Infrared thermal wave detection and compression experiment of accreted ice

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Abstract. Icing environment incurs great inconvenience to production and life. In order to study the physical characteristics of accreted ice, an experimental platform for ice detection is performed in this paper, and the influence of icing parameters is analyzed by using active infrared thermal wave nondestructive detection system and universal mechanical testing machine, we analyze the influence of icing parameters are icing height, icing diameter and freezing time. With the help of the logarithmic function of temperature difference and time in infrared thermal wave experiment, the relationship between the inflection point of stress-strain curve in compression strength tests and icing parameters is discussed. Results show that larger icing height, smaller icing diameter and longer freezing time will delay the turning point of logarithmic temperature difference curve with time; whereas larger icing height, appropriate freezing time and larger icing diameter will enhance the compressive strength of accreted ice. In addition, the strain level is also one of the factors closely related to the compressive strength. These conclusions lay the foundation for further research on the physical characteristics of the infrared detection of ice.

1. Introduction

At icing weather conditions, supercooled water drops are easy to be frozen into ice. Ice accumulation on the surface of ships, aircraft, wind turbines, etc., will affect the operation of these equipment, and even lead to casualties. Especially because of the growing extensive use of composites in aircraft structures, it is necessary to further understanding the ice threat [1].

Ice has been studied for a long time, and the physical properties of ice vary greatly due to the change of icing conditions. The study of these parameters such as density, adhesion strength, compressive strength and tensile strength of accreted ice is mainly focused on destructive experiments. The density measurements tend to indicate high densities of 810 ~ 915 kg/m−3 [2]. Johnson performed a series of mechanical tests on ice cylinders in the temperature range of −5 ~ −30 °C to study the ice behavior, and they found that the failure stress rises from values of about 5 MPa at −5 °C to about 12MPa at −30 °C [3]. Reich’s statistics showed that the tensile strength of frost ice is lower than that of bright ice; the tensile adhesion strength of the frost ice is about 0.12 MPa, while that of bright ice is 0.62~2.3 MPa [4].

In order to further study the physical properties of ice, a variety of detection methods are proposed. These detection systems can be based on thermal, optical, and mechanical principles [5]. Jackowski proposed a light detection and ranging beam across ice surface to measure the shape of ice [6]. Rashid used infrared signature to detect the pure and saline ice, and revealed that the detection mechanism with the introduction of active heating concept is unique compared to the previous passive infrared detection
[7]. Among various detection methods, infrared detection has attracted much attention due to its wide detection range, timely display, and non-contact to testing samples.

In this paper, an active infrared thermal wave detection is used to detect the accreted ice, and the compressibility of ice with the icing parameters of height, diameter and freezing time is discussed. The study aims to provide guidance for the research of infrared detection and mechanical properties of ice.

2. Theory
The principle of infrared thermal wave detection is based on thermal wave theory. When two objects have different temperatures, a heat flow exchange occurs between the objects, and the corresponding heat waves are generated in this process. The infrared nondestructive testing equipment can detect and record this heat wave generation and propagation. The final result is presented as a thermal image. In fact, the thermal wave is changed over time with its propagation in temperature field. The transmission of heat waves in the medium follows a certain volatility law, and its transmission varies in different types of media, so that specific targets can be detected.

In order to determine the temperature field distribution of the heat wave in the ice, a differential equation is usually used to establish the relationship between the material properties and the heat wave. The three-dimensional thermal conductivity differential equation is given as follows:

\[
\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \frac{Q}{\rho c} \tag{1}
\]

where \(T\) is the temperature, \(t\) is the time, \(\alpha\) is the thermal diffusion coefficient, \(\varphi_i\) is the heat generating rate, \(\rho\) is the density, \(c\) is the specific heat, \(\nabla^2\) is Laplacian operator, respectively.

In the processing of infrared thermal image, first the temperature sequence with a certain pixel in the ice region is selected from the infrared thermal image; then the initial temperature of the ice layer is subtracted to obtain the temperature increment sequence; finally, the following formula is used to fit the above-mentioned temperature difference sequence:

\[
\Delta T = \beta t^{-1/2} \left[ 1 + \beta_2 \exp \left( \beta_3 t^{-1} \right) \right] \tag{2}
\]

where \(\Delta T\) is temperature difference, \(\beta_1\), \(\beta_2\), and \(\beta_3\) are coefficients related to ice height.

3. Experiments
The infrared thermal detection system is usually divided into three parts: thermal excitation system, data acquisition system (infrared thermal imager), and data processing system as shown in Figure 1(a). The thermal excitation controller connects the thermal excitation equipment, the thermal imager and the image processing and control system. When the thermal excitation releases energy, the controller starts the thermal imager to take photos, and reads the instantaneous temperature field of the ice samples. The measurement system is a cooling infrared camera with a resolution of 640 × 512 pixels and a sensitivity better than 20 mK. The infrared thermal active excitation is used 2 × 2 matrix arrayed xenon lamps, and its maximum output energy is 12 kJ.

