Experimental and Numerical Studies of Ice Accretion on Atmospheric Icing Laboratory at Different Icing Pattern and Time

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Abstract: The purpose of this paper was to explore a suitable icing test method which can achieve the requirement of the experimental conditions better and faster in atmospheric Icing Laboratory. So, the effects of varying the spray method and spray time of different conditions were studied in experiment. The ice shape and profile of ice accretion obtained in atmospheric icing laboratory were investigated with variable air temperature. The icing object was exposed to the one aerosol cloud——freezing rain. In addition, the heat balance model of dynamic process of single droplet would be set up, the experimental condition of distance between nozzles and icing object was analysed by simulation calculation for the model. At the same time, appears the effects of different distances on the mass, ice shape and ice accreted of profile under different conditions in experiment.

1 Introduction

The atmospheric icing was a complex natural phenomenon, while it will present major hazard to many areas of modern equipment such as aircraft , power lines and warship. For aircraft, it would destroy the normal flow of air, reduce the aircraft’s performance and lift, increase resistance. For power line, it could lead failure of power line conductors [1]. For warship, it could cause serious influence on stability and floating.

Over the past years, research mostly focus on the impact and freezing processes of a water droplet on different smooth cold solid surfaces[2],[3]. The Hayashi et al. divided the frost formation process into three different periods: namely, the crystal growth, the frost layer growth, and the frost layer full growth periods [4]. Ice accretions at mixed conditions were test and it shows ice accretion shapes on a cylinder model deduced from NRC studies at RATFac [5],[6]. Extensive ice particle impact studies have been conducted by Hauk et al [7]. Wu et al. illustrated the icing of droplets on the surface [8]. Hoke observed the frost on a variety of plates and found that the water distribution on the plate at the end of the condensation period was strongly dependent on plate temperature, humidity [9]. The author also carried out wind tunnel tests and numerical simulations on the blade icing both for HAWT and VAWT [10]. Homola researched the turbine size and temperature dependence of icing on wind turbine blades [11].

Most of the existing experimental data corresponds to the air temperature and air humidity. But in most practical situations, especially in the icing climatic& environmental test based on the MIL-STD-810G[12], the experimental conditions not only involve those factors which were the air...
temperature, air humidity and droplet diameter, but there were other important influence factors which were spray method, spray time and the distance between nozzle and icing object. Because those factors will influence the test process and test results. But those experimental data for a continuous variation of distance or spray method appear to be lacking in the literature, and the validation of theoretical models for distance remains difficult in the absence of such experimental.

The spray method in experience may be inclined in three different spray ways relative to the droplet trajectories as sketched in (i) vertical; (ii) oblique; (iii) parallel. As well as two different sprays time which was (i) continuous and (ii) interrupt. So, in this paper, the main goal of the present studied was to study the effects of the different spray methods and spray time defined with the ice accreted on variable icing conditions. A subsidiary goal was to study the effect of different distance for ice accreted under different icing conditions. Finally, those findings can give certain guidelines for implementation process in testing technology.

2 The experimental setup
Experiments were performed in the atmospheric icing Laboratory (5m×2.5m×3m) at the Aero-Polytechnology Establishment in Beijing. The temperature could be cooled down to -25℃. To vary spray ways, the nozzles were fixed to some adjustable on the frame. To different spray time, the program was supported with different interval time for obtaining different spray time.

Different spray methods and spray time were applied to model different air temperature for different ice shape. In order to try to achieve a uniform distribution of impinging water along the test specimen. The nozzles were supplied with tap water at 0℃~10℃. A constant wind speed of 0.2m/s was measured near the nozzle. The wind and droplet supply were two independent systems, so, the wind speed was deemed steady. The air temperature was performed under -15℃, -10℃, -7℃ and -3℃, and the precipitation rate was 25mm/h that was same as MIL-STD-810G [12]. Through the accumulation of a large number of engineering tests, it was known that the mass of test specimen was less than 1.5kg, the interval of reaching stability state of temperature was about 60min. Therefore, when the temperature of atmospheric icing laboratory reached the setting values, the icing experiments was started after 60min.

During the icing period, all inputs were held constant. At the end, the detail of ice accretion was measured ice length. And it would also take digital photographs of ice accretion from different perspectives.

3 Numerical calculation and theoretical analysis
As we known, the distance from nozzle to icing object was a very important factor in icing experimental. Because this distance could make the droplet become super-cooled. And this distance was also need to be long for droplet to be mixed in the air flow. In this section, single droplet model would be established, and thermodynamic analysis and calculation would be carried out.

