\dot{Q}\cdot h_d}{\lambda_d} \tag{3}$$

The thickness of dendritic layer is:

$$h_d = z_2 - z_1 = c_r r_c \tag{4}$$

The tip's radius of an ice dendrite is:

$$r_c = c + d/\Delta T \tag{5}$$

The heat dissipation rate through the solid layer and water film. The mass and heat balance equations are:

$$\rho_w\left[\frac{\partial h_f}{\partial t} + div(\bar{u}h_f)\right] = u_\infty \cdot LWC\cdot\beta - \dot{M}_{ice} \tag{6}$$

$$\dot{Q}_{imp} + \dot{Q}_{film} + \dot{Q}_{wall} = F\dot{M}_{ice}L \tag{7}$$

Where $\bar{h}_f$ is the thickness of water film, $\bar{u}_f$ is a mean velocity of film, u_∞ is the velocity of incoming flow, β is the collection of droplet in the point, LWC is the average liquid water content in air, ρ_w is density of water, and $\dot{m}_{ice}$ is water mass lose rate due to solidification. $\dot{Q}_{imp}$ is the heat contained in droplets impinged, $\dot{Q}_{film}$ is the heat flux through water film and $\dot{Q}_{wall}$ is the heat flux dissipated through icing object.

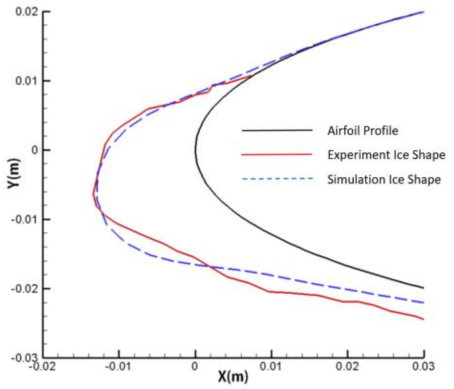
B. Validation example comparsion and verification

In this paper, the ice wind tunnel test results under different conditions in reference [15] are compared with simulation results to verify the reliability of the ice simulation algorithm used in this paper. The example conditions are shown in Table 1.

Fig.1 shows that the simulation results of ice shape under typical frost ice and glaze ice state are in good agreement with the experimental results, which indicates that the ice calculation method has good simulation accuracy for ice shape and can be effectively used in the calculation of ice thickness.

TABLE I
VALIDATION EXAMPLES WITH DIFFERENT ICING CONDITIONS

	1	2
Temperature(°C)	250.4	262.04
Speed(m/s)	102.8	102.8
AOA（°）	3.5	3.5
LWC（g/m³）	0.55	0.55
MVD(μm)	20	20
Time（s）	420	420



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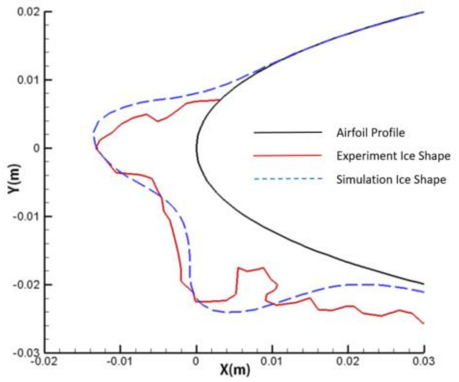

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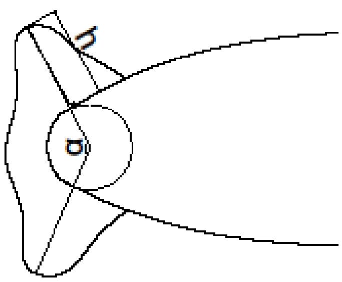
Fig.1 The comparison between simulation results with ice wind tunnel experiment 错误!未找到引用源。 results. (a) case 1 results, (b) case 2 results.

