Simulation and Experimental Investigation of DC Ice-Melting Process on an Iced Conductor

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Abstract: Since a large-scale icing disaster took place early in 2008 in southern China, Chinese researchers have being studying the transmission line DC (Direct Current, DC) ice-melting technology. With regard to the pressing issues of unreasonable choosing parameters in engineering practice for transmission lines ice-melting, a mobile interface of conductor DC ice-melting model abased on tests is proposed, and a simulation on physical process of DC ice-melting is carried out by this paper. The relationship between ice-melting time and current density, wind speed, environment temperature and ice thickness is also analyzed by this article. Simulation results have been verified by the test carried in the artificial climatic chamber. Test results indicate that the process of DC ice-melting for conductor is shown as the dynamics moving process of the inner surface of ice layer. With the ice melting of the conductor, the melt-water drain from the gap, an elliptical air gap formed between ice and conductor. The formation of air gap influence heat transfer of ice melting process, the shape of ice-melting and ice-melting volume dramatically. The main factors which influence the ice-melting time are current density, wind speed, ambient temperature and ice thickness, etc.

Keywords: **Icing disaster; Transmission line; Ice-melting current density; Ice-melting time**

Index:

symbol	meaning	units	symbol	meaning	units
a	Short oval	m	L	length	m
h	Heat exchange coefficient	W/(m^2.K)	D	Conductor diameter	m
J	Current density	A/mm^2	I	current	A
C	Specific heat	J/(kg.℃)	R	Conductor radius	m
L_F	Latent heat of ice melting	335 kJ/kg	T	temperature	℃
b	Ellipse major axis	m	t	time	s
r_T	T(℃) DC resistivity of conductor	Ω/m	V	Volume	m^3
P	Thermal power	W	v_a	Wind speed	m/s
λ	Thermal conductivity	W/(m.℃)	ρ	Density	kg/m^3

subscript	meaning	subscript	meaning	subscript	meaning
c	Conductor	g	Air gap	i	Ice
al	Aluminum conductor	fe	Steel of conductor	a/e	Air/environment

1 INTRODUCTION

After the icing disaster took place in early 2008 in southern China, there were 7541 transmission lines with above 10kV rated voltage and 859 substations with above 35kV rated voltage were forced to out of service[1]. The direct economic loss of that was more than 19 billion U.S. dollars. And people's life and work was impacted by this disaster seriously. So it is significant to develop effective anti-icing and de-icing methods for the safe operation of power grids in China. Although the research of anti-ice disaster on the power grid has being been carried for decades internationally [2,3], there are none effective measures now to overcome the ice disaster as which took place in early 2008 in southern China. As a result of the diversity of the grid structure and energy distribution to other countries, DC ice-melting method is utilized as the main scheme in China. DC ice-melting time is influenced by the current density, wind speed, ambient temperature and so forth.

In order to ensure the ice-melting is accomplished in specified time, the current density for ice-melting must be determined according to wind speed, ambient temperature and ice thickness etc, and then the facilities for ice-melting can be chosen depend on the current density. DC ice-melting for transmission line have been carried out in Hunan, Guizhou and other places in China, while sometimes the ice-melting was not completed even in more than a dozen hours as a result of inaccurate estimated ice-melting time and unreasonable arrangements for ice-melting facilities.

Since the 50s of last century, ice disaster on power grids took place frequently, many experts and scholars as well as companies carried out special studies on ice-melting for transmission lines, and a lot of models for solving ice-melting time have been established.

To sum up, ice-melting models can be roughly classified into two categories: static model for ice-melting and dynamic simulating model for ice-melting. Static model ignores the impact of changing state variable during the ice-melting process, and the ice-melting model is established based on the state parameters.

Take the bibliography [4,5] for example, it is believed that only the ice layer on the upper surface of conductor will melt during the ice-melting process, but the ice layer on the both sides and lower side of conductor won't melt as a result of the gap heat resistance. Therefore the shape of cross section for air gap formed by the melted ice layer is similar to cylindrical. As long as the ice thickness is known, the volume of ice-melting and ice-melting time can be obtained through the geometric relationship.

The advantage of this type of model is that calculation is simple and convenient. However, due to conductor temperature, ice thickness and other changing factors in the melting ice process do not take into account; there is a relatively large difference between the results of this type of model and the actual situation. Another model attempts to simulate the ice-melting process dynamically, including continuous thinner changing of ice and changing temperature of ice and conductor in the process. In order to distinguish the first types of models, the paper classify the latter model as the dynamic model of ice-melting. At present, the more representative of the dynamic model has the literature [6-8]. They is divided the ice-melting model into four heat transfer regions: conductor, meltwater ice and the environment. Four regions divided by three separate interfaces: conductor-water, water-ice and ice-environmental.

In the ice-melting process, as the melting of ice, water-ice interface moving outward continuously to form a typical Stefan problem[9]. Compared with the literature [4, 5], the ice thickness, temperature and other parameters are taken into account in the literature [6-8], which change with time constantly. Therefore, it is closer to the actual situation. However, in order to simplify the calculation, the moving down physical process caused by the gravity is neglected in the literature [6-8] when the ice-melting model is established. And it assumed that the round center of water-ice interface is always the conductor center, and gradually move to the outer surface of the ice. In accordance with the assumption of the literature [6-8], ice-melting process was completed when the ice on the conductor melt completely, this is clearly inconsistent with the actual situation. So the calculated ice-melting time accordance with the literature [6-8] is longer than the ice-melting time of the actual situation. In this paper, a number of advantages of establishment of the dynamical ice-melting model in the literature [6-8] are absorbed, and the question of the ice-melting looked as a mobile interface problem (Stefan problem). At the same time a number of assumptions which do not match with the actual situation in the literature [6-8] are abandon, and the downward movement of ice due to the factors of gravity is took into account. Therefore a ice-melting process which is different from the literature [6-8] is obtained. There are a good accordance between the calculation results and DC ice-melting results took in the artificial climate chamber.