3.1 The droplet model
A brief description of droplet model was presented as follows. In this model, the left side of droplet was set to the fan in order to simulation the uniform air speed, the opposite side was set to the outflow and the other sides were set to the adiabatic boundary.

3.2 The computation method
The temperature field and the boundary condition will be dispersed by the finite difference method and the cable element method.

For the anyone control volume \( V \), the surface area was \( S \), the energy equation without inner thermal source was:

\[
\frac{\partial}{\partial t} \int_V \rho e dV = \int_S k \cdot \nabla T \cdot \hat{n} dS \tag{1}
\]
Where: \(e\)—the internal energy of per mass, \(k\)—the thermal conductivity, \(T\)—the temperature of control volume, \(n\)—the normal vector outside the surface.

Due to \(\rho e = \rho h - PV\), the pressure had nothing to do with the time, so:

\[
\frac{\partial}{\partial t} \int_V \rho dV = 0
\]

(2)

The Equ.1 could be solved by:

\[
\frac{\partial}{\partial t} \int_V \rho h dV = \int_S k \cdot \nabla T \cdot \hat{n} dS
\]

(3)

The enthalpy and temperature of equation as a stay function, it was suitable for all regions, then the Equ.3 become

\[
\rho \frac{\partial h}{\partial t} = k \cdot \nabla^2 T
\]

(4)

Where \(\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\);

The relationship between the enthalpy and temperature was \(\frac{dh}{dT} = c \cdot c\) was specific heat. So the Equ.4 could become

\[
\rho e \frac{\partial h}{\partial t} = k \cdot \nabla^2 h
\]

(5)

Then, the relationship between enthalpy and temperature was:

\[
T = \begin{cases} 
\frac{h}{c_{p_s}} & h \leq c_{p_s} T_m \\
T_m & c_{p_s} T_m \leq h \leq c_{p_s} T_m + r \\
\frac{[h - r - (c_{p_s} - c_{p_l})] / c_{p_l}} & h \geq c_{p_l} T_m + r
\end{cases}
\]

(6)

Where \(T_m\) was phase change temperature of control volume, \(r\) was latent heat of phase change.

\[
H(T) = \begin{cases} 
c_{p_s} T & T < T_m \\
c_{p_s} T_m + r & T = T_m \\
r + (c_{p_s} - c_{p_l}) T_m + c_{p_l} T & T > T_m
\end{cases}
\]

(7)

The effective thermal in phase change process:

\[
c_{p\text{eff}} = \frac{r}{T_{m2} - T_{m1}} + c_{pl}
\]

(8)

The relationship of unit of heat capacity and temperature was:

\[
c_p(T) = \begin{cases} 
c_{p_s} & T < T_{m1} \\
\frac{r}{T_{m2} - T_{m1}} + c_{p_l} & T_{m1} \leq T \leq T_{m2} \\
c_{p_l} & T > T_{m2}
\end{cases}
\]

(9)

3.3 The results and analysis

In this model, the diameter of droplet was 100μm, the initial droplet temperature was 3℃, the air temperature was -5℃ and the air speed was 1m/s.

Through a series of computation based on the above computation method, the temperature area of droplet presents in Figure.1.
Figure 1 presents that the temperature of droplet decreases very quickly before 0.03s, and the temperature would keep a long time around 0℃. When t=0.65s, the release of the phase change latent heat of droplet would basically complete. In order to analyze temperature changes of a single water droplet better, the temperature of several typical points of water droplets was detected, such as the front end, the last end, the center of the droplet and the side edge of the droplet.

In order to determine the effect of some factors further, the computation would be repeat for different droplet diameter and air temperature. Figure 2 shows the influence of droplet diameter on the distance (the droplet temperature dropped to air temperature) and time (the droplet temperature dropped to air temperature) of the ice accretion. Other conditions remain unchanged. From Figure 2, it could see that all computation results increase with increase droplet diameter. It means that the distance between nozzle and icing object would be longer with the increase of droplet diameter in icing experimental. But actually, the freezing rain droplet diameter was almost lower than 100μm, otherwise, the length or height of the test equipment would be limited. Therefore, the suitable droplet diameter must be chosen to achieve the icing experiment. In other words, in the actual ice test process, different distances according to different test equipment and test conditions by the calculation results would be chosen. This influence law had important guiding significance for better determining the process of test implementation.