C. *Calculation conditions and analysis methods*

The analysis and calculation of the thickness and rate of aircraft ice accumulation are based on the typical conditions of the natural icing flight test of the passenger aircraft. The chord length of the horizontal tail section is 1.2m. The speed is 220 knots (about 113.2m/s). The temperature is -11℃. The average particle size (MVD) and the average liquid water content (LWC) are 20μm and 0.2g/m3 respectively. On this basis, we separately analyzed the effects of different particle diameters, different average cloud water content and different temperatures on the ice accumulation rate.

This paper focuses on the definition method of ice horn and ice height. As shown in Fig.2, when the ice horn is perpendicular to the wall, the distance from the highest point of ice horn to the wall is the ice height; when the ice horn is not perpendicular to the wall, the vertical length from the ice horn to the wall is the ice height. The ice growth rate is the ice height growth divided by the icing time.



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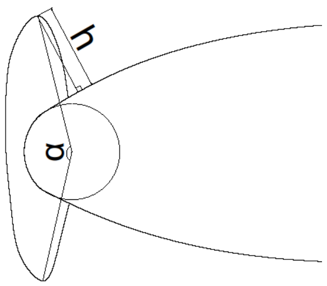


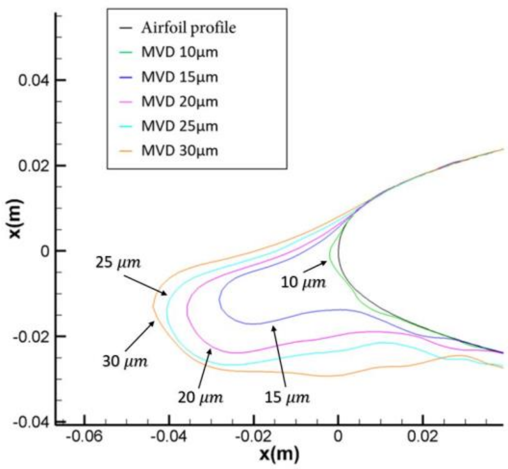
(b)

Fig.2 Schematic diagram of ice height and ice angle measurement methods. The circle in the figure is the inscribed circle of the leading edge of the airfoil. (a) the ice angle is perpendicular to the wall surface, (b) the ice angle is not perpendicular to the wall surface.

III. Ice Accretion Law Under Tppical Natural Icing Condition

A. *Effect of Particle Size on Ice Accretion*

The influence of droplet size is shown in Fig.3. It can be seen from Fig. 3 (a) that when the particle size is less than 25 μm, the droplet size has a great influence on the icing height. When the droplet size is larger than 25 μm, although the ice shape size increases significantly with the increase of droplet size, the increase of ice height is small. The reason is that with the increase of droplet size, the inertia of droplets increases, which makes it more difficult for droplets to follow the flow around the airfoil, so that the proportion of impinging on the wall increases. It can be seen from Fig. 3 (b) that with the increase of droplet size to more than 25 μm, the icing height gradually approaches the maximum icing height that can be reached theoretically (the droplet is completely collected). Therefore, the effect of increasing particle size on the height of ice accretion is limited. The above results show that a certain size of water droplet is a necessary condition to obtain a larger icing height. Water droplets with a particle size of less than 15μm will contribute less to the ice accumulation.