2 DC CURRENT ICE-MELTING TESTS

2.1 TEST DEVICE, METHOD AND TEST PRODUCTS

The experimental investigations were carried out in the multi-function artificial climate chamber (7.8m in diameter, 11.6m in height), Glaze Icing natural conditions were simulated and the conductor passes DC current to melt the ice. The specimens are LGJ-240/30 and LGJ-400/35 type ACSR, their profiles and parameters are shown in Tables 1. r20 and rT are the rate of resistance at 20℃ and T℃ respectively, their conversion relationship is

$$r_T = r_{20}\left[1+\alpha(T-20)\right] \qquad (1)$$

Where α is the temperature coefficient of resistance of aluminum and equals to 3.6×10-3/℃.

Tab.1 Basic parameters of the conductors

Conductor models	D_c/mm	D_{fe}/mm	r_{20}/(Ω/m)
LGJ-240/30	21.60	6.90	0.1085×10^{-3}
LGJ-400/35	27.63	7.20	0.07389×10^{-3}

The length of sample conductor is 3.5m, test connection the principle and layout are shown in Fig. 1and Fig. 2 respectively.

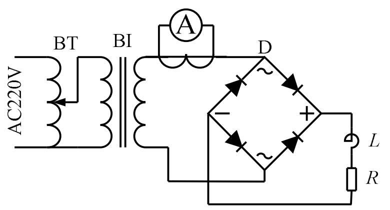


Fig. 1 Experiment circuit (D: Bridge rectifier; L: smoothing Reactor; R: sample Resistance; BT: Regulator; BI: Transformer)

Fig. 2 The picture of experimental connection

2.2 ANALYSIS OF DC ICE-MELTING PROCESS

The actual ice-melting test carried in the artificial climate is shown in Fig. 3. Taking into account the ice-melting weather generally lower than 0 ℃, in this article all the testing and analysis are the assumption that the ambient temperature ≤ 0 ℃. Before ice-melting, it's necessary to make sure the ice temperature and the ambient temperature are equal. From the Fig. 3 the ice-melting process is found and can be divided into three stages:

(1) Conductor and ice temperature rising stage. This stage start from the passing of current stage until the beginning of the inner surface of the ice temperature rose to 0℃. Due to the temperature of the inner surface of the ice below 0℃, the melting ice does not occur. In this stage, to remove heat loss of the outer surface of the ice due to radiation and convection, all Joule heat generated by conductor is used to heat up and ice conductor.

(2) Ice melting stage. When temperature of the inner surface of the ice is up to 0 ℃, the ice-melting stage starts. At this stage, with the ice melting, air-gap will be formed between the ice and conductor. And the ice move down caused by gravity, so that air-gaps around conductor distributed unevenly, and the heat flow form outer surface of conductor to the ice distributed unevenly too. The density of heat flow is big because upper surface of conductor contact with the conductor closely, so that the ice melt faster than other parts and the cross-section shape of the ice-melting develop into oval shape.

(3) Ice off stage. Ice falling from the conductor is a very complicated mechanical process, and relative to the ice owns weight as well as its shear strength. When the gravity of the ice beyond the shear strength of ice, the ice loss from the conductor. Literature [4] has studied this process, and puts forward a formula used for calculating the ice off time. However, in the test process it is found that it is difficulty to estimate the gravity of remaining ice and the shear strength of ice, so that a lot of errors of ice off time exist by using the calculating formula in literature [4]. But in reality, as well as the impact of the wind, the calculation of time off the ice even is more complex. Based on this, this paper adopts the ice off conditions given by literature [10], that is, when the thickness of ice on upper surface of the conductor is 0, the ice fall from the conductor, and the off time can be ignored.

3 DC ICE-MELTING MODELS AND THEIR CALCULATION SCHEME FOR CONDUCTORS

3.1 MATHEMATICAL AND PHYSICAL MODEL

Transmission line will twist in the icing process due to the gravity torque of ice layer, which take on uniform cylindrical. In the ice-melting process, air-gap will form between the ice layer and conductor, and the ice-melting water will flow away by the way of the gap. A large amount of experiment results show that the cross section of air-gap (include conductor) will be ellipse (shown as in Fig. 4(a)) if the ice layer out of the transmission line is uniform cylindrical and its thickness is less than diameter of the conductor. The heat transfer along the axial of conductor can be ignored if the conductor is long enough and iced evenly. Result for the above matters, the ice-melting model can be simplified as a 2-D (2-Dimensional) heat transfer model of cross section, shown as in Fig. 4(b). The heat transfer process of ice-melting by Joule-heat occurs in the following 5 regions:

Θ_1-Steel core of conductor;

Θ_2-Aluminum layer of conductor;

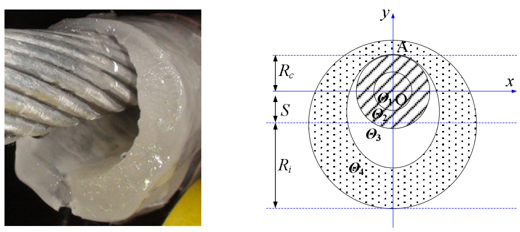
Θ_3-Air-gap;

Θ_4-Ice-layer;

Θ_5-Environment;

The above 5 regions can be separated by 4 interfaces, namely steel core- aluminum layer of conductor (Γ_{12}), conductor-air gap (Γ_{23}), air gap-ice layer (Γ_{34}) and Ice layer- environment (Γ_{45}).

