EXPERIMENTAL STUDY ON THE INFLUENCE OF FREEZING TEMPERATURE AND FREEZING WATER'S ELECTRIC CONDUCTIVITY ON THERMAL CONDUCTIVITY OF ICE

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***Abstract**:* The freezing temperature and freezing water's electric conductivity are different in icing events occur at different areas and different time. But there is little research about the effect of freezing temperature and freezing water's electric conductivity on the thermal conductivity of ice. The paper experimentally studies the effect of freezing temperature and freezing water's electric conductivity on thermal conductivity of ice, based on the transient hot probe method. The result show that the thermal conductivity of ice increases and decreases with the decrease of freezing temperature and increase of freezing water's electric conductivity; the higher the freezing temperature is, the greater influence of freezing water's electric conductivity on thermal conductivity is; the glaze in nature is greatly influenced by freezing water's electric conductivity.

1. INTRODUCTION

The icing of transmission lines is a serious threat to the safety and stable operation of the power system. At the beginning of the year 2008, the southern ice disaster caused a large area of tower collapse, line breaking, tripping-out, etc. As a result, the national economy and the daily life of people were seriously influenced, and suffered huge loss[1][2]. Afterwards, In order to prevent similar disasters, the state has invested a lot of manpower, material and financial resources on the study of transmission line icing and ice-melting.

At present, in the study of icing and ice melting, the choose of the thermal conductivity of ice is mainly refers to the empirical formulas[3] given by Abels, Jason, Devaux, Yoshida and others. However, there are certain differences between these empirical formulas, which brings a certain amount of confusion to the selection of the thermal conductivity. In fact, not only the density of ice formed at different weather condition is different, but also the freezing water conductivity and the ambient temperature are different, when the ice formed at different areas. In addition to considering the influence of density, the freezing water conductivity and the ice formation temperature should also be taken into account during the process of icing and ice melting. Therefore, the study of the ice thermal conductivity and its influencing factors can provide strong technical reference to the prediction of ice growth, the reasonable selection of the ice melting current and the estimation of the ice melting time.

2. RESULTS AND DISCUSSION

Several ice samples under different conditions were tested according to above methods and steps, the thermal conductivity results are shown in Tab.1.

Table.1 Testing results of thermal conductivity of ice W/(m·°C)

Temperature \ Conductivity	25.49	395.5	807.7	1260	1791
-5	2.19	2.06	1.95	1.86	1.74
-10	2.20	2.08	2.03	1.99	1.95
-15	2.22	2.16	2.11	2.10	2.07
-20	2.26	2.17	2.10	2.13	2.07
-25	2.25	2.19	2.12	2.11	2.09

The thermal conductivity of the sample decreases with the increase of the conductivity, and changes smoothly with the decrease of the freezing temperature. This is because with the increase of the conductivity, there are much salt contained in the ice, the amount of pure ice decreases simultaneously, leading to lower thermal conductivity. When the temperature decreases, the salt precipitation increases, and when the temperature decreases to a certain extent, most salt in the sample is precipitated, making the thermal conductivity changes moderately.

3. CONCLUSION

Thermal conductivity of the ice has something to do with the freezing temperature, it increases with the decrease of the temperature, when the temperature drops to a certain extent, it changes not too much with the further drop of the temperature. The thermal conductivity is also related to the conductivity of the freezing water which forms the ice, it drops with the increase of the electrical conductivity, the extent of its decline has something to do with the freezing temperature, the lower the temperature is, the more gently it decreases. Moreover, In the case of natural glaze, the thermal conductivity of ice influences a lot by the freezing water conductivity.

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Experimental Study on the Influence of Freezing Temperature and Freezing Water's Electric Conductivity on Thermal Conductivity of Ice

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Abstract--**The thermal conductivity of ice is one of the key parameters for studying the icing and ice-melting in electrical power system. It characterizes the speed of hot transfer, which determines the speed of ice accretion and ice-melting. So, the thermal conductivity of ice is the basis to predict accretion, to choose reasonable ice-melting current and to predict the ice-melting time. In present studies on icing and ice-melting, the thermal conductivity of ice is selected from empirical equations given by Abels, Jason, Devaux and Yoshida when the ice density is small, and it is selected as the pure ice's thermal conductivity when the ice density is large. The freezing temperature and freezing water's electric conductivity are different in icing events occur at different areas and different time. But there is little research about the effect of freezing temperature and freezing water's electric conductivity on the thermal conductivity of ice. The paper experimentally studies the effect of freezing temperature and freezing water's electric conductivity on thermal conductivity of ice, based on the transient hot probe method. The result show that the thermal conductivity of ice increases and decreases with the decrease of freezing temperature and increase of freezing water's electric conductivity; the higher the freezing temperature is, the greater influence of freezing water's electric conductivity on thermal conductivity is; the glaze in nature is greatly influenced by freezing water's electric conductivity.**