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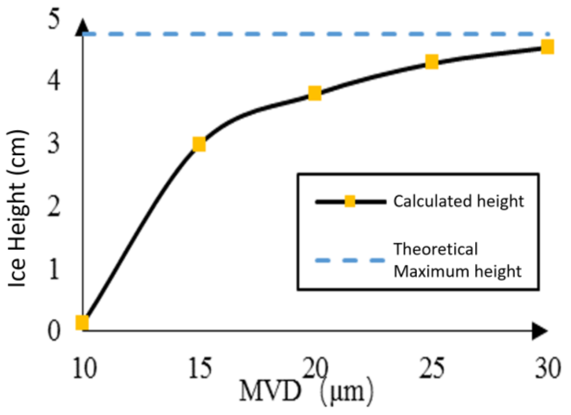
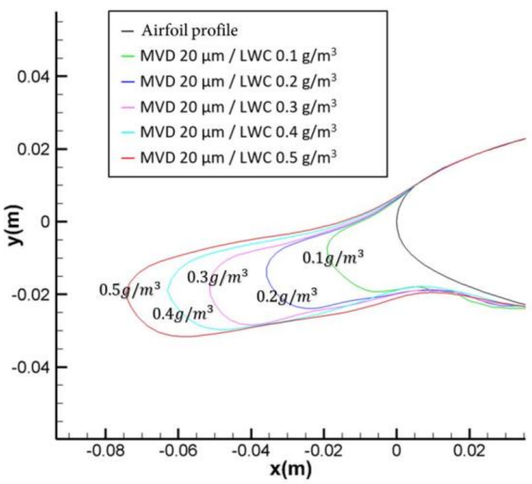


(b)

Fig.3 The results in 45 min with 10μm, 15μm, 20μm, 25μm and 30μm droplet size when temperature and liquid water contents keep constant. (a) ice shape with different droplet size. (b) maximum ice height with different droplet size, the dotted line represents the maximum height of ice in theory.

B. Effect of Average Water Content on Ice Accretion

The influence of mean water content on the height of ice accretion is shown in Fig.4. Fig.4 (a) (b) shows that the variation of water content has a great influence on the height of ice accretion. However, when the water content is higher than 0.3g/m3, it is obvious that the trend of icing height with the increase of water content slows down. Under the condition of a certain water droplet collection rate, the amount of water collected on the wall should have a linear relationship with the average water content of the cloud. Therefore, theoretically, the relationship between ice height and wall area should be linear. However, Fig.4 (c) shows that only when the water content is very small, the relationship between ice height and water content is satisfied. When the water content increases, the actual icing height is further away from the theoretical icing height. That is to say, the higher the water content, the more difficult it is for the water collected on the wall to accumulate into ice. When the particle size is 30 μ m and the water content is 0.5g/m3, the difference between the maximum icing height and its corresponding theoretical value is about 1 / 3.



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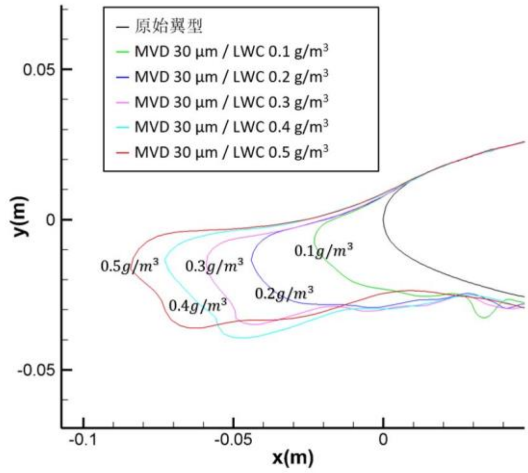

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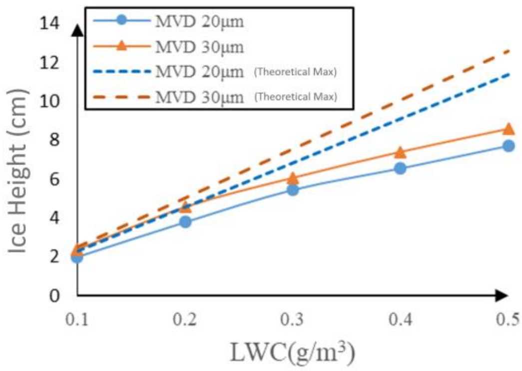

(c)

Fig.4 Same temperature and different droplet size simulation results in 45 min with 0.1 g/m^3, 0.2 g/m^3, 0.3 g/m^3, 0.4 g/m^3 and 0.5 g/m^3 liquid water contents. (a) ice shapes with 20μm MVD. (b) ice shapes with 30μm MVD. (c) ice height at different conditions, the dotted line represents the maximum height of ice in theory.

