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### Article

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## Study on finite element analysis of the external heat resistance of cables in ductbank<sup>☆</sup>

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### Abstract

Power cable engineering is a critical method for urban power supply, and ductbank laying of cables is a way of underground cable lines. Considering the cost and construction, MPP pipes with poor heat dissipation performance are often used in ductbank. Many cables are arranged densely in the piping group, which reduces the ampacity of cable lines. According to the formula for calculating the ampacity in IEC60287 standard, the external thermal resistance of cable is affected by the laying environment, which is an important factor affecting the ampacity of cable. However, calculation method for the external thermal resistance of directly buried cable and cable laid in air is given in the standard merely, while the external thermal resistance of cable laid in ductbank is not given for each hole. In this paper, using the definition formula of external thermal resistance and finite element analysis method, the thermal resistance of each hole of ductbank is studied, and the external thermal resistance of the ductbank is obtained accurately, which is conducive to the analysis of the ampacity of cable and the rational arrangement of the cable laying hole position.

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*Keywords:* Cable ductbank laying; Equivalent thermal resistance; Finite element method; Cable ampacity

### 1. Introduction

Safe and stable power supply is the foundation to ensure the rapid development of cities. Underground power cable lines play an important role in cities where land is precious. The common laying methods of underground cables include direct burial, cable trench, ductbank, tunnel and Bridge etc. Among them, the laying method of power cable ductbank has the advantages of saving investment, occupying less area, flexible route, and convenient construction, hence it is widely used in urban cable engineering.

Electric power pipes are stacked with several pipes, and the pipes are separated by sleepers, and the external pipes are covered with brick or reinforced concrete. The different heat dissipation paths of each hole in the row

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lead to different heat dissipation performance of each hole. Accurate calculation of the external thermal resistance of the cable is helpful to arrange the location of the cable reasonably, and calculation of cable ampacity could be more precise.

The ampacity of cable is affected by environmental temperature, AC resistance, electromagnetic loss, thermal conductivity of material, grounding mode and external environment [1]. In 1999, 2001, 2006 and 1985 International Electrotechnical Commission issued IEC60287 and IEC60853 series standards. Formulas for calculating the ampacity of cables under various laying conditions have been given. However, simplified formulas for calculating external thermal resistance are only given in the specifications, while those for cables in complex and irregular laying environments could not be calculated.

The structure of ductbank could not be simplified by circular or rectangular model, and the heat transfer path of cable lay in it is difficult to be explained by simple model. Therefore, the calculation of thermal resistance coefficient of environment is relatively complicated. According to the different location of holes, the cable located at the edge of pipe group is close to the surrounding soil and has smaller thermal resistance. Cables located at the center of the tube group need to pass through multi-layer results in heat transfer, so they will have greater thermal resistance.

In order to improve the short-term ampacity of laying cables with row pipes, Sakata and Iwamoto [2] improved the genetic algorithm to improve the calculation accuracy of cable resistance and ampacity. Moutassem [3] studied the optimization strategy of laying power cables in ductbank under unequal loads based on the standard IEC ampacity calculation formula. Compared with the settlement results of CYMCAP software, the optimized cable ampacity can be increased by at least 10%, but the calculation process did not consider the mutual restriction among the cables in each loop. The results are not accurate enough. Zarchi et al. [4] proposed a reasonable layout method of underground cables considering current harmonic effect and cable life cycle [5] respectively, and applied it into the laying of ductbank to improve the transmission capacity of the transmission lines.

Accurate calculation of the external thermal resistance of laying cables in ductbank is helpful to analyze the ampacity of cables. Considering that it is difficult to solve the external thermal resistance by using existing standards, the finite element method is used to discretize the characteristics of solving complex boundary problems [6].

In this paper, the finite element method is used to analyze the temperature field of cable system. Based on the finite element theory, the finite element model of cable is constructed. The model is meshed and the boundary conditions are set. Considering that the external thermal resistance of cable laid in the row pipe is affected by many environmental factors, the laying of cable in the row pipe is analyzed here. The external equivalent thermal resistance of the cable is identified by the ratio of temperature difference to heating power, and then the thermal resistance of each hole position of the cable is analyzed.