The equipment for ice compression tests is a universal testing machine as shown in Figure 1(b). The maximum compression force is 10 kN, the displacement rate of indenter is 12 mm/min, and its measurement accuracy is 0.5%. Inputting the actual size (diameter, length, original gauge length) of the accreted ice into the control data board of the machine, the test force, deformation, displacement, time of the samples can be recorded and then converted into the required result data.

The icing sample was fabricated in a freezer as shown in Figure 1(c). The fresh water was filled into a cylindrical can, and the quality was measured with a balance for calculating the ice density. When reaching a setting freezing time, the ice samples were taken out from the freezer. The experimental parameters were set as icing height, icing diameter, and freezing time.
4. Results and discussion

4.1. Infrared detection of ice

In order to observe the relationship between icing parameters and detection time more intuitively, we take the logarithm of temperature difference and time on both sides of the above Eq. (2) [8]. At the same time, in order to ensure the smoothness of the fitting temperature difference and time curve, it is usually required that the data points are dense enough. Under the experimental conditions, the relationship between the icing height, icing diameter and freezing time with detection time can be obtained as shown in Figure 2.

As can be seen from Figure 2(a), in the processing of icing detection, when the pulse heat is applied to the ice sample, first, the temperature difference along the ice height direction follows a linear decline. However, when it reaches the sample bottom, the temperature distribution changes greatly with a non-monotonic trend. Furthermore the larger height of accreted ice samples the latterly the inflection points arrive. In fact, when the thermal wave propagates along the ice height direction, the greater the sample thickness, the longer the heat transfer time to reach the bottom surface.

Note that the heat is transferred not only along the height of the sample, but also along the diameter direction after the sample is activated by the flash lamps. As can be seen from Figure 2(b), the larger diameter of the sample, the earlier the inflection point of the temperature difference slope reaches. However, this conclusion needs to be further demonstrated due to the limited experimental data.

In addition, freezing time is also an important factor affecting the detection of accreted ice. When the height and the diameter of the sample remain unchanged, it can be seen from Figure 2(c) that the longer the freezing time is, the earlier the inflection point of temperature difference slope reaches. The reason is that the longer the freezing time, the better the freezing state of ice, the better the thermal
conductivity of ice. If the freezing time is shorter, the water in the middle of the sample column might be not completely frozen into ice, resulting in the decrease of thermal conductivity.

4.2. Compression characteristics of ice

After the compression experiment of accreted ice is carried out, the data of stress and strain are collected, and the compression strength of ice is calculated by the formula:

\[ \sigma = \frac{F}{A} \]

where \( F \) is the force corresponding to the maximum point on the load-displacement diagram in mechanical compression tests, \( A \) is the original cross-sectional area of ice cylinder sample.

\[ (3) \]

\[ \epsilon = \frac{\Delta L}{L_0} \]

where, \( \Delta L \) is axial deformation of ice, \( L_0 \) is the initial height of ice.

In order to study the relationship between the stress and strain of accreted ice, the strain is given out as

\[ (4) \]

\[ \epsilon = \frac{\Delta L}{L_0} \]

Figure 3 shows the ice compressive strength varies with the parameters of accreted ice. As shown in Figure 3(a), when the freezing temperature is −50 °C, as the increase of the sample thickness, the ice compressive strength lies in the range of 0.2~1 MPa, and shows an approximately linear uptrend. As for the influence of icing diameter as shown in Figure 3(b), the situation gets complicated, and the sample diameter has a strong positive effect on compressive strength under the two combination conditions of freezing time and temperature, i.e. (180 min, −40 °C) and (300 min, −40 °C), whereas it has little effect under the other combination of (720 min, −40 °C). In addition, freezing time also affects the change of ice compression properties as shown in Figure 3(c). Obviously, the ice compressive strength varies non-monotonically with freezing time. First, the compressive strength enhances with the increase of freezing time until its maximum value at 180 min (−40°C), then decreases with the increase of freezing time. This is induced by the fact that the sample in a shorter preparation time is not completely frozen. The longer the freezing time, the stronger the brittleness of the ice and the weaker the compressive strength.
5. Conclusions
In this paper, the infrared detection and compression performance experiments of accreted ice were carried out by using active infrared detection system and universal testing machine. The effects of icing height, diameter and freezing time on ice accretion are discussed. The icing infrared detection experiment revealed that the larger the ice height, or the smaller the diameter, or the shorter the freezing time the later the logarithmic inflection point of temperature difference with time lags behind. That is because the ice samples with shorter transmission path and higher thermal conductivity are more prone to sudden temperature change. While the ice compressive strength experiments showed that the compressive strength is almost linear positively correlated with the icing height; while it varies non-monotonically with freezing time, first showing a positive correlation until the maximum value, and then a positive correlation. The icing diameter also affects the compressive strength, but the strength is hardly affected by the diameter of long freezing time samples (reach 720 min). Meanwhile, the compressive strength changes with strain in different icing conditions. In order to further study the relationship between accreted ice detection and physical properties, more samples need to be added to obtain more accurate analysis.

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