C. Effect of Temperature on Ice Accretion

The effect of temperature on ice shape is shown in Fig.5. Fig.5 (a) shows that the ice shape at different temperatures changes little with temperature, and mainly accumulates in the direction of incoming flow. It can be inferred that it is mainly in the state of frost and ice. In Fig.5 (b), with the increase of temperature, the ice shape changes from flow ice to horn ice. At the same time, Fig.5(c) shows that the ice accretion height varies significantly with temperature under the two different water droplet sizes. When the particle size is 20μm, the temperature has little effect on the ice shape and icing height. When the particle size is 30 μm, the temperature has a great influence on icing. At a temperature of -7°C, the ice accumulation height with a particle size of 30μm is even close to that at 20μm. This shows that the appearance of ice angles will significantly reduce the maximum ice accumulation height.

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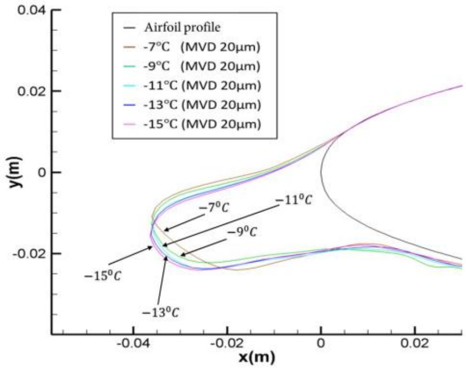

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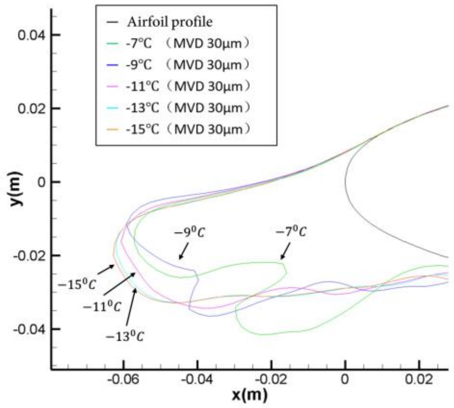

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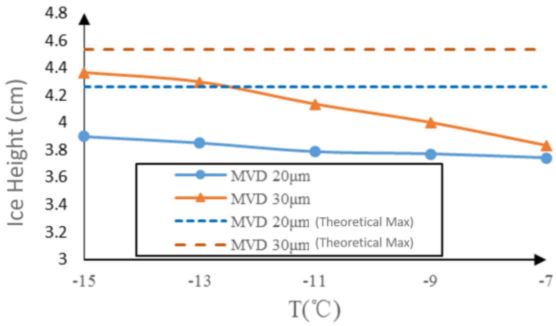


(c)

Fig.5 Same liquid water contents and different droplet size simulation results in 45 min with -7°C, -9°C, -11°C, -13°C and -15°C ambient temperature. (a) ice shapes with 20μm MVD. (b) ice shapes with 30μm MVD. (c) ice height at different conditions, the dotted line represents the maximum height of ice in theory.

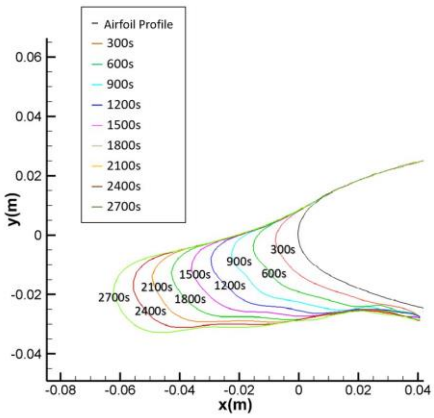
Combined with the above results, it can be seen that the influence of environmental conditions on aircraft icing height is nonlinear under the condition of typical aircraft icing test. The icing height of aircraft in a certain period of time is affected by water droplet collection and overflow state. Under the condition of frost ice / flow ice, the icing thickness mainly depends on the water droplet collection and cloud water content. While under the condition of horn ice, the icing thickness is obviously lower than the theoretical height due to overflow.