Keywords-thermal conductivity; icing; ice-melting; electric conductivity; transient hot probe method; freezing temperature

I. INTRODUCTION

The icing of transmission lines is a serious threat to the safety and stable operation of the power system. At the beginning of the year 2008, the southern ice disaster caused a large area of tower collapse, line breaking, tripping-out, etc. As a result, the national economy and the daily life of people were seriously influenced, and suffered huge loss[1][2]. Afterwards, In order to prevent similar disasters, the state has invested a lot of manpower, material and financial resources on the study of transmission line icing and ice-melting.

There are two ways to prevent power system icing disaster. One is using painting, heat etc. to delay or even eliminate ice before the formation of ice[3-5]; the other one, whose main development direction is the thermal method, is to de-icing effectively using mechanical method[6,7] or by laser[8,9], man power, heat power[10-12], etc. after the formation of ice. In order to provide more technical support to the anti-icing and de-icing to the power system, we must understand the icing and de-icing process of the power system from the essence (mechanism). Either icing or ice-melting includes the two processes: heat transfer and phase change. Moreover, the heat-transfer character is characterized by thermal conductivity, so the thermal conductivity of the ice layer is a key parameter when studying icing and ice melting.

At present, in the study of icing and ice melting, the choose of the thermal conductivity of ice is mainly refers to the empirical formulas[3] given by Abels, Jason, Devaux, Yoshida and others. However, there are certain differences between these empirical formulas, which brings a certain amount of confusion to the selection of the thermal conductivity. In fact, not only the density of ice formed at different weather condition is different, but also the freezing water conductivity and the ambient temperature are different, when the ice formed at different areas. In addition to considering the influence of density, the freezing water conductivity and the ice formation temperature should also be taken into account during the process of icing and ice melting. Therefore, the study of the ice thermal conductivity and its influencing factors can provide strong technical reference to the prediction of ice growth, the reasonable selection of the ice melting current and the estimation of the ice melting time.

II. THE MEASUREMENT PRINCIPLE OF THERMAL CONDUCTIVITY

The transient hot needle method, based on the line heat source model, is a simple method of measuring thermal conductivity[13-17]. It applies a constant current (or voltage) to heat the probe, which is been inserted into the infinite homogeneous samples, measuring the slope of the probe temperature varies with time, so as to obtain the thermal conductivity of the sample[13-17]:

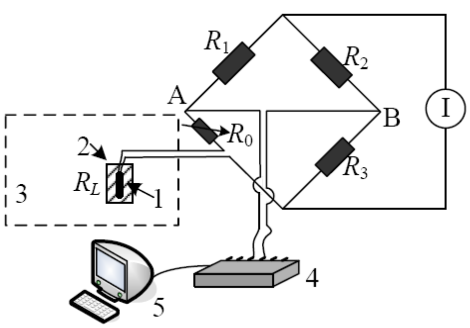
$$k = \frac{q}{4\pi} \Big/ \frac{dT}{d(\ln \tau)} \tag{1}$$

Where, k is the thermal conductivity of the sample; q is the heating power of per meter hot line; T is the average temperature rise of the probe and τ is the heat-up time of the probe.

Based on the hot needle principle, this paper uses Pt100 platinum thermistor (see fig.1), whose value is 100 ohm when the temperature is zero centigrade, and varies linearly with temperature, as the "hot needle". Heat it up applying constant current (or voltage), determine its resistance change by measuring the voltage (or current) change between its both ends, and get the temperature change according to the relationship between temperature and resistance. The measuring principle can be seen in fig.2.

Figure.1 Pt100 platinum thermistor

As shown in Figure 2, R_L is a strictly selected thermal resistance whose zero resistance is 100 ohm, R_1~R_3 is 0.01 precision resistors with low temperature coefficient.



