Experiments and Analysis of Crystallization Effect during the Freezing Water Transition from Liquid to Solid Phase in Natural Environment

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ABSTRACT

Icing flashover accident is an important issue which influences the security operation of transmission lines. A great deal of research work about flashover performance of ice-covered insulators has been taken by many experts in the world so far. However, while the research work carried out, whether we can take the conductivity of icing water and ice amount as the characteristic values of the icing flashover voltage of the insulator strings, and whether there is an equivalence existing between the conductivity of icing water and melting ice water, the researchers haven't achieved the mutual recognition. The spatial distribution of the conductive ions in the ice layer at the freezing water phase transition process is discussed in this paper. The physical process of the electrolyte crystallization during the freezing water transition from liquid to solid phase in nature environment was researched in Xuefeng Mountain icing observation station, Chongqing University. In the experiments, the spherical specimens which have the same bulk and different original conductivity were frozen naturally. And the experiment results showed that there is the maximal ion concentration in the external surface area of the ice specimens during the freezing water transition from liquid to solid phase. The reason of the uneven distribution of the conductive ion in the ice layer was analyzed, and the essence of the differences between the freezing water and the melting ice water was revealed. The expression of the total ice layer resistance based on an insulating plane was proposed, and the recommendation that the crystallization effect should be taken into account while researchers analyze the icing flashover performance of the insulators was also proposed in this paper.

Index Terms —**Freezing water, conductivity, melting ice water, phase transition, crystallization effect, insulator**

1 INTRODUCTION

ATMOSPHERIC icing episode is one of the chief risk factors to the security operation of transmission lines, and which has troubled the high power consuming Country in the world so many years. As the result of atmospheric icing of power networks, a great deal of accidents such as tower collapse, wire breakage, galloping, icing flashover or even large area power blackout have brought great losses to the power grid in Canada, China, USA and other countries in recent years, which have made a great impact on human's life in those countries. More construction of UHV transmission project will be started coupled with the implementation of "west-east power transmission, nationwide power networking" in China. The transmission distance is too long to these UHV transmission project, and unfortunately, quite a few of these transmission lines need span the high altitude areas where severe icing accidents occur easily. So the insulator strings of these UHV transmission project must suffer from atmospheric icing inevitably [1-5]. Therefore, further study of the influencing factors of icing flashover is significant to ensure the reliability, safe and stable operation of UHV transmission system.

Ice deposit is a special contamination, which can lead the external insulation performance of the transmission lines to deteriorate or, in more serious cases, even icing flashover. In icing seasons, the contamination deposits on the insulator surface in two ways: one is that the contamination layer on the insulator surface has been formed before icing; and the other is that the supercooling droplets capture the small conductive particles suspended in the air as they fall, namely the supercooling droplets have been contaminated before freezing. To the second case, the conductive material which dissolved in the supercooling water will crystallized to the surface of the ice layer while the liquid water froze solid, and this interesting phenomenon during the freezing water transition from liquid to solid phase can be distinguished as “Crystallization Effect”.

Experiments show that there are only two ways of the discharge path to the ice-covered insulators: one is along the inner surface of the ice deposit, namely the discharge path is close to the surface of the insulators; the other is along the external surface of the ice deposit. Even if the ice layer melts gradually, the discharge path of the ice-covered insulators are no more than these tow ways [6]. It can be seen that in either case above mentioned, the water film on the ice layer external or inner surface will dissolve the conductive material in the surface layer of the ice deposit on the insulators because of “Crystallization Effect”. Consequently, the icing flashover voltage of the insulator strings will be decreased. Unfortunately, while the icing flashover experiments carry out, the conductivity of the water film on the ice layer is very difficult to measure. Therefore, some researchers take the conductivity of the freezing water and ice amount as the characteristic values of the icing flashover voltage. However, while the research work carried out, whether we can take the conductivity of icing water and the ice amount as the characteristic values of the icing flashover voltage, and whether there is an equivalence existing between the conductivity of icing water and melting ice water, there is a lack of qualitative analysis at present.

In order to study the redistribution of the conductive material which dissolved in the supercooling water during the freezing water transition from liquid to solid phase, the freezing experiment of spherical specimens was carried out in Xuefeng Mountain icing observation station, Chongqing University. The influence of the “Crystallization Effect” on the redistribution of the conductive material in the supercooling water with various initial conductivity have been studied in this paper. That supplied some information for further research on the relationship between ice deposit and icing flashover voltage.

2 TEST PRINCIPLE, METHOD AND SPECIMENS

2.1 TEST PRINCIPLE

The results in Ref. [4, 6] show that no matter what contaminated way the ice-covered insulators belong to, the water film on the ice surface will dissolve the conductive material in the surface layer of the ice deposit in the ice melting process. Thus, the conductivity of the water film on the ice layer will be increased remarkably, and the icing flashover voltage of the insulator strings will be decreased. Although the icing flashover experiment show that something has changed within the conductive ion distribution in the ice deposit, and the tendency is the concentration of the conductive ion is higher in the surface ice layer [6, 7]. So far, the relationship between the conductivity of the spatial distribution in the ice deposit and the freezing water lack system and deep research.

In order to analysis the “Crystallization Effect” of the freezing water during it’s transition from liquid to solid phase qualitatively, the authors take spherical icing specimens as the research object. When the specimens are still in a liquid state, the conductivity is the same in the spatial of the specimen. The spatial distribution of the conductive ion in the specimen will be changed during the transformation. There is a hypothesis that the change trend of the conductive ion distribution along the center to each direction is identical, that is, if the distribution of the conductive ion in the specimen has been changed, then the conductivity at two test points arbitrary *a* and *b* which apart from the centre of the spherical specimen at the same distance should be identical, as shown in Figure 1.

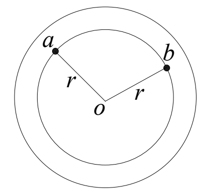


Figure 1 Test points *a* and *b*

2.2 TEST METHOD AND SPECIMENS

The spherical containers with a radius of 34 mm and a capacity of 164.6 ml used in the experiments are ordinary ocean balls. Because the thickness of the hollow sphere wall is very thin, the authors ignore its thickness. Prepare some spherical containers with the same specification. Carve out a water injection hole with a radius of 4 mm on each ball with a sharp blade. Wash the balls with deionized water ($\gamma_{20}\leq 6$ μS/cm) and then dry it. The balls were filled with specimen solution. The specimens are the freezing water with six kinds of conductivity which adopt 15, 30, 90, 160, 200μS/cm and 310μS/cm (it has been converted to the conductivity at 20°C), respectively.

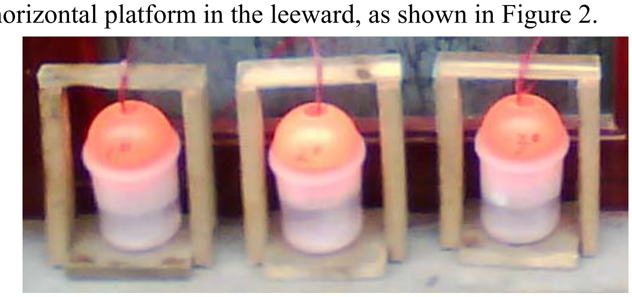
The experiments carried out in Xuefeng Mountain icing observation station from Feb.2 to Feb.18, 2010. The altitude of the test site is 1400m.

The experimental procedures as follows:

1) Move the prepared specimens to the test apparatus, and put them on the measuring cups of low temperature-resistance to keep balance. The water injection hole is vertical upward.

2) Put a thin string which fastened a small fraction of aluminum wire at the head end in the container through the water injection hole, and make the Al wire located at the centre of the sphere exactly. Because the string and the Al wire are very small, when put them into the container, there is no icing water overflow.

3) The tail end of the string was tied to the beam of the test apparatus, and each specimen has one test apparatus independently. Place the pre-numbered specimens on a horizontal platform in the leeward, as shown in Figure 2.



(a) Specimens of No. 1-3

(b) Specimens of No. 4-6

Figure 2 A groups of specimens in testing

The experiment was carried out in low temperature, rain, snow and freezing weather to get a steady low temperature condition. A temperature and humidity sensor (PTU) which linked to a computer was installed close to the test platform. The PTU records and saves the temperature, humidity and wind velocity etc. every 5 min automatically. The freezing water will not be overflowed from the container during its transition from liquid to solid phase because the wall of the hollow sphere used in the experiment has certain elasticity. Because the spherical container is opacity, the testers could not observe the phase transition process in the containers. Therefore, put a transparent monitor measuring cup close to the test apparatus with a radius of 32.8 mm and height of 95 mm which contains 200 ml random specimen solution. Through the observation of the phase transition process in the monitor measuring cup, we can see the freezing conditions in the spherical containers, as shown in Figure 3.

Figure 3 The freezing water in the monitor cup transition from liquid to solid phase completely

While the freezing water in the monitor cup transits from liquid to solid phase completely, it means that the freezing water in the containers had been finished the phase transition process. Then the next measurement experiment could be carried out.

The measurement procedures are as follows:

1) Move the test apparatus to the laboratory, and remove the shell of the spherical icing specimens with a sharp blade, as shown in Figure 4. Here the authors ignored the influence of uneven velocity of the dendritic growth in all directions, and suppose that the specimens are kept in perfect round shape after phase transition. The testers must wear rubber gloves to reduce the measurement errors.

Figure 4 One specimen which finished phase transition

2) The tail end of the string was tied to the beam of the test apparatus, and put a measuring glass with maximum range of 20ml just bellow the spherical icing specimen. Adjust the length of the string to make the space between the bottom of the specimen and the plane of the measuring glass mouth from 3-5 mm.

3) Open the heating system in the laboratory, and the preset temperature is 30 °C. The surface layer of the spherical icing specimens began to melt with the increasing of temperature. The thin water film on the ice layer gathered into water drop at the bottom of the ice ball. Adjust the temperature properly to make the droplet drop down every 5-10 sec.. Because the melting rate is very slow, the authors suppose that the melting rate of the ice ball is identical in all directions. That is, the melting thickness x is identical in all directions in the same time t, as shown in Figure 5.

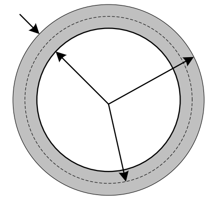


Figure 5 Schematic diagram of ice melting

4) While the melting ice water in the measuring glass has reached 15 ml, then replace the measuring glass with a new measuring glass before the next droplet drops down quickly, as shown in Figure 6. Then, measure the conductivity of the melting ice water and record the corresponding temperature at the same time.

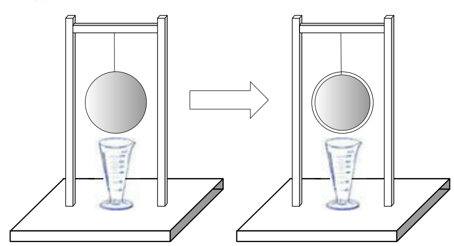


Figure 6 Sketch diagram of test procedure

3 TEST RESULTS AND ANALYSIS

3.1 TEST PRINCIPLE

During the experiment procedure, the average ambient temperature is -5 °C, the average relative humidity is >98%, the wind velocity is <0.5 m/s. The freezing time is 48±1 hours. There are 36 groups experiment data obtained in the experiments. The authors have not carried out the experiments in other climatic conditions for the restriction of the field experiment conditions.

Convert the measurement value of the melting ice water conductivity into the value which at 20 °C according to IEC 507:1991. All the conductivity mentioned in the following sections is the value which at 20 °C. The test results are shown in Table 1. Where r is the distance between the test point and the centre of the sphere. Here the authors suppose that the test point is the midpoint of the melted ice layer in the i times, namely $r=(r_i+r_j)/2$, as shown in Figure 5. Where r_i and r_j are the radius of the ice ball before and after the i times natural melt, respectively.

Table 1 Radial distribution of the melting ice water conductivity

r /cm	$\gamma(x)$ /μS/cm					
	15	30	90	160	200	310
3.46	48.8	136.9	333.8	622.9	844.1	1180.1
3.35	15.6	42.5	145.2	160.1	197.1	115.1
3.23	11.9	35.5	105.7	147.3	100.3	77.1
3.09	10.3	18.5	51.6	99.0	140.6	239.3
2.95	8.3	16.9	53.1	53.6	227.9	274.0
2.79	7.8	17.7	53.5	57.6	163.7	241.1
2.61	8.6	21.1	53.1	74.8	143.2	203.6
2.39	14.9	18.6	35.5	93.6	95.7	203.8
2.13	13.4	20.2	45.6	155.8	109.8	255.5
1.77	15.8	9.3	50.7	106.5	103.6	283.9

The experiment error is from 0.2%-4.1%. The conductivity was normalized to facilitate the analysis. Then, the relationship between the conductivity of the melting ice water and the melting ice thickness x was obtained, as shown in Figure 7.

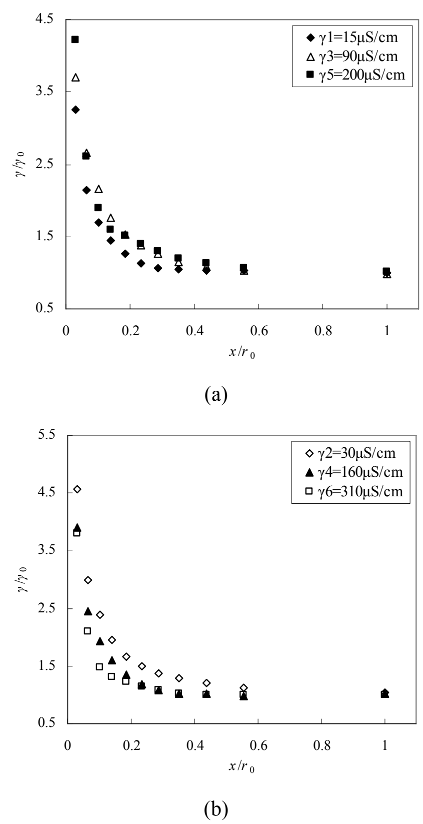


Figure 7 The relationship between the conductivity of the melting ice water and the melting ice thickness

According to Table 1 and Figure 7, it's known that the conductivity of surface ice layer is greater than the centre layer obviously.

3.2 TEST RESULTS ANALYSIS

There is a hypothesis that the change trend of the conductive ion distribution along the center to each direction is identical, and supposes that the specimens are kept in perfect round shape after phase transition. Fit the test results as shown in Figure 7, the relationship between the conductivity of the melting ice water $\gamma(x)$ and the melting ice thickness x under the same meteorological conditions and the same freezing time can be expressed as:

$$\gamma(x)=\frac{\gamma_0}{1-a\cdot e^{-b\cdot x/r_0}} \tag{1}$$

where a, b is constant; γ_0 is the initial conductivity of the icing water; r_0 is the radius of the ice ball.

The fitting results of a and b are as shown in Table 2 and the entire square of the correlation coefficient R^2 are more than 0.996.

Table 2 Fitting value of a, b and R^2 according to the test results of Fig.7 with equation (1)

	γ_0 /μS/cm					
	15	30	90	160	200	310
a	0.882	0.892	0.848	0.915	0.918	1.023
b	27.187	15.120	16.656	23.427	21.040	36.890

According to Table 1, Table 2, Figure 2 and Figure 7, it is known that:

1) The specimens are not kept in perfect round shape after phase transition. This is mainly because that the rate of the dendritic growth in vertical direction is greater than in horizontal direction, the shape of the specimens will deform after phase transition. The deformed coefficient between vertical direction and horizontal direction is from 1.06 to 1.10 in the experiments;

2) The spatial distribution of the conductive ion in the solution has changed after the freezing water finished phase transition. The overall trend is that the ion concentration in the surface ice layer is greater than in the centre layer obviously;

3) The relationship between $\gamma(x)$ and x can be described by a negative exponent function. This is to say that the conductivity of the melting ice water $\gamma(x)$ will decrease with the increase of crystal thickness x;

4) The coefficients a and b are related to the conductivity of the icing water. For example, when γ_0=30, 160μS/cm and 310μS/cm; a=0.892, 0.915 and 1.023; b=15.120, 23.427 and 36.890, respectively. It is shown that the overall trend is that the coefficients will increase with the increase of γ_0.

The experiment results show that the conductive ion which distributed uniformly in the freezing water migrates to the surface of the ice ball during the freezing water transition from liquid to solid phase. This "Crystallization Effect" of the freezing water during its phase transition is related to the phase transition and mass transport mechanism of solution in physics.

1) The phase transition mechanism of “Crystallization Effect”

There are a large number of single and associated water molecules in the liquid water, and these water molecules will be associated to a large associated molecule after the liquid water finished phase transition [8]. There are four hydrogen atoms around one oxygen atom in the associated water molecules. Where the oxygen atom and two hydrogen atoms which relatively near it are held together by covalent bonds, the three atoms constitute a water molecule. The other two hydrogen atoms belong to other water molecules, and these water molecules are held together by hydrogen bonds. It can be seen that the arrangement of the water molecules in the large associated molecule which consist of several water molecules is relatively loose structure. That is to say, the space between the water molecules will be increased after the liquid water finished phase transition. Because the hydrogen bonds have certain directivity, after the large associated molecule formed by the single and small associated molecules, the structure of water has been changed. First, the arrangement of the single molecules in the associated molecule become more regularly. Second, the spaces between molecules become larger [9].

Moreover, when the nucleation phenomenon begins, the dendrites grow rapidly and then release its latent heat faster than the heat that is being removed from the system [10]. The authors think that the conductive ions absorbed the latent heat which had no time to remove from the system, so the conductive ions could get enough energy to migrate to the surface layer. The regular arrangement and larger space of the molecular structure are beneficial to the migration. That is why the spatial distribution of the conductive ions in the specimens will be changed during the freezing water transition from liquid to solid phase.

2) The mass transport mechanism of “Crystallization Effect”

The growth rate of the ice crystal is very slow during the freezing water transition from liquid to solid phase. Therefore, the ice crystal growth process could be regard as a thermodynamic equilibrium process. That is, the phase transition process of the freezing water could be regard as a quasi-static growth process. Generally speaking, the solute concentration at the solid-liquid interface is related to the crystal growth rate, the natural and forced convection of the solution. Thus, the spatial distribution of the conductive ions in the ice is also related to these factors. Because the quasi-static growth process is very slow, the spatial distribution of the solute in the unfrozen solution could be regard as homogeneous in the crystal growth process [11].

In the solution used in the experiments, water is solvent and NaCl is solute. The total content of NaCl in the ice-water system remains constant during the freezing water transition from liquid to solid phase. As the solute in the solution, the segregation coefficient of NaCl is greater than 1 according to the mass transport mechanism. Therefore, the solute concentration is higher in the surface ice layer. And the solute concentration will be decrease along the freezing direction with the increase of icing thickness. Consequently, during the freezing water transition from liquid to solid phase, the distribution rule of the conductive ions along the radial direction in the specimen is that the conductive ions concentration is higher in the surface ice layer, and the ions concentration will be decreased along the radial to the centre of the ice ball.

3.3 ELECTRICAL RESISTANCE OF ICE DEPOSIT

The electrical resistance of an ice layer deposit depends on its thickness, length, width and the initial conductivity of the icing water. It’s supposed that the ice deposit is perfect pure ice with the density of 0.9g/cm^3, and the water film is only formed on the upper surface of the ice deposit. Because the conductivity of the water film is 100-300 times higher than the dry ice below it [12], it can be considered that the conductivity of the water film is far higher than the bottom dry ice. Therefore, the conductance of the bottom dry ice is negligible, and the electrical resistance of total ice deposit can be expressed as:

$$R = \frac{L}{W}\frac{1}{\gamma_w \cdot t_w} \qquad (2)$$

where L is the dry-arc length; W is width of the ice deposit; γ_w is the conductivity of the water film on the ice layer; t_w is the thickness of the water film.

Substitute Eq. (1) into Eq. (2), if the melting thickness $x<d/2$, where d is the ice thickness, then the total ice layer resistance R can be expresses as follows:

$$R = \frac{L}{W}\frac{1 - a \cdot e^{-2b \cdot x/d}}{0.9 \cdot x \cdot \gamma_0} \qquad (3)$$

As insulator geometry modifies the ice layer away from the simple rectangular shape described in Eq. (3), a geometric correction factor should be introduced.

4 CONCLUSION

1) The conductive ions in the ice deposit will migrated to the surface of the ice layer during the freezing water transition from liquid to solid phase. The conductive ions concentration is higher in the surface ice layer. This “Crystallization Effect” is related to the initial conductivity of the freezing water;

2) The “Crystallization Effect” of the freezing water during its phase transition is related to the phase transition mechanism in physics. In fact, the crystallization phenomenon of the conductive ions is the mass transport process of the solute (NaCl) in the solution during its transition from liquid to solid phase;

3) The conductivity of the melting ice water is not equivalent to the initial conductivity of the freezing water. Therefore, while the researchers study the influence factors of the icing flashover performance, not only the conductivity of the freezing water, but also the “Crystallization Effect” of the

freezing water should be taken into account;

4) The approximate formula of the total ice layer resistance is proposed.

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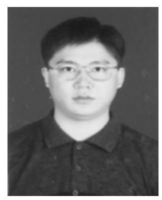

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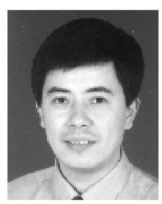

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