The influence of mean water content on the height of ice accretion is shown in Fig.4. Fig.4 (a) (b) shows that the variation of water content has a great influence on the height of ice accretion. However, when the water content is higher than 0.3g/m3, it is obvious that the trend of icing height with the increase of water content slows down. Under the condition of a certain water droplet collection rate, the amount of water collected on the wall should

IV. Mechanism Analysis of Ice Accretion Rate

A. Evolution of Icing Speed on Aircraft Surface

The last section mainly discusses the law of ice accretion height in a certain time. But why the height decreases with the increase of overflow is related to the evolution of surface icing. It is necessary to analyze the process of ice formation rate. This section focuses on the analysis of the changes in the shape and growth rate of different types of ice with time under the same conditions, as shown in Fig.6. It can be seen from Fig.6 (a) and (d) that when the temperature is - 15 °C, the ice is in frost state. At this time, the increase of ice height is basically linear. Fig.6 (e) also shows that the change of ice growth rate is very small. When the temperature increased to -11°C, the degree of ice overflow increased significantly, and two small ice horns were formed on the ice. At this time, the ice accumulation speed begins to decrease (Fig.6 (d)). When the temperature increases to -7°C, the ice shape has become obvious horn ice. Under this condition, the growth rate of ice in the first 1000 seconds is still not obvious, but its growth rate gradually slows down as time progresses. This can be clearly seen in Fig.6 (d) and (e). Combining the ice shape results, the difference in ice shape at different temperatures at the initial growth stage is not large, but the difference becomes larger and larger as time progresses. Therefore, the change of ice growth rate is closely related to its shape.



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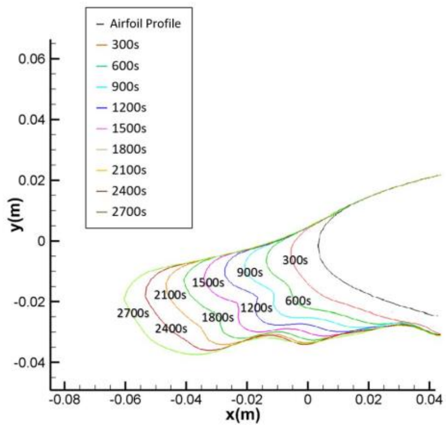

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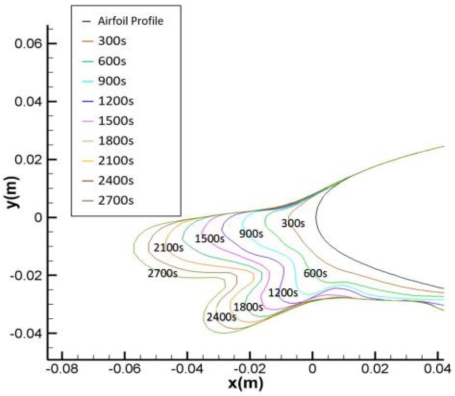

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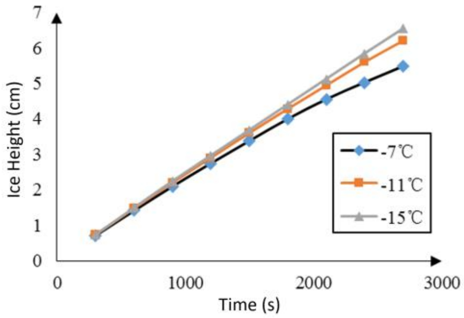