1: Pt100 platinum thermal resistance; 2: sample (ice); 3: artificial climate chamber; 4: Data Acquisition Card (DAQ Card); 5: computer; I: Constant current source; R_1=R_2=R_3=R=200Ω; R_L: Resistance of Pt100; R_0: Adjustable resistor.
Fig.2 schematic diagram of measurement

R_L, R_0 and R_1~R_3 constitute a Wheatstone bridge, balance the bridge by adjust R_0 before the measurement, namely make R_L+R_0=200Ω. Suppose the resistance increment of the thermal resistance is dR_L when the stability output current of the constant current source is I, the current of R_1 and R_2 branch at this time are as follows, respectively.

$$I_1 = \frac{R_2 + R_3}{R_1 + R_2 + R_3 + R_L + R_0 + dR_L} I = \frac{400}{800 + dR_L} I \tag{2}$$

$$I_2 = \frac{R_1 + R_L + dR_L}{R_1 + R_2 + R_3 + R_L + R_0 + dR_L} I = \frac{400 + dR_L}{800 + dR_L} I \tag{3}$$

Therefore, the change of the voltage between point A and B due to the resistance alteration of the thermal resistance is:

$$dU = I_2 R_2 - I_1 R_1 = \frac{200 dR_L}{800 + dR_L} I \tag{4}$$

During the measurement, the heat current I is 100mA, causing less than 10Ω resistance change of the thermal resistance, omitting dR_L in the denominator of formula (4) dose not cause too much error[18,19], hence,

$$dU \approx \frac{1}{4} I dR_L \tag{5}$$

The resistance of the platinum resistor can be expressed as:

$$R_L = R_L(0)[1 + \lambda T] \tag{6}$$

Where R_L and $R_L(0)$ denotes the resistance of the platinum resistor when the temperature is T and 0 centigrade, λ is the temperature coefficient of the platinum resistor.

The differential of formula (6) is:

$$dR_L = \lambda R_L(0) dT \tag{7}$$

Therefore,

$$dT = \frac{dR_L}{\lambda R_L(0)} = \frac{4dU}{I\lambda R_L(0)} \tag{8}$$

The change of the current through the thermal resistance caused by the variable of the thermal resistance is not large during the measurement, suppose the current is invariant[18], namely the current through the thermal resistance is I/2, the heating power of the thermal resistance per unit length is:

$$q = \frac{(I/2)^2 R_L}{L} = \frac{I^2 R_L}{4L} \tag{9}$$

Where L the length of the platinum thermal resistance, m. Substitute formula (8) and (9) in (1), we can obtain:

$$k = \frac{\lambda I^3 R_L R_L(0)}{64\pi L} \Big/ \frac{dU}{d(\ln \tau)} \tag{10}$$

Therefore, so long as to get the gradient of time logarithmic of voltage change of the bridge circuit, we can obtain the ice thermal conductivity.

III. TEST METHOD AND PROCEDURE

A. *Calibration of the thermal resistance temperature coefficient λ*

Five Pt100 thermal resistances with 100Ω zero resistance have been strictly selected as "hot needle" during the test. As there might be errors the thermal resistances themselves, we need to calibrate there temperature coefficient. Using the resistance of Pt100 actually measured at different temperatures, according to formula (6), the temperature coefficient λ can be obtained, see table .1.

Table.1 Temperature coefficient of thermal resistance

	1#	2#	3#	4#	5#
λ ($\times 10^{-3}$)	3.921	3.897	3.929	3.869	3.919

B. Calibration of the measurement system

As formula (1) and (10) are one-dimensional heat-conducting ideal models based on a series of hypotheses and approximation, there are discrepancies between them and the actual measurement [20]. Furthermore, the measurement itself has error too. Therefore the measurement system must be calibrated before measuring the ice conductivity. The calibration method is to get the thermal conductivity (W/(m·°C)) of the standard sample using this measurement system， the ratio of it and the standard value is the calibration coefficient α. This paper calibrated the measurement system using 20 centigrade distilled water as standard sample, each thermal resistance measured 5 times, take the average of them as the measured value of the thermal conductivity. The measurement system calibration coefficients when using different thermal resistances are shown in Table 2.