In the process of ice-melting, heat will delivered from aluminum layer (Θ_2) to ice-layer (Θ_4) by air-gap (Θ_3), the ice layer (Θ_4) will melt from the inner surface, the air gap (Θ_3) will from between the conductor and ice layer, and the ice-melting water will flow away by the way of the gap.



(a) Physical photo (b) Sketch picture

Fig. 4 Cross section of ice-melting conductor

The short-circuited ice-melting time is between 0.5 and 3 hours, which is short correspondingly. The impact of sunshine can be ignored for the effect of current Joule-heat is always much larger than solar radiation. In the ice-melting process, the Joule-heat produced by current lost mainly in the following 3 aspects: ① the heat loses produced by convection and radiation for the outer surface of the ice layer; ② the latent heat absorbed by conductor and ice in the process of ice melting; ③ heat the conductor, ice layer and air-gap:

$$\begin{aligned} & I^2 r_T - \pi\left(D_c + 2D_i\right)h(T_{io} - T_e) \\ & = \rho_i L_F \frac{dV_m}{dt} + \sum_{k=1}^{4} \rho_{\Theta k} V_{\Theta k} C_{\Theta k} \frac{dT_{\Theta k}}{dt} \end{aligned} \tag{2}$$

In the above formula, r_T presents the resistivity of conductor, whose unit is Ω/m; R_i presents the radius of the round out of the ice layer, whose unit is m; h presents the heat exchange coefficient (include heat transfer by convection and heat dissipation by radiation) between the outer surface of ice layer and environment, whose unit is W/(m^2.K). V_m presents the cross section area lost in the process of ice-melting (with unite size volume), whose unit is m^2. $\rho_{\Theta k}$ presents the density of the region Θ_k , whose unit is kg/m^3; $C_{\Theta k}$ presents the specific heat capacity of the region Θ_k , whose unit is J/(kg. ℃); $T_{\Theta k}$ presents the temperature of the Θ_k , whose unit is ℃.

In the ice-melting process, $T_{\Theta k}$ (k=1,2,3,4) is always changing, which is the function of time and space, namely $T_{\Theta k} = T_{\Theta k}(x,y,t)$. Based on the formula (1), the calculation model of ice-melting can be expressed as follows:

$$t = \frac{\int_{V_m} \rho_i L_F dV + \sum_{k=1}^{4} \int_{\Theta k} \int_{t_0}^{t} \rho_{\Theta k} C_{\Theta k} T_{\Theta k}(x,y,t) dt dV}{I^2 r_T - \pi\left(D_c + 2D_i\right)h(T_{io} - T_e)} \tag{3}$$

Supposed the volume of ice is known, whose value is $V_{m,}$ and the absorbed heat because of warming of conductor, air gap and ice layer can be ignored, namely $\sum_{k=1}^{4} \int_{\Theta k} \int_{t_0}^{t} \rho_{\Theta k} C_{\Theta k} T_{\Theta k}(x,y,t) dt dV = 0$, so the formula is the static ice-melting model. Thus, we can obtain a conclusion that the static model is a simplified dynamic model.

As the temperature distributed function varies with the downwards displacement of ice layer and the thickness of air gap in the ice-melting process, it is difficult to obtain the analytical solution for dynamic model as for static model.

3.2 CALCULATION FOR THE ICE-MELTING MODEL

3.2.1 CONDITION FOR THE ICE SHEDDING FROM THE CONDUCTOR

With the melting of ice layer, the air gap-ice layer (Γ_{34}) qualifies continually, and the ice layer move downwards with the effect of gravity. Based on the bibliographic reference [10], we can obtain a conclusion that when the air gap-ice layer (Γ_{34}) is tangent the ice layer- environment (Γ_{45}) on the surface of the conductor, the ice layer will break off from the conductor. The condition of ice dropping off from conductor can be expressed as the following:

$$S \geq D_i \tag{4}$$

3.2.2 COMPUTATION SCHEME

The key step of computing formula (3) is to obtain the temperature distribution of the conductor and ice layer. The finite-element method in space and finite-difference method in time is to solve the formula (3) in this paper.

Shown as in the Fig. 4(b), the cross section of icing conductor is divided into N small enough triangle units with n nodes. When the value of N is large enough, the arc of the round can be seen as deemed as a beeline approximately. So the temperature distribution of the cross section can be dispersed as the temperature in n nodes.

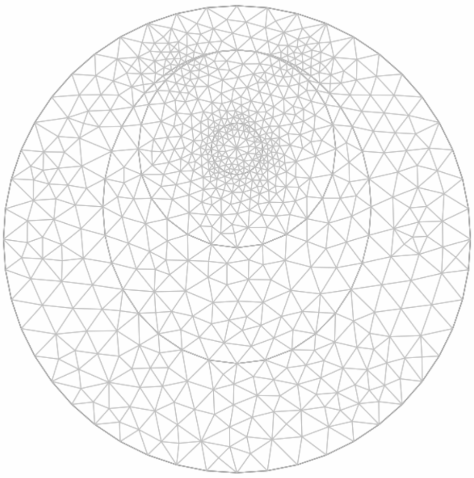


Fig.5 The ice melting model mesh

In time $\Delta t= t_{p+1}-t_p$, The short axis and long axis of the ellipse air gap increase Δa_p, Δb_p and ΔS_p separately. At time of t, the total downwards displacement of ice layer is $S=\sum \Delta S_{p}$. If S satisfies the condition of dropping ice shown as in formula (4), ice will drop from conductor, and t_p is the ice melting time. The calculation flow is:

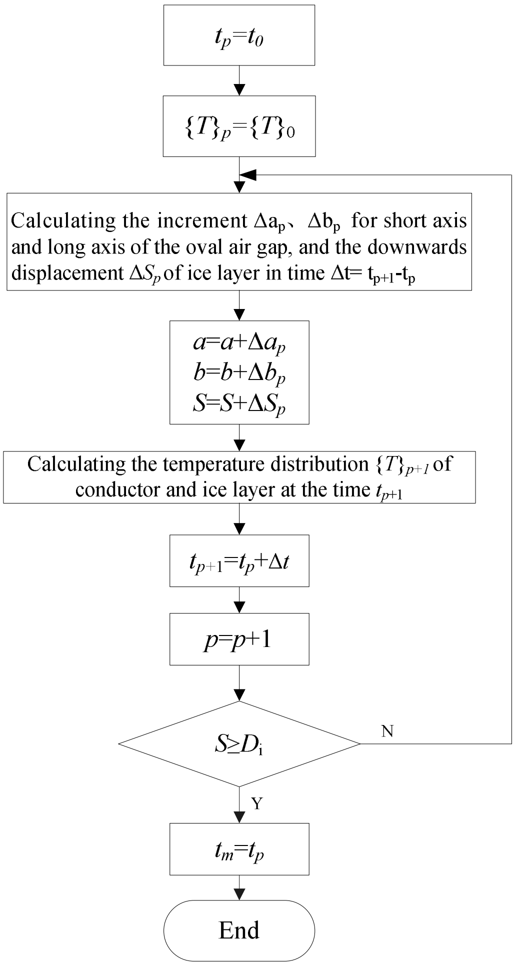


Fig.6 Flow chart of calculation

(1)Temperature at initial time

It is supposed that the temperature before ice melting is T_0. As a result of power ready before ice-melting, the temperature of conductor and environment is balanceable. Namely,

$$\begin{aligned}\{T_0\} &= (T_1 \quad T_2 \quad \dots \quad T_n)^T \\ &= (T_e \quad T_e \quad \dots \quad T_e)^T\end{aligned} \tag{5}$$

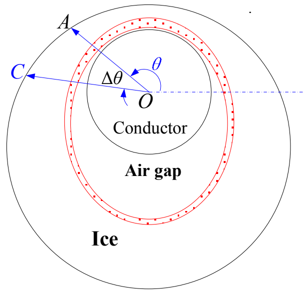
In the formula (5), $\{T_0\}$ is the initial temperature vector (n×1) in each nodes of icing conductor.

(2) The increments Δa_p, Δb_p and ΔS_p for the short axis and long axis of the ellipse air gap at the time $\Delta t= t_{\mathrm{p}+1}-t_\mathrm{p}$

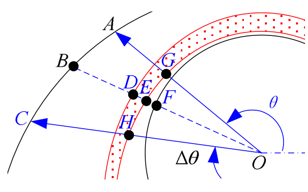
If the ice melting time $t=t_\mathrm{c}$ and the temperature at the inner surface arrives at 0℃, the inner surface of ice layer begin melting, and the beginning time of melting is t_c. At the time of $t_p(t_\mathrm{p}\geq t_\mathrm{c})$, and the increment of ice melting time is $\Delta t= t_{\mathrm{p}+1}-t_{\mathrm{p}}$, it is supposed that the wind speed and the environment temperature don't change if Δt is small enough. The unit volume of ice melted is shown as the shadow in Fig.7. The ice melted in time Δt is:

$$\Delta V_m{}^p = \frac{1}{\rho_i L_F}\left[\begin{array}{l}\left(I^2 r_T - \sum\limits_{boun} l_E h(T_E^p - T_e)\right)\Delta t \\ -\sum\limits_{E=1}^{N}\left(\rho_E C_E V_E \Delta T_E{}^p\right)\end{array}\right] \tag{6}$$

In the above formula, *boun* presents the boundary element of the outer surface for ice layer. $\Delta V_\mathrm{m}{}^\mathrm{p}$ presents the cross-section area (m^2) of melted ice layer in time $\Delta t= t_{\mathrm{p}+1}-t_{\mathrm{p}}$. l_E presents the outside arc length (m) of boundary element E for the out surface of the ice layer. ρ_E presents the density of element E, and its unit is kg/m^3. V_E presents the cross-section area or unit volume and its unit is m^2. C_E presents the specific heat capacity of the element E whose unit is J/(kg.℃). $\Delta T_E{}^p$ presents the changed temperature of element E in time $\Delta t= t_{\mathrm{p}+1}-t_{\mathrm{p}}$, and its unit is ℃.



(a) Global sketch



(b) Local sketch

Fig.7 Melted volume in the time Δt

It is supposed that the air gap thickness is the function of θ and t. And supposing that the air gap thickness at the time t_p is $D_g^p(\theta)$. A polar equation which is to lead the center of conductor as the origin can be established and it is supposed that $\psi = b^2\cos^2\theta + a^2\sin^2\theta$. Any angle θ of the thickness for air gap can be obtained based on the polar equation for the outer round of conductor and the inner ellipse:

$$\begin{cases} D_g{}^p(\theta) = R_c + \dfrac{ab - a^2 R_c}{\psi}\sin\theta \\ -\dfrac{ab\sqrt{\sin^2\theta(a^2 + R_c{}^2) + 2bR_c\cos^2\theta - R_c{}^2}}{\psi} \end{cases} \tag{7}$$

(a) The air gap increment at the time of $t_p<t_c$

At the time of $t_p<t_c$, the temperature at the inner surface of ice layer is smaller than 0℃, if ice layer do not melt, it is can be obtained from $D_g^p(\theta)=0$.