## 2. Principle of finite element analysis for temperature field of line

### 2.1. Thermodynamics finite element analysis principle

In this study, the distance and span of cable laying in ductbank is large, and a section can be cut for plane analysis. The temperature of cable laying in ductbank is analyzed by finite element equation of plane temperature field.

The basic equation of finite element calculation of temperature field can be obtained either from functional variations or from differential equations by weighted residual method. In the weighted residual method, Galerkin method and least square method can get good results, but Galerkin method is more widely used. The basic equation of finite element method derived from Galerkin method is discussed here.

The differential equation of temperature field with internal heat source in plane under unsteady state is as follows:

$$D[T(x, y, t)] = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q_v - \rho c_p \frac{\partial T}{\partial t} = 0 \quad (1)$$

Take the heuristic function

$$\tilde{T}(x, y, t) = \tilde{T}(x, y, t, T_1, T_2, \dots, T_n) \quad (2)$$

In Eq. (2),  $T_1, T_2, T_3, \dots, T_n$  are  $n$  undetermined coefficients.

By substituting Eq. (2) into Eq. (1), we can obtain by domain integral:

$$\iint_D W_l \left[ k \left( \frac{\partial^2 \tilde{T}}{\partial x^2} + \frac{\partial^2 \tilde{T}}{\partial y^2} \right) + q_v - \rho c_p \frac{\partial \tilde{T}}{\partial t} \right] dx dy = 0 \quad (l = 1, 2, \dots, n) \quad (3)$$

The definition of weighted function in Galerkin method can be written as follows:

$$W_l = \frac{\partial \tilde{T}}{\partial T_l} \quad (l = 1, 2, \dots, n) \quad (4)$$

For the convenience of writing, we might replace  $\tilde{T}$  with  $T$ . Applying Green's formula, Eq. (3) could be rewritten as follows:

$$\begin{aligned} & \iint_D k \left[ \frac{\partial}{\partial x} \left( W_l \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( W_l \frac{\partial T}{\partial y} \right) \right] dx dy \\ & - \iint_D \left[ k \left( \frac{\partial W_l}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y} \frac{\partial T}{\partial y} \right) - q_v W_l + \rho c_p W_l \frac{\partial T}{\partial t} \right] dx dy = 0 \quad (l = 1, 2, \dots, n) \end{aligned} \quad (5)$$

Relations on the boundary of region  $D$  is as follows:

$$-\frac{\partial T}{\partial y} dx + \frac{\partial T}{\partial x} dy = \frac{\partial T}{\partial n} ds \quad (6)$$

It could be found in substitution (5)

$$\begin{aligned} -\frac{\partial J^D}{\partial T_l} &= \iint_D k \left[ k \left( \frac{\partial W_l}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y} \frac{\partial T}{\partial y} \right) - q_v W_l + \rho c_p W_l \frac{\partial T}{\partial t} \right] dx dy \\ &- \oint_{\Gamma} k W_l \frac{\partial T}{\partial n} ds = 0 \quad (l = 1, 2, \dots, n) \end{aligned} \quad (7)$$

Eq. (7) is the basic equation for finite element calculation of plane temperature field.

## 2.2. Meshing method of finite element model

Delaunay triangulation method is used to mesh the finite element model. Delaunay triangulation is a method to generate unstructured meshes. This method is based on computational geometry rules. Delaunay triangulation connects a set of given points in a plane into a triangle.

The triangular mesh generated by Delaunay generation is closest to the regular triangle, which can minimize the singularity of the finite element matrix and improve the calculation accuracy.

## 2.3. Boundary conditions and initial conditions

In the steady state heat transfer process, three kinds of boundary conditions can be used to describe the characteristics of the boundary location. The first type of boundary conditions specifies the temperature value on the boundary; the second type of boundary conditions specifies the heat flux value on the boundary; the third type of boundary conditions specifies the surface heat transfer coefficient and fluid temperature between the object and the surrounding fluid on the boundary. Boundary and initial conditions are set according to the placement of ductbank.