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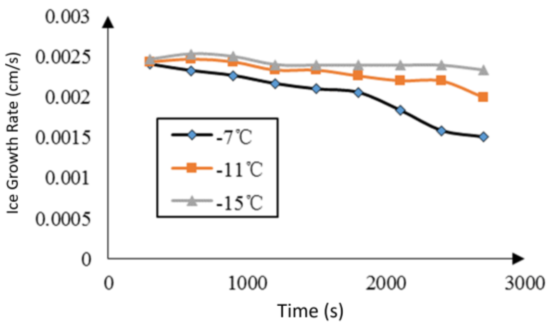


(e)

Fig.6 Ice shape, ice height and growth rate change with time at different temperatures with 30μm droplet size and 0.2 g/m^3 water content. (a) Ice shape at - 15℃ every 300 seconds, (b) Ice shape at -11℃ every 300 seconds, (c) Ice shape at -7℃ every 300 seconds, (d) Ice height at different times. (e) Ice growth rate at different time.

B. Evolution of Collection Rate

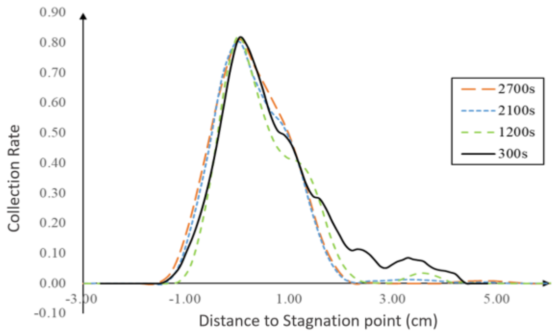
The growth process of ice shape is the result of the coupling evolution of flow field, droplet collection and overflow icing process, which is a complex process with many factors and physics. In this paper, we mainly observe the changes of the main characteristics in the process to analyze the reasons for different growth states. Fig.7 shows the collection rate results of three typical ice states at different times to analyze the reasons for the change of ice shape and growth rate.

In the state of rime ice as shown in Fig.6 (a), the shape of ice front has little change. Therefore, the position and value of the maximum droplet collection rate at different times have little change, except that the collection rate on both sides of the rime ice changes slightly, as shown in Fig.7 (a). This shows that in this case, the collection rate of water droplets and the icing state in most areas of the rime ice change little, so the growth rate of ice height changes little.

Different from the previous result, the collection rate in Fig.7 (b) changes greatly with time. At 300 seconds, the results of the collection rate are close to those in Fig.7 (a), which are asymmetric single peaks. But then it quickly divided into two peaks. This corresponds to the shape of the ice in Fig.6 (b) divided into two ice horns. With the change of ice shape, the stagnation point bulges, and the bimodal collection rate curve begins to merge again. In this process, the maximum collection rate decreased.

In Fig.7 (c), the change of droplet collection rate with time is more obvious. At 300 seconds, the collection rate of water droplets is still single peak. But at 1200 seconds, it has been divided into two peaks. The distance between the two peaks continues to increase. In this process, the maximum value and position of collection rate did not change significantly.

From the above results, it can be seen that with the change of ice shape from flow ice to horn ice, the surface water droplet collection rate will change greatly. The main feature is that it changes from a single peak to a double peak, which corresponds to the two ice horns of the ice shape. Although the maximum value of collection rate does not change, the appearance of ice horn indicates that there is obvious overflow of liquid water on the surface. At this time, the collected water will flow for a certain distance before freezing. In this paper, there is no further analysis on the distribution of ice surface water overflow, but from the icing results, it can be found that the overflow makes the whole ice horn shape and windward area increase, and the collection rate does not increase correspondingly. Therefore, the average growth rate of ice shape will decrease with time, and the decreasing range is positively related to the ice angle.