Figure 2 also shows the influence of air temperature on the distance (the droplet temperature dropped to air temperature) and time (the droplet temperature dropped to air temperature) of the ice accretion. From Figure 2, it could see that all computation results decrease with decreased air temperature. That means that the lower air temperature, the shorter distance between nozzle and icing object and time in icing experimental.

4 Experiment and discussion
In above section, through numerical calculation and theoretical analysis, it was known that the distance, the air temperature had very important effect on icing test. So, in this section, the effect of different spray method, two spray time, four different air temperature and three different distances on the ice shape of ice accretion for freezing rain conditions with numerical calculation would be discussed by experiment. And the range of boundary conditions as given in Table 1.
Table 1 Test boundary conditions with variation steps and range

| Boundary condition | Variation range |
|--------------------|-----------------|
| Fluid flow parameter |                 |
| Spray method        | Vertical, Oblique, Parallel |
| Spray time          | Continuous, Interrupt |
| Droplet diameter    | 50um~100um       |
| Air temperature     | -3℃,-7℃,-11℃,-15℃ |
| Distance            | 0.5m,1m,1.5m     |
| Wind speed          | 0.2m/s           |
| Exposure time       | 10min,20min,30min |

4.1 Spray methods

Figure 3 shows the time of the shape of ice deposit obtained by spray methods of vertical, oblique (45°) and parallel under freezing rain condition. From the phenomenon of overall icing thickness, under the same test time, air temperature and distance, the icing thickness of vertical jet was the thickest, followed by oblique 45 degrees, and finally parallel. The specific values were shown in Table 2.

Table 2 The results of different spray method and time

| Method       | Oblique(45°) | Parallel | Vertical |
|--------------|--------------|----------|----------|
| Time         | Continuous   | Interrupt (spray 2min stop 1min) | Continuous | Interrupt (spray 2min stop 1min) |
| T            | -7℃          |          |          |          |          |
| Distance     | 50cm         |          |          |          |          |
| 10min        | 11mm         | 6mm      | 8mm      | 4mm      | 10mm     | 6mm      |
| 20min        | 17mm         | 11mm     | 13mm     | 9mm      | 18mm     | 17mm     |
| 30min        | 20mm         | 16mm     | 23mm     | 13mm     | 32mm     | 22mm     |

For the ice thickness, when the test sample body was injected vertically, it was placed directly on the ground of the test box. When the droplet was ejected from the nozzle, it will be affected by both gravity and nozzle pressure at the same time. The droplet reaches the surface of the test sample body, the latent heat of droplet had not been fully released, so the droplet also appears liquid, and the droplet would collide with the test sample body and the ground, which would make the droplet become a droplet with a smaller diameter, and then the smaller droplet would backsplash surface and surrounding of the test sample body. Otherwise, because the adhesion of droplets to the surface of the test piece will increase under low temperature environment, the droplets with smaller particle size would mostly adhere to the surface of the test piece under these two kinds of impact conditions. The number of droplets on the test piece would be more than that of oblique and parallel spraying, which will eventually lead to the thickness of the vertical ice layer greater than that of oblique and parallel spraying.

From the point of view of ice type, there were all hard ice. This was consistent with meteorological phenomena. And this also proves the correctness and effectiveness of experiment.

In terms of uniformity, there was little difference between oblique and parallel directions, and the vertical direction was the worst. Comparing oblique injection with parallel injection, it could be seen from Figure. 3 that the ice thickness of the lower half of the test piece decreases significantly in oblique, while the ice thickness of the whole test piece was relatively uniform in parallel, showing symmetry of axis. However, there was still much room for improvement of the surface of the whole test piece, and the study of improving the ice uniformity would be done in the future.
4.2 Spray times
Since there was a process of releasing latent heat inside the droplet after the droplet was ejected from the nozzle, it could be seen from the previous simulation calculation that certain distance and time were needed. In the actual ice test process, this distance could be predicted by calculation, but there were still some deviations. So, in order to make the droplets fully release latent heat after contacting with the test piece, changing the injection time sequence, change the continuous injection to 2 minutes and stop for 1 minute, and the experimental results were shown in Figure. 4 and table2. There were three injection modes.

It could be seen from Figure. 4 that the regularity of icing phenomenon was consistent with the performance of Figure. 3. The thickness of vertical ice layer was still the largest. When oblique jet was applied, the lower half of the ice layer of the test piece was missing a lot. Compared with vertical and oblique, parallel injection show good performance in terms of ice shape, thickness and uniformity. Therefore, for the icing test in laboratory, the parallel injection method would be adopted. The determination of this method had important guiding significance for the implementation of the icing test and was conducive to the repetition of the icing test. In addition, compared with figure. 3, and table2, it could be seen that the ice thickness of continuous spraying was obviously better than that of interrupt spraying, and the ice shape had not changed, and the uniformity of the ice layer on the test pieces was basically the same. Therefore, through the experimental study in this paper, it was suggested that the continuous spraying method should be used in the freezing test of atmospheric icing laboratory, and the test quality could be guaranteed in high efficiency.

4.3 Different air temperature
In order to verify the influence of different air temperatures on the freezing test, four different temperatures (-3℃, -7℃, -11℃ and -15℃) would be tested by three different spraying methods. The specific test results were shown in Figure. 5.

It could be clearly seen that the ice shape were rain ice when the air temperature was -3℃ for the three spraying modes, and the ice shape were hard ice when the air temperature was – 7℃, and when the air temperature were – 11℃ and – 15℃ respectively, the ice type produced by the three spraying methods were all soft frost, which were all the same as the actual meteorological conditions. For the ice thickness, shows that the ice thickness would be bigger in the lower temperature for three spray method at the same test time. In other words, the time to complete the icing test would decrease as the temperature decrease.
Therefore, according to the test results, it could effectively guide the requirements of different ice types in the subsequent freezing test of the test chamber.

4.4 Different distance between nozzle and icing object
In order to verify the influence of different nozzle-to-specimen distance on freezing test, two typical different injection methods would be used to test the different parameters of distance 0.5m, 1m and 1.5m.

Under the same droplet flow rate, the most effective freezing process for freezing test was that the droplets could collides with the test piece immediately when the latent heat of the droplet was releases. This could make the droplet have liquid property before contacting the test piece. When contacting the test piece instantly, the final latent heat was released immediately and adhered to the test piece to form an ice layer.

Figure 6 presents a series of pictures on the profiles of ice deposits obtained under freezing rain condition of distance between jet and object with different spray method. And shows the results of ice thickness for different distance. It could be seen from the figure that for the injection modes, the farther the distance was, the smaller the ice thickness was. The reason was that the longer the distance was, the longer the latent heat release time. Therefore, when the freezing test was carried out in this laboratory, the larger the distance was, the latent heat release of the droplets were completed before reaching the test piece, and the ice layer would be formed and cannot adhere to the test piece. In addition, there was another factor was the number of droplets. When the distance was 50 cm, it shows the characteristics of maximum ice thickness. According to the observation of the test process, when the droplets reach the test piece, the droplets are not completely frozen. The reason for the thickness was that the closer the distance was, the larger the number of droplets contacted with the test piece. So, the droplet volume was obviously larger than the other two test distances, the ice thickness was larger than the other two test data. In conclusion, the distance between nozzle and test piece had obvious influence on freezing test. Specifically, the distance should be adjusted before each test, according to different test pieces and test conditions. At the same time, from the view of the ice type, it could be seen that the ice type was hard ice for the parallel and oblique in different distance, but there was a slight change for the oblique in the ice type.

5 Conclusions
The dependence of the thickness and uniformity of ice deposits accreted on different test object in different spray method and time were investigated in atmospheric icing Laboratory. Three different spray method and two different spray time were applied to different air temperature and distance
between nozzles to object. The effects of the different factors as they were varied may be summarized as follows:

a) From the ice thickness, the three-icing spray method of vertical, parallel and oblique could meet the test requirements, but from the uniformity and consistency, this result means that the parallel spray method and oblique spray for arbitrary air temperature could be validated, but the parallel was the best.

b) The icing effect of continuous injection was better than that of discontinuous injection for atmospheric icing Laboratory.

c) Experiments with different temperature appear the ice shape would be changed with air temperature. Rain ice was sawed when the air temperature was greater than -5℃, and rime ice would be observed when the air temperature was less than -10℃, and hard frost would appear when the air temperature was between -5℃~10℃. The important of this result was emphasized by the fact that the same phenomena were achieved at different ice conditions and geometry in atmospheric icing Laboratory.

d) The distance between the nozzle and the test piece had a great influence on the freezing test, we could use the single droplet model to predict the icing condition of distance between nozzle and object, by using values from those calculated, it might have been possible to get better icing affect in atmospheric icing Laboratory.

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