The Joule-heat generated by the ice-melting current is balanceable to the heat loss produced by the convection, radiation and the heating of conductor and ice layer.

(b) The air gap increment at the time of $\Delta t= t_{p+1}-t_p$ while $t_p=t_c$

It is can be seen from the Fig.8(a) that the temperature at the surface of conductor rise to 0℃and the inner surface of ice layer is to be in critically ice-melting statement. At this time of day, the air gap between the conductor and ice layer have not been formed, and at anywhere whose angle is θ, it is that $D_g^p(\theta)=0$. The temperature distribution of conductor and ice layer is radicalized symmetrical, so is the heat flow from conductor to the ice layer. So at any directional, the increment of ice-melting thickness $\Delta D_g^p(\theta)$ (m) is:

$$\Delta D_g^p(\theta) = \frac{\Delta V_m^p}{2\pi R_c} \tag{8}$$

(c) The air gap increment at the time of $\Delta t= t_{p+1}-t_p$ while $t_p>t_c$

The air-gap will be produced between conductor and ice layer at the time of $t_p>t_{cday,}$. The heat transfer along conductor to ice layer is uneven because the air-gap distribution along the conductor surface is not even. The ice-melting thickness along the direction of θ is discrepant at the time of $\Delta t= t_{p+1}-t_p$day. It is can be seen from the Fig.3, if a small enough unit $\Delta\theta$ can be obtained, and the ice-melting thickness in $\Delta\theta$ is even. The tiny region *OABCO* satisfies the heat equation (2) if a small enough unit $\Delta\theta$ in which the ice-melting thickness is even. The heat absorbed by the air-gap can be ignored because the change of air-gap quality and temperature is so small. So the ice-melting increment $\Delta D_g^p(\theta)=DE$ satisfies the following:

$$\Delta D_g^p(\theta) = \frac{1}{l_g}\begin{pmatrix} R_c\lambda_a\Delta t\cdot\dfrac{\overline{T}_{cs}^p(\Delta\theta)}{\overline{D}_g}\Delta\theta\cdot\Delta t \\ -\dfrac{h[\overline{T}_i{}^p(\Delta\theta) - T_e]l_i}{\rho_i L_F}\Delta t \\ -\dfrac{\rho_i C_i V_i(\Delta\theta)}{\rho_i L_F}\Delta\overline{T}_i{}^p(\Delta\theta) \end{pmatrix} \tag{9}$$

Where, $\overline{T}_{cs}^p(\Delta\theta)$ and $\overline{T}_i{}^p(\Delta\theta)$ present the average temperature at the conductor surface with $\Delta\theta$ and ice layer surface separately, and its unit is $^\circ C$. l_i presents the arc *ABC* with unit m. l_g presents the arc *GEH* with unit m. h presents the heat exchange coefficient between the outer surface and air[11], and its unit is W/(m^2.K). $V_i(\Delta\theta)$ presents the cross section area of the ice layer with intersection angle $\Delta\theta$. $\Delta\overline{T}_i{}^p(\Delta\theta)$ present the average temperature change at the time of $\Delta t=t_{p+1}-t_p$ in the intersection angle $\Delta\theta$, and its unit is℃.

(d) The long and short axis of ellipse increase separately as following:

$$\begin{cases} \Delta a_p = \Delta D_g{}^p(0°) \\ \Delta b_p = \dfrac{\Delta D_g{}^p(90°) + \Delta D_g{}^p(270°)}{2} \end{cases} \tag{10}$$

The downwards of ice layer at the time of $\Delta t=t_{p+1}-t_p$ is:

$$\Delta S_p = \Delta D_g(90°) \tag{11}$$

(3) The temperature distribution of conductor, ice layer and air-gap at the time of t_{p+1}.

The heat transfer equation of ice-melting of conductor [12] is:

$$D_{T(x,y,t)} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + q_v - \rho C_p\frac{dT}{dt} = 0 \tag{12}$$

The variation [13] of formula (12) can be realized by weighted residual method as:

$$\frac{\partial J^D}{\partial T_l} = \iint_D \begin{bmatrix} \lambda\left(\frac{\partial W_l}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y}\frac{\partial T}{\partial y}\right) \\ -q_v W_l + \rho C_p W_l \frac{\partial T}{\partial t} \end{bmatrix} dxdy - \oint_\Gamma W_l \lambda \frac{\partial T}{\partial n} ds \quad (l = 1,2,\ldots n) \tag{13}$$

Where, W_l is the weight function of the node l (l=1,2,…n), the line shape function of triangle unit is adopted by this paper[14]. $-\lambda\partial T/\partial n$ presents the heat flow density at the direction of vertical direction, and its unit is W/m^2.

During the ice-melting process, the heat transfer between the ice layer and environment (Γ_{45}) satisfies the following condition:

$$-\lambda \frac{\partial T}{\partial n}\bigg|_{\Gamma 45} = h(T - T_e) \tag{14a}$$

Where, h is the heat exchange coefficients between the ice layers out-surface and air [11], and its unit is W/ (m^2.K). The inner surface (Γ_{34}) is mixture of ice and water at the beginning of melting of ice layer, and its temperature keep 0℃, namely:

$$T\big|_{\Gamma 34} = 0 \tag{14b}$$

The formula (13) can be integral, and substituted by the boundary condition (14), then an equation can be obtained as:

$$\begin{cases} [K]\{T\}_t + [N]\{\frac{\partial T}{\partial t}\}_t = \{P\}_t \\ \{\frac{\partial T}{\partial t}\}_t = \left(\frac{\partial T_1}{\partial t}, \frac{\partial T_2}{\partial t}, \ldots, \frac{\partial T_i}{\partial t}, \ldots, \frac{\partial T_n}{\partial t}\right)_t \end{cases} \tag{15}$$

