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Study on Fractal Characteristics of Aircraft Icing Microstructure

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Abstract: The fractal behavior of the microstructure of aircraft icing was investigated based on the theories of fractal geometry. The fractal dimension was calculated by the box-counting algorithm, and the fractal dimension of the leading ice and runback ice under different conditions were obtained, and the relationship between the fractal dimension and the icing characteristics was analyzed. The results indicate that the lower the flow velocity or the higher the flow temperature, the smaller the ice fractal dimension, and vice versa. Under the same condition, the fractal dimension of runback ice is lower than the leading edge ice.

Key words: aircraft icing, fractal geometry, microstructure

1.INTRODUCTION

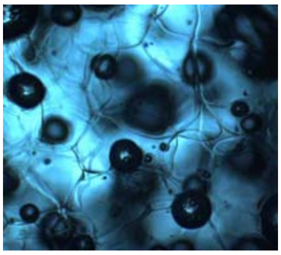
Aircraft icing has long been recognized as a fundamental problem and a serious hazard in flight process. Under different icing conditions, the icing characteristics show their varieties in appearance and thermophysical properties such as density, heat conductivity and the adhesion characteristics on the surface of flight as well. It is great difficult to describe the icing types by classical stereology because of the irregularity and random of icing characteristics. So far, the types of icing are qualitatively divided into glaze ice, rime ice and mixed ice[2] according to their appearance features, and their thermal physical parameters are simply given by the empirical method. This description method can only offer discrete evaluation parameters for different icing types, while can not establish the quantitative relationship between the icing characteristics and the corresponding icing conditions. Up to now, the accurate prediction of icing rate and the energy demand for anti/de-icing still has many difficulties.

Fractal geometry provides an ideal tool for describing the random and irregular objects, and has been demonstrated to be a very useful method in many areas of science and engineering since it was introduced by Mandelbrot in 1970s[3]. The microstructure characteristics of aircraft icing was investigated by the theories of fractal geometry in this work to establish an quantitatively description method for different icing characteristics.

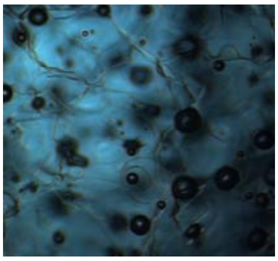
2 EXPERIMENTAL TESTS

To study the different characteristics of aircraft icing, the model of YUN-8 is used as experimental model and icing tunnel(0.3m×0.2m) experiments were conducted. Fig.1 shows the icing experiment on the leading edge of YUN-8 model in icing tunnel. Then the ice was taken off from the model and the metallographic tests were conducted under low temperature condition. The microstructure images(50 magnification) under different icing conditions(temperature and velocity are varied while MVD and LWC keeping constant) were captured and the data were recorded by the computer. Fig.2 shows the microstructure images of ice at the velocity of V=3m/s,V=8m/s, and v=25m/s when the inflow temperature is -5℃. From the images it can be seen that the microstructure of different ice characterizes as self-similarity distribution of spatial air bubble even though the size and the distribution of bubbles are different.

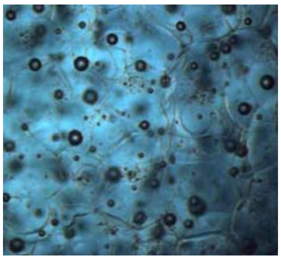
Fig.1 Icing test of airfoil surface in icing wind tunnel （t=-5℃，V=8m/s）



（a）t=-5℃，V=3m/s



（b）t=-5℃，V=8m/s



（c）t=-5℃，V=25m/s

Fig.2 Microstructure images of ice at different flow velocity

3 BOX-COUNTING METHOD

Fractal dimension is an important indicator of fractal objects. One of the most common methods for calculating the fractal dimension of a self-similar fractal is the box-counting method. For each non-empty subset F of R^n, the upper and lower box-counting dimensions of F are respectively defined as

$$\underline{\dim}_B F = \underline{\lim}_{\delta\to 0} \frac{\ln N_\delta(F)}{-\ln\delta} \tag{1}$$

$$\overline{\dim}_B F = \overline{\lim}_{\delta\to 0} \frac{\ln N_\delta(F)}{-\ln\delta} \tag{2}$$