## 3. Calculation of external thermal resistance of cable by finite element method

### 3.1. Finite element method for calculating external thermal resistance of cable

The thermal resistance coefficient is the reciprocal of the thermal conductivity coefficient. It represents the absolute temperature rise per unit length (m) through power of 1 W in terms of K·m/W.

According to the definition of thermal resistance coefficient, when calculating unit length with finite element analysis software, the temperature rise of cable model is calculated as the equivalent value of  $T_4$  under certain heating power.

The detailed steps of finite element analysis are as follows:

(1) Establishing the plane model of laying cables in ductbank;

Here is the calculation of the external thermal resistance  $T_4$  of the cable, focusing on the temperature changes on the surface of the cable, while the thermal resistance of the inner layers of the cable can be marked by  $T_1 \sim T_3$ . Therefore, the gradient of the temperature distribution inside the cable can be ignored when calculating the external thermal resistance, and the cable can be modeled as a single material cylinder with the diameter of the cylindrical cross section as the outer diameter of the cable.

Cables are laid in pipes. Concrete is used to cover the outside of pipes. Considering the difference of thermal resistance between MPP pipe and concrete, and ignoring the influence of pipe pillow, a plane finite element model of row pipes is established according to the structure size of row pipes in the national network general design code.

(2) Setting up the thermodynamic parameters of cable model, drainage pipe, concrete, soil and air;

(3) Setting the location of the cable’s hole and the heating power of the cable model. The value of power is generally taken as the unit heat dissipation of the cable. Taking YJLW02-64/110kV-1\*800mm as an example, according to the *Design Manual of Cable Ampacity*, the maximum current could be about 800A when the cable lay in soil and the maximum current varies with the circumstance attributes. Here we set the current as 800A uniformly, combining with the AC resistance of the cable ( $5.77 \times 10^{-5} \Omega/m$ ), the releasing heat power would be 36.9 W/m. The temperature rise of the cable is calculated by steady-state analysis.

(4) Calculate the external thermal resistance  $T_4$  of the cable at the hole position according to the formula of external thermal resistance calculation.

$$T_4 = \frac{t_2 - t_1}{P} \tag{8}$$

where:

$t_1$  is the initial temperature of the cable, K;

$t_2$  is the temperature of the cable after heating, K;

$P$  is heating power, W/m.

It should be noted that all the calculation is based on unit length, so the dimension of external thermal resistance obtained should be K·m/W.

### 3.2. Finite element method for calculating external thermal resistance of cable

Taking the typical 3 \*4 section row pipe laying power cables in the *General Design of Power Transmission and Distribution Engineering of State Grid* as an example, the laying mode of three-loop single-core AC cables is studied.

Pipe layout section is shown in Fig. 1.

The finite element model is established according to the structure size of the pipe as shown in Fig. 2.

According to the general design manual, the top of concrete covered by row pipes is 0.7 m away from the ground, and the cables laid in pipes are electrified and heated, which are transmitted to the air inside the pipe through the layers of the cables, and then distributed to the atmosphere through MPP pipes, concrete and soil.

The material parameters of the model are set according to the material information of the pipe arrangement. The parameter information table is shown in Table 1.

**Table 1.** Materials of ductbank.

Material	Density (kg/m <sup>3</sup> )	Thermal conductivity (W/(m·K))	Constant pressure heat capacity (J/(kg·K))
Pipe	1150	0.26	1700
Air	1.293	0.026	1003
Concrete	2300	1.8	880
Soil	1800	0.7	168

Taking YJLW02-64/110kV-1\*800mm as an example, the equivalent thermal resistance of cables is calculated. Since only the external thermal resistance of cables is calculated here, the thermal resistance of each inner layer of cables can be calculated by IEC60287. Instead of considering the layering of cables, the cables are established as a whole cylinder. The model is shown in Fig. 3.