Where, $[K]$ is temperature coefficient matrix (n×n), $[N]$ is the temperature rise matrix (n×n), $\{P\}_t$ is the constant vector (n×1), which is related to the heat source and boundary condition, $\{T\}_t=(T_1,T_2,\ldots,T_n)$ (n×1)is the node temperature vector at the time t. $\{\partial T/\partial t\}_t$ (n×1) is the temperature rise ratio vector at the time t. The equation at the time $t=t_p$ and $t=t_{p+1}$can be expressed as following:

$$\begin{cases} \{\frac{\partial T}{\partial t}\}_p = [N]^{-1}\left[\{P\}_p - [K]\{T\}_p\right] \\ \{\frac{\partial T}{\partial t}\}_{p+1} = [N]^{-1}\left[\{P\}_{p+1} - [K]\{T\}_{p+1}\right] \end{cases} \tag{16}$$

Galerkin difference method [15] can be applied here, and its format is:

$$\begin{cases} \frac{2}{3}\left\{\frac{\partial T}{\partial t}\right\}_{p+1} + \frac{1}{3}\left\{\frac{\partial T}{\partial t}\right\}_p \\ = \frac{1}{\Delta t}\left(\{T\}_{p+1} - \{T\}_p\right) \end{cases} \tag{17}$$

The formula (17) can be substituted by (16), and then the temperature of ice-melting conductor at each node can be obtained as:

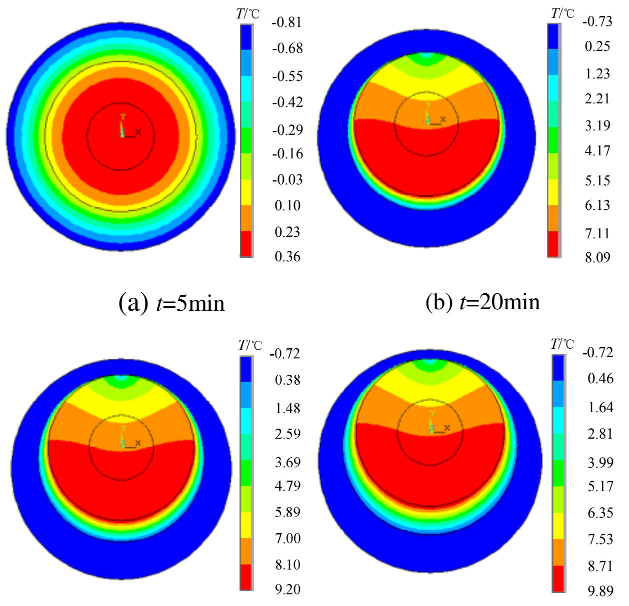
$$\begin{cases} \{T\}_{p+1} = \frac{\Delta t}{3}\left([E] + \frac{2\Delta t}{3}[N]^{-1}[K]\right)^{-1} \\ \times [N]^{-1}\left(2\{p\}_{p+1} + \{p\}_p\right) \\ + \left([E] + \frac{2\Delta t}{3}[N]^{-1}[K]\right)^{-1} \\ \times \left([E] - \frac{\Delta t}{3}[N]^{-1}[K]\right)^{-1}\{T\}_p \end{cases} \tag{18}$$

Where, $[E]$ is an identity matrix whose dimension is n×n.

4. THE SIMULATION RESULTS AND EXPERIMENT VERIFICATION

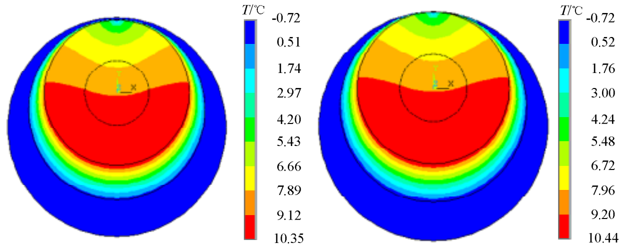
4.1 SIMULATION RESULTS OF DC ICE-MELTING PROCESS OF CONDUCTOR

According to the ice-melting experiment conditions of Fig. 3 and formula (18), This paper uses commercial software COMSOL3.4 to simulate. Fig. 8 shows the simulation results of DC ice-melting of conductor. The color in Fig. 8 is the temperature distribution of conductor cross-section. We can see from Fig. 8, The simulation results agrees with test results.



(a) t=5min (b) t=20min

(c) t=30min (d) t=40min

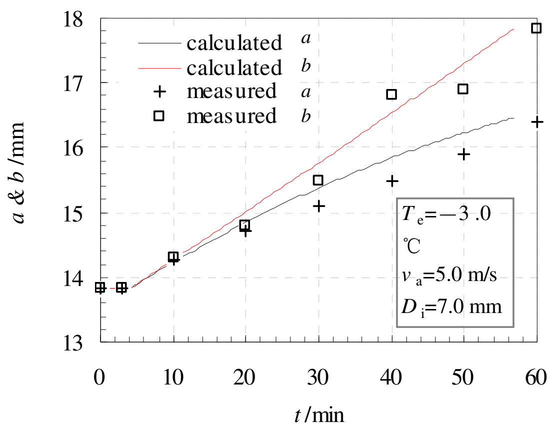


(e) t=50min (f) t=57min

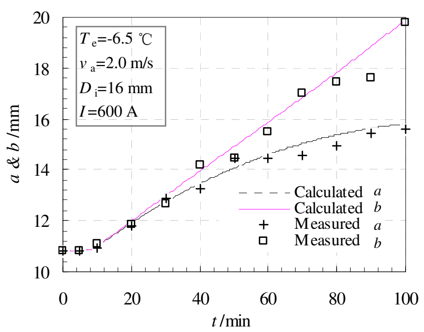
Fig. 8 Simulation of ice-melting process (for LGJ-400/35 conductor at T_e=-3℃,v_a=5m/s,D_i=7mm,I=800A)