Table 2. Calibration coefficient of the measurements system

No.	1	2	3	4	5
Measured value	0.675	0.741	0.681	0.722	0.698
Standard value[15]	0.597				
Calibration coefficient α	1.13	1.24	1.14	1.21	1.17

C. Preparation of the samples

Ice samples are prepared by using freezing water with five different conductivities, freezing water with different conductivities are obtained by adding NaCl to deionized water, the freezing water conductivities of the prepared samples are shown in tab. 3. As the freezing water with a certain conductivity needs several icing tests under different conditions, each freezing water is prepared about 2 liters at one time, and installed in the pot sealing with plastic wrap, in order to the consistency of the freezing water conductivity in each test, as shown in Figure 3.

Table 3. Electrical conductivity of freezing water (μS/cm)

No.	1	2	3	4	5
Conductivity	25.49	395.5	807.7	1260	1791

Figure 3. Freezing water

Take freezing water with different conductivities, each 250mL, infunde them into five number written measuring cup (Φ32mm×95mm), respectively, fix a thermal resistor in the centre of each measuring cup, and submerged by freezing water. Then put the pots with freezing water and thermal resistors into the artificial climate chamber, whose temperature could be adjusted from 0 ~ -45^{o}C, to freeze, see Figure 4. Each kind of freezing water is frozen to be samples at -5^{o}C, -10^{o}C, -15^{o}C, -20^{o}C, -25^{o}C, respectively. The density of ice frozen as such process is more than 0.9g/cm^3.

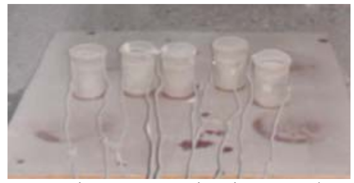


Figure 4. Testing ice sample

D. Test procedure

- Cooling down the artificial climate chamber until the temperature reaches the target value, put the measuring cups with freezing water and thermal resistors into the chamber, than freeze the water keeping the target temperature unchanged. During the freezing, measure resistance of each thermal resistor every 15 minutes, in order to determine whether the samples are completely frozen and balance with the ambient temperature. Shown in Fig. 5 is the resistance of the thermal resistor in 1# pot versus time in the process of freezing when the temperature is -20^{o}C.

- As shown in Fig.5, the resistance of thermal resistor versus time in the process of freezing can be divided into four stage: the resistance decreases with time in section AB, that means temperature of the freezing water drops from normal to frozen point (0^{o}C); the resistance keeps unchanged at the value 100Ω (Namely the temperature is 0^{o}C) in section BC, that means this is ice formation stage, there are ice water mixture in the measuring cup; in section CD, the resistance keep decreasing denotes that the water is totally frozen, and the temperature drops to ambient temperature; in section DE, the temperature keeps unchanged again, that denotes that the sample temperature and the ambient temperature reaches equilibrium.

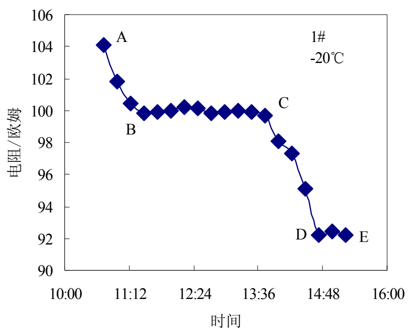


Figure 5. Resistance versus time in the process of freezing

- When the sample temperature and the ambient temperature (Predetermine temperature) reach equilibrium, measure the thermal resistance under this temperature, access the leads of the thermal resistor to the measurement system shown in Figure 2. Before heating up the thermal resistor, applying 5mA current through it and adjust R_0 in Fig.2 to balance the bridge (The voltage difference between A and B is 0 read in the computer), than regulate the constant current source, using 100mA current to heat the thermal resistor up. Simultaneously, collect the voltage change signals between point A and B using acquisition card and store in the computer. The temperature in the chamber maintains the value when the water freezes during every measuring process.
- After the measurement of the sample with each conductivity at one certain temperature is completed, repeat the above steps to test the thermal conductivities of the sample under other freezing temperatures.

IV. Test Results And Analysis

Several ice samples under different conditions were tested according to above methods and steps, the thermal conductivity results are shown in Table 4.

Table 4. Testing results of thermal conductivity of ice W/(m·°C)

Conductivity / Temperature	25.49	395.5	807.7	1260	1791
-5	2.19	2.06	1.95	1.86	1.74
-10	2.20	2.08	2.03	1.99	1.95
-15	2.22	2.16	2.11	2.10	2.07
-20	2.26	2.17	2.10	2.13	2.07
-25	2.25	2.19	2.12	2.11	2.09

According to Tab.4, thermal conductivity of the ice versus freezing temperature and electrical conductivity of freezing water are shown in Figure 6 and Figure 7.

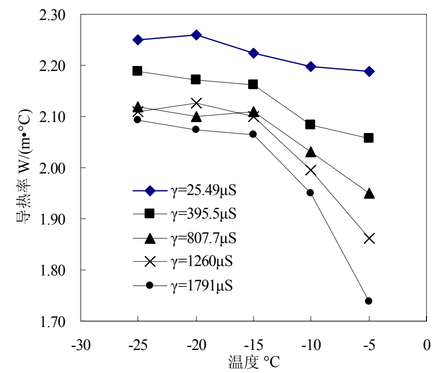


Figure 6. Thermal conductivity versus freezing temperature

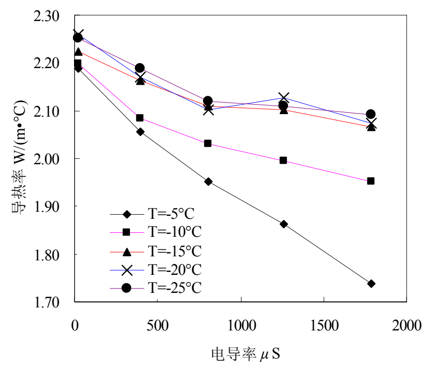


Figure 7. Thermal conductivity versus electrical conductivity of freezing water

From Fig.6 we know: the thermal conductivity of ice formed by freezing water with various electrical conductivity decreases when temperature drops, while it does not change significantly when the temperature decreases to a certain level; the thermal conductivity of ice formed by freezing water with smaller conductivity changes more gently than that with lager conductivity. This is mainly because the frozen ice sample consists of pure ice, saltwater cells and bubbles[21], and the thermal conductivity of each composition is quite different, therefore the thermal conductivity of the sample is decided by the proportion of the three compositions. In these three substances, the thermal conductivity of pure ice is the largest, followed by saltwater cells, the smallest one is bubbles, so the larger the proportion of ice is, the bigger is the thermal conductivity of the sample. Generally speaking, as the temperature decreases, there is more salt precipitated from the freezing water during the freezing process[22], so the proportion of pure ice increases, which increases thermal conductivity. In addition, with the freezing temperature drops, the number of bubbles in the frozen ice decreases, and the ice density increases[23], namely the content of pure ice increases and the thermal conductivity increases. Since there is not too much salt in the freezing water with small conductivity, it changes smoothly. When the temperature is reduced to a certain extent, most salt has been precipitated, so the salinity does not change much with the further reduce of the temperature, that is say, the content of pure ice turns to be stable, and therefore, the thermal conductivity does not change significantly.

Fig.7 shows: the thermal conductivity of the sample decreases with the increase of the conductivity, and changes smoothly with the decrease of the freezing temperature. This is because with the increase of the conductivity, there are much salt contained in the ice, the amount of pure ice decreases simultaneously, leading to lower thermal conductivity. When the temperature decreases, the salt precipitation increases, and when the temperature decreases to a certain extent, most salt in the sample is precipitated, making the thermal conductivity changes moderately.

Glaze, which is a harmful accident to the transmission lines, generally forms at 0~-5°C environment. Fig.7 shows that the thermal conductivity of ice formed at this temperature range varies rapidly with the change of the conductivity of the freezing water. Such as -5°C, the conductivity increased from 25.49μS to 1791μS, and the thermal conductivity decreased by 20.5%. Therefore, the influence of the freezing water conductivity on the thermal conductivity should be considered during the study of the actual line icing.

V. CONCLUSIONS

Based on the experimental study of the ice thermal conductivity in this paper, we can draw the following conclusions:

(1) Thermal conductivity of the ice has something to do with the freezing temperature, it increases with the decrease of the temperature, when the temperature drops to a certain extent, it changes not too much with the further drop of the temperature.

(2) The thermal conductivity is also related to the conductivity of the freezing water which forms the ice, it drops with the increase of the electrical conductivity, the extent of its decline has something to do with the freezing temperature, the lower the temperature is, the more gently it decreases.

(3) In the case of natural glaze, the thermal conductivity of ice influences a lot by the freezing water conductivity.

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