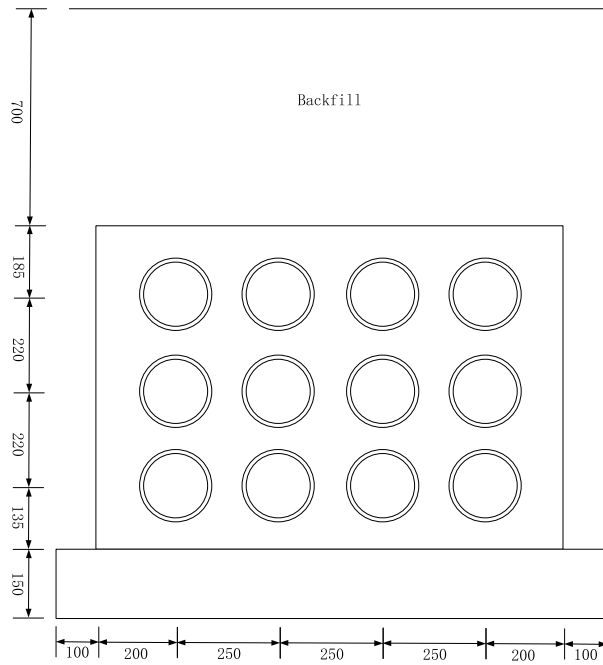


Fig. 1. Section picture of ductbank.

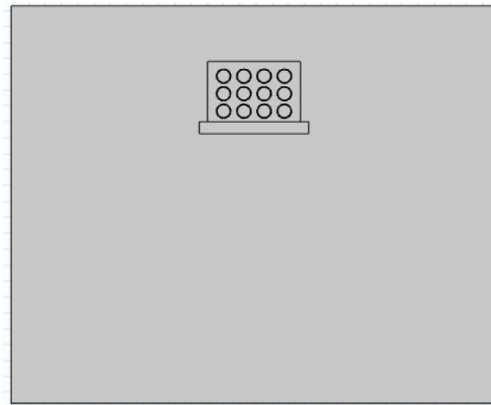


Fig. 2. Finite element model of pipe arrangement plane.

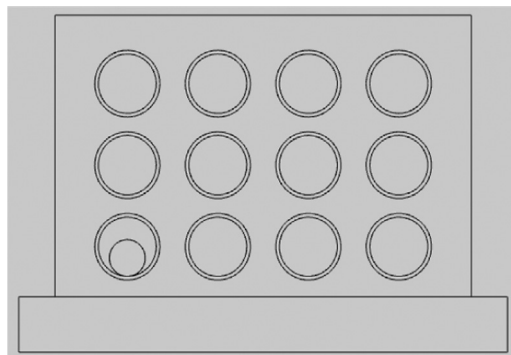


Fig. 3. Cable lay in ductbank.

The outer diameter of the cable is 98 mm, and the number of the hole position of the row pipe is 3 \*4 matrix. The cable is laid in the first row of the third row, which is simplified by [3,1].

Delaunay method is used to mesh the model, and the resulting mesh model is shown in Fig. 4.

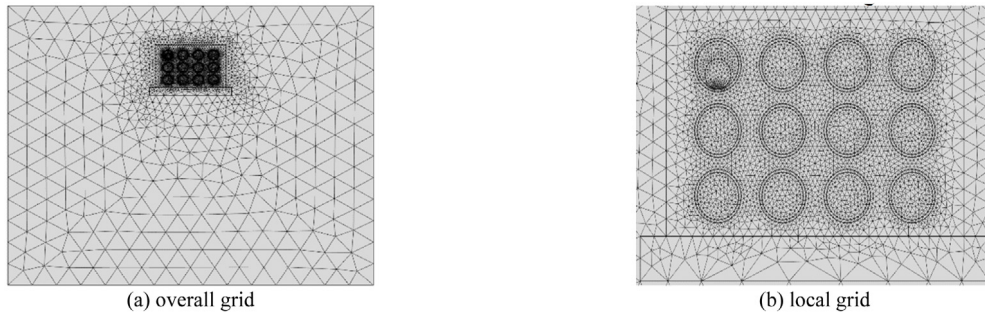


Fig. 4. Grid model.

From the results of mesh model, it can be seen that the soil part of the model is sparse and the pipe part is denser, especially the cable model and the pipe contact part, which belongs to line contact, and the grid density is high, which meets the requirement of mesh generation at the location where the temperature gradient varies greatly.

### 