4.2 EXPERIMENT VERIFICATION OF AIR GAP GROWTH

Fig.9 shows the simulation and experiment values of short and long axis of oval-shaped air-gap growth. From the simulation and experiment values in Fig. 9 , we can see that with the ice-melting time increasing, the short axis(a) of oval-shaped air-gap tends to increase saturated, while the long axis (b) of oval-shaped air-gap tends to increase unsaturated.



(a) LGJ-400/35



(b) LGJ-240/30

Fig. 9 Increase process of air-gap

4.3 EXPERIMENT VERIFICATION OF ICE-MELTING TIME

Table 2 lists the comparison of ice-melting time calculation and experiment values of different ice-melting test conditions. From Table 2, we can see that the model calculation and experiment value of ice-melting time is agreed. If the wind speed, environment temperature and the ice thickness parameters and so on are measured accurate, the error of the ice-melting time simulation and experimental values can be controlled at less than 15%.

Tab.2 Contrast between tested ice-melting time and calculated one

Conductor Type	J/(A/mm^2)	v_a/(m/s)	T_e/℃	D_i/mm	t/min	
					Tested	Calculated
LGJ-400/35	2.00	5	-3	7	63	57
LGJ-400/35	2.00	5	-1	15	74	73
LGJ-240/30	2.50	4	-3	11	87	80
LGJ-400/35	1.50	1	-7	14	141	139
LGJ-400/35	2.12	0.7	-7	10	87	89
LGJ-400/35	2.12	3.8	-6	15	171	178
LGJ-400/35	2.12	1.5	-6	14	149	141
LGJ-400/35	2.65	4	-7	16	106	102
LGJ-240/30	2.50	3.5	-5	15	170	160
LGJ-240/30	3.00	3	-6	12	77	73
LGJ-240/30	2.50	1	-5.8	10	78	77
LGJ-240/30	3.00	3	-5	13	55	56
LGJ-240/30	3.00	1.5	-7	16	103	99

5. THE INFLUENCE FACTORS OF ICE-MELTING TIME

5.1 THE RELATIONSHIP BETWEEN ICE-MELTING TIME AND CURRENT DENSITY

The condition of conductor ice-melting is that Joule heat must be greater than the convection and radiation heat loss of the outer surface of ice.

$$J_c = \frac{\sqrt{\pi(D_c + 2D_i)h(T_{io} - T_e)/r_T}}{A_c} \tag{19}$$

Where, A_c: effective area of the conductor cross-section, mm^2. By formula (2), we can see that when the ice-melting current density J>Jc, the ice melting. In this paper, take ice-melting Jc as critical current density [11].

Fig. shows the relationship between ice-melting time and current density calculated values from the ice-melting model. From Fig. 10, we can see that when the current density increases, ice-melting time reduces. When current density near the critical current, the influence of current density change to ice-melting time is great, current density increased can obviously reduce ice-melting time. With the ice melting current density increasing, the influence of current density change to ice-melting time is smaller.

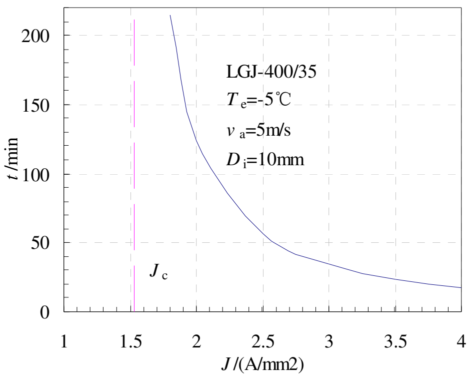


图 10 The relationship between Ice-melting time and current density

5.2 THE INFLUENCE OF WIND SPEED TO ICE-MELTING TIME

Neglecting the natural convection heat transfer of the ice outer surface, the heat exchange coefficient of ice outer surface and environment can be expressed as:

$$\begin{aligned} h &= 4\varepsilon\sigma(T_e + 273.15)^3 \\ &+ \alpha\lambda_a (D_c + 2D_i)^{\beta-1} v^{1/3-\beta} a_v^{-1/3} v_a^{\beta} \end{aligned} \tag{20}$$

Where, ε is the emissivity of ice outer surface , ε = 0.95; σ is the radiation constant, 5.567 × 10_{-8} W / (m^2. ℃ 4); av is the thermal diffusion rate ,to 0 ℃ for air, a_v = 1.88 × $10_{-5}m^2$ / s; α, β as the coefficient determined by Reynolds number . When 40 ≤ Re ≤ 4000, when, α = 0.683, β = 0.466; When 4000 <Re≤40000,α=0.193,β=0.618; when40,000<Re≤400,000,α=0.0266, β= 0.805.

Put formula (20) into formula (2), we have,

$$\begin{cases} t = \dfrac{\int_{V_m} \rho_i L_F dV + \Re}{I^2 r_T - \left(C_1 + C_2 \cdot v_a{}^{\beta}\right)} \\ \Re = \sum\limits_{k=1}^{4} \int_{\Theta k} \int_{t_0}^{t} \rho_{\Theta k} C_{\Theta k} T_{\Theta k}(x,y,t)\,dt\,dV \\ C_1 = 4\pi\varepsilon\sigma\left(D_c + 2D_i\right)(T_e + 273.15)^3 (T_{io} - T_e) \\ C_2 = \pi\alpha\lambda_a v^{1/3-\beta} a_v{}^{-1/3} (T_{io} - T_e)(D_c + 2D_i)^{\beta} \end{cases} \tag{21}$$

From formula (21), we can see that the wind speed greater, the forced convection heat loss of ice outer surface loss more, and required longer ice-melting time.

$$v_{ac} = \sqrt[\beta]{\frac{I^2 r_T - C_1}{C_2}} \tag{22}$$

Where: v_{ac} is the critical wind speed, m/s; C_1, C_2 are the same as formula (21). when the wind speed $V_a \geqslant v_{ac}$, the ice melting phenomenon will not appear. Fig. 11 shows the calculation results of the previous model. From Fig. 11, We can see the wind speed have a very significant impact on the ice-melting time, and the wind speed greater , the influence to ice-melting time is greater.

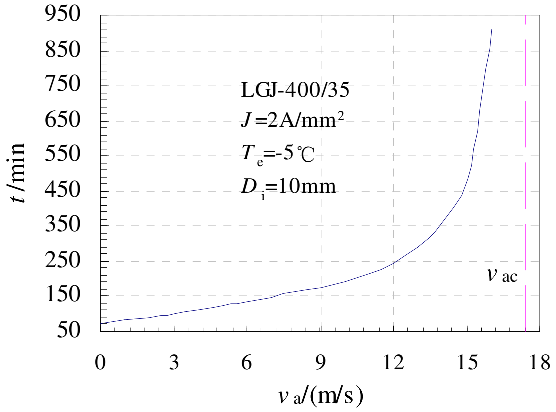


Fig.11 the influence of Wind speed to ice-melting time

5.3 THE INFLUENCE OF ENVIRONMENT TEMPERATURE TO ICE-MELTING TIME

Ice-melting time is affected by the environment temperature through the radiation and convection heat loss at the outer surface of ice layer. According to the formula (21) and Fig. 12 shows, when the ambient temperature reduces, the radiation and convection heat loss of the ice outer surface increases, so that ice-melting time become longer. The same as influence of wind, when the current density, ice thickness and wind speed is pre-determined, the environment temperature is below a certain critical temperature, the ice will not melt whether how much time.

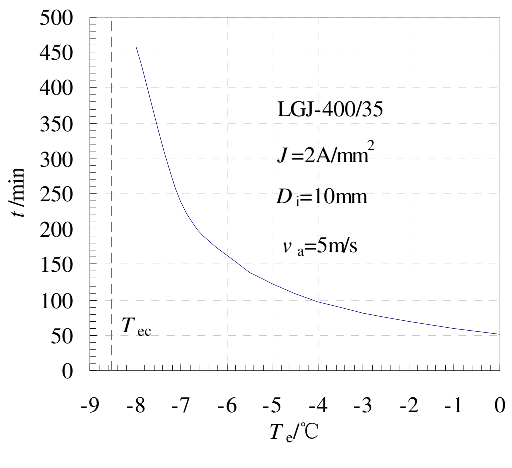


Fig 12 he influence of Environment temperature to ice-melting time

5.4 THE INFLUENCE OF ICE THICKNESS TO ICE-MELTING TIME

It is can be seen from Fig.13 that ice-melting time is longer with the ice thickness increasing. Ice-melting Time is almost linear with ice thickness.

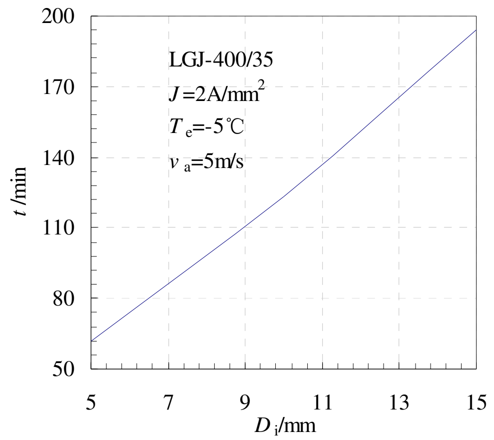


Fig 13 the influence of Ice thickness to ice-melting time

6 CONCLUSION

(1) During the process of ice melting, an oval-shaped air-gap will form between the conductor and ice, and the ice gradually increases, temperature of conductor surface is higher than 0℃ due to the high thermal resistance of the air gap,.

(2) When the wind speed, ambient temperature, and ice thickness are pre-determined, the ice-melting time decided by the current density. Current density is greater than the critical current density of ice-melting, the ice will melt. When the Ice-melting current density is greater, the ice-melting time is shorter.

(3) If current density, ice thickness and the environment are pre-determined, the ice-melting time is impacted significantly by the wind speed, and the greater of the wind speed,, the longer the ice-melting time. When the wind speed is greater than the critical wind speed, the ice will not melt. Different current density corresponds to different critical wind speed, the greater the current density, the greater the wind speed.

(4) If current density, ice thickness and the environment temperature are pre-determined, the ice-melting time is impacted significantly by the environment temperature, and the lower ambient environment temperature, the longer the ice-melting time. When the environment temperature is lower than the critical environment temperature, the ice will not melt. Different current density corresponds to different critical environment temperature, the greater the current density, the lower the critical environment temperature.

(5) Ice-melting time is almost linear with ice thickness, and the thicker the ice, the longer ice-melting time.

(6) A DC ice-melting time calculation model is also established by this paper and the model calculation results are verified by test. In case of the absence of solar radiation, and cooling water droplets in air never hit the conductor, DC ice-melting time can be estimated by this model.

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