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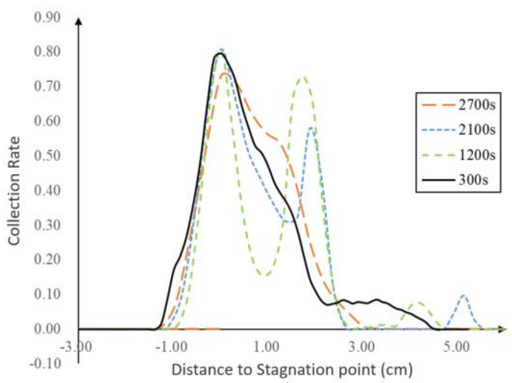

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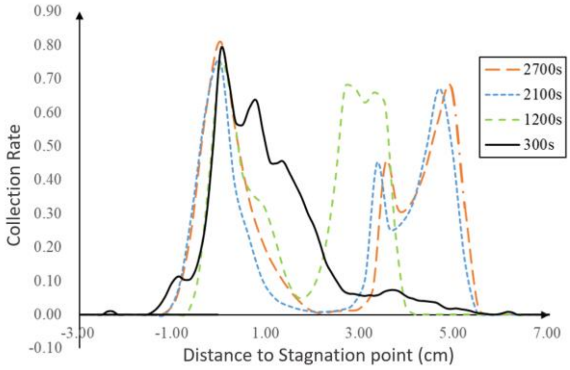

（c）

Fig.7 Surface collection rate changes over time. (a) results at -15℃, (b) results at -11℃, (c) results at -7℃.

V. The Law of Ice Accretion Rate in Aircraft Flight Test

Based on the above calculation results, we can give the minimum icing conditions for the aircraft to reach 2 inches (5.08cm) of ice accretion in the horizontal tail, which can guide the evaluation of the natural icing flight test conditions of civil aircraft, as shown in Fig.8. The figure shows that under certain temperature and droplet size conditions, the minimum water content requirement of ice thickness is reached. The results show that the increase of droplet size and the decrease of temperature can effectively reduce the requirement of water content in the environment under typical icing flight test conditions. When the droplet size is less than 20 μm, the water content will increase sharply. At the same time, the environmental temperature has a great influence on the water content needed for ice accretion. When the temperature is high, the increase of ice thickness caused by the increase of particle size is not obvious.

Therefore, in order to reach the specified icing thickness, the temperature, water droplet size and water content need to reach certain standards. The results can be used to evaluate the success rate of icing test.

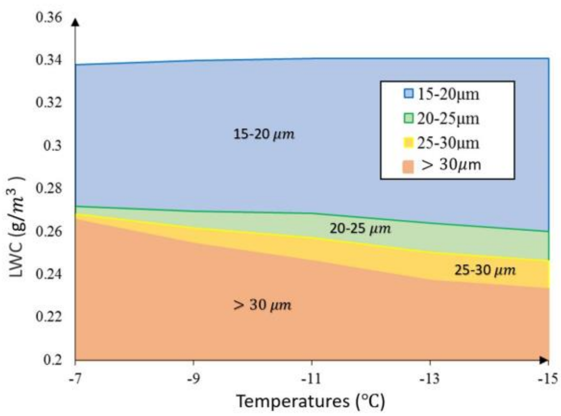

Fig.8 Minimum water content for ice accumulation reaches 2 inches in 45 minutes at different temperatures and droplet size.

VI. Conclusion

This paper aimed at the evaluation of the effective conditions of the civil aircraft's natural icing flight test. The growth rate of the surface ice height under different conditions is studied through numerical simulation. Combined with the change of water droplet collection rate, the reasons for the different ice growth rate are analyzed. Based on the actual flight test environment, the time required for the aircraft to accumulate ice up to 2 inches was studied. The results show:

1) Under different conditions, the aircraft surface icing height depends on the water droplet collection rate and surface overflow degree;

2) With the same particle size and water content, the growth rate of ice in frost state is the largest, but it decreases with the increase of overflow;

3) The growth rate of ice height is basically linear in frost ice state, but decreases with time in horn ice state. The decreasing range is proportional to the ice opening angle. This is because the shape of horn ice reduces the maximum water collection rate, and the overflow disperses the accumulation of ice.

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