If these values coincide, the common value is called the box-counting dimension of F and denoted by

$$D_B = \dim_B F = \lim_{\delta\to 0} \frac{\ln N_\delta(F)}{-\ln\delta} \tag{3}$$

In order to calculate the box-counting dimension for a fractal object, imagine this fractal lying on an evenly-spaced grid, and count how many boxes are required to cover the set. The box-counting dimension is calculated by seeing how this number changes as we make the grid finer.

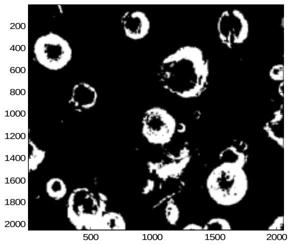
Before the calculation of the fractal dimension, the microstructure of ice images are filtered, enhanced, and binary images are obtained. Then the binary digital images were converted into a huge matrix only involving the value of 1 and 0. The rows and columns of matrix are accordant with the rows and columns of binary digital images, and each number in matrix is recorded “1” when the pixel in image is black or “0” when the pixel is white. The box-counting method computes the number of cells required to entirely cover an object, with grids of cells of varying size. Practically, this is performed by superimposing regular grids over the binary image and by counting the number of “0” or “1” of the matrix.

The logarithm of N(F), the number of occupied cells, versus the logarithm of δ, where 1/δ is the size of one cell, gives a line whose gradient corresponds to the box dimension. This allows the computation of several box dimensions by plotting the logarithm of combination of cells: completely occupied, completely non-occupied and partially-occupied.

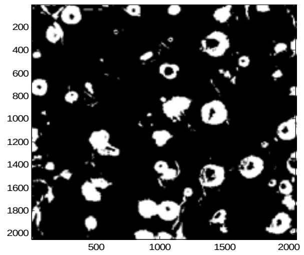
4 FRACTAL CHARACCTERISTICS OF ICE MICROSTRUCTURE

4.1 Influence of airflow velocity on fractal dimension

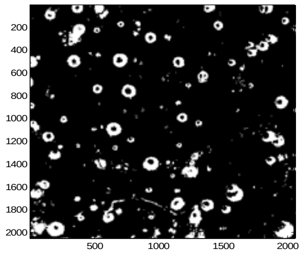
Fig. 3 shows the binary image of ice at different flow velocity. Calculating the fractal dimension of the binary images by the program, the fractal dimension of different images were obtained and showed as Fig. 4.



（a）t=-5℃，V=3m/s



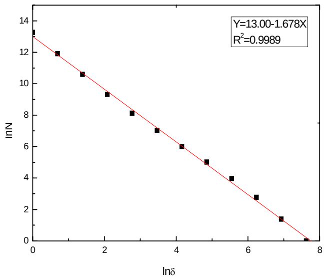
（b）t=-5℃，V=8m/s



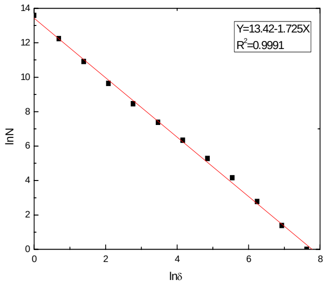
（c）t=-5℃，V=25m/s

Fig.3 Binary images of ice microstructure

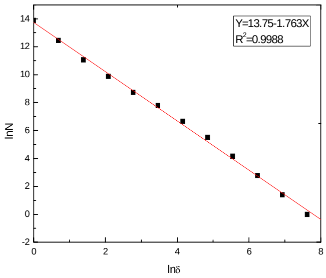
As can be seen from Fig. 2 - Fig.4, the size, number and distribution of air bubbles in the ice formed under different condition are varied. With the increasing of the velocity, the number of bubbles increase and the volume of the bubbles decrease. Accordingly, the fractal dimension of the leading edge ice is 1.678, 1.725, and 1.7631 when v=3m/s, 8m/s and 25m/s respectively at t=-5℃. The reason is that when the supercooled water droplets impinge on the surface of the model, the air bubbles crushed. The larger the velocity, the stronger the impinging force, the more and smaller the bubbles. Accordingly, the higher the flow velocity, the larger the fractal dimension, and vise versa. Fig.4 shows the curve of fractal dimension of ice versus the airflow velocity. It can be seen that with the increasing of the velocity, the fractal dimension increases in general. However, the large dispersion of data reveals the complexity of the influence on the fractal dimension values.



（a）t=-5℃，V=3m/s



（b）t=-5℃，V=8m/s



（c）t=-5℃，V=25m/s

Fig. 4 Fractal dimension of different velocity

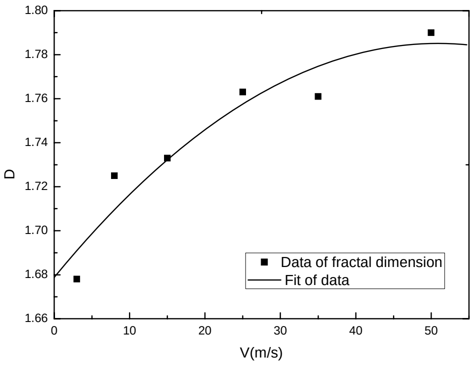
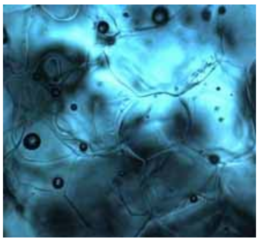


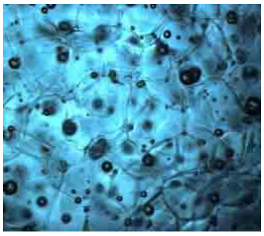
Fig. 5 Fractal dimension versus airflow velocity

4.2 Influence of temperature on fractal dimension

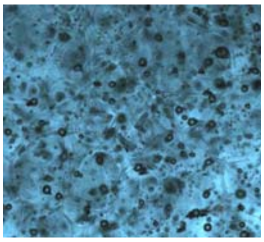
To study the influence of temperature on the fractal characteristics of ice microstructure. Experiments were conducted by changing the airflow temperature and keeping the airflow constant. Fig.6 shows the microstructure image at -3 ℃, -10 ℃ and -17 ℃ respectively when the airflow is maintained at 35m / s.



（a）t=-3℃,V=35m/s



（b）t=-10℃,V=35m/s



（c）t=-17℃,V=35m/s

Fig.6 Ice microstructure of different temperature

The same method can be used to obtain the fractal dimension of the ice microstructure at different temperature (Fig. 7). It can be seen from Fig. 6 and Fig. 7 that the higher the flow temperature is, the less the air bubbles, the bigger the crystal particle, and the small the fractal dimension will be. The reason is that in the same airflow velocity, the lower the flow temperature, the colder the water droplet and the more the critical crystal nucleus formed. With the increasing of the amount of crystal nucleus, the crystal particles will have more opportunities to meet which limiting the growing-up of crystal. Therefore, the crystal particles will have not enough space to grow up at the same time and the smaller crystal particles formed. Conversely, the higher the flow temperature, the warmer the water droplet, the less the critical crystal nucleus and the bigger the crystal will be formed. Moreover, at high icing temperature, the crystallization time become longer, the bubbles escaping become easy and the stayed bubbles in crystal will be relatively less. The fractal dimension just reflects the difference of the irregularity degree of difference ice microstructure images.

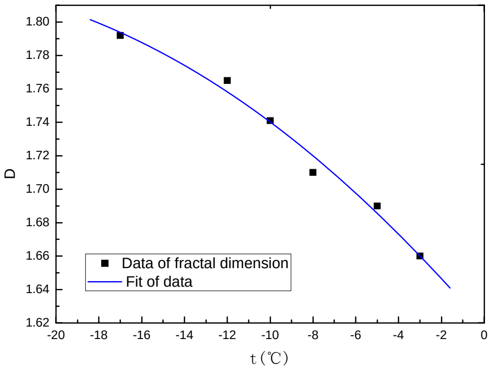
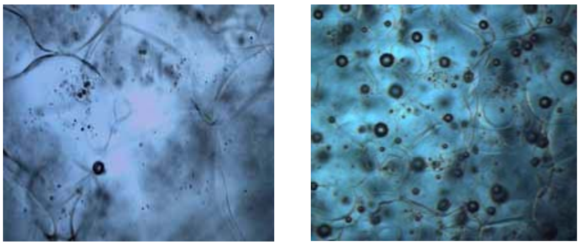


Fig.7 Fractal dimension versus temperature for leading edge ice

4.3 Comparison of fractal characteristics between leading edge and runback ice

To study the differences of microstructure characteristics between the leading edge and runback ice, runback icing experiments were conducted in icing tunnel and the microstructure images were obtained(Fig. 8). Fig. 9 shows the comparison of the microstructure between the leading edge and runback ice under the condition of t =- 5 ℃ and V = 25m / s.

Fig.8 Runback icing test in icing tunnel



(a) Runback ice (b) Leading edge ice

Fig.9 Comparison of microstructure between leading edge and runback ice (t=−5℃, V=25m/s)

Fig. 10 shows the comparison of fractal dimension between leading edge and runback ice. It can be seen that with the increasing of the airflow velocity, the fractal dimension tends to rise. Under the same condition, the fractal dimension of leading edge ice is greater than the runback ice, indicating that the microstructure of leading edge ice is more complex than the runback ice. Accordingly, the apparent and thermal properties of these icing types are so different.

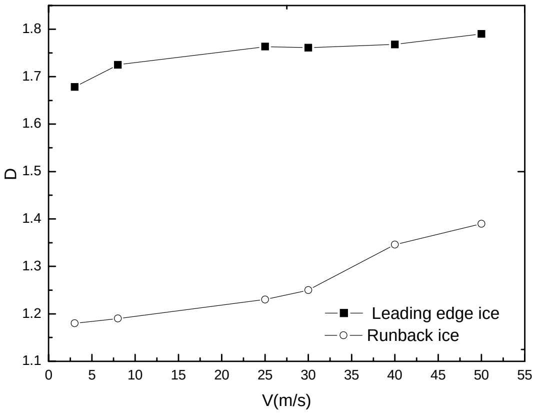


Fig.10 Comparison of fractal dimension between leading edge and runback ice

5 CONCLUSIONS AND ANALYSIS

The microstructure characteristics of the aircraft icing has been studied by the method which combine the icing wind tunnel experiments with metallographic tests and the main conclusions are obtained as follows.

The microstructure of aircraft icing has obvious fractal characteristics, and the airflow temperature and velocity have significant influence on the fractal dimension. The lower the flow velocity, the larger the size of crystal particles, and the smaller the fractal dimension will be. Conversely, the smaller the size of crystal particles and the greater the fractal dimension will be. On the other hand, the lower the temperature, the smaller the crystal particles, the more the air bubbles, and the greater the fractal dimension. Accordingly, the ice appears less transparent, and vise versa.

Under the same condition, runback ice is more transparent and compact than leading edge ice, but the microstructure fractal dimension of the former is smaller than the later. In other words, the former ice microstructure is different from the latter in complexity and irregularity. The microstructure properties will greatly influence on its macroscopic performances, and the physical properties are therefore different between the runback ice and leading edge ice, which can supply the references for taking different anti/de-icing measures for different icing types.

Fractal dimension is an important indicator of the inner features of fractal objects, and the microstructure characteristics are closely related to its forming conditions. So the research of fractal characteristics of aircraft icing contributes to understand the relationship between the crystal condition and the icing characteristics from a new perspective. It is possible that the fractal geometry can be used quantitatively to describe the different icing types, and establish the relationship between the flight icing conditions and the macroscopic performances or the thermal physical properties for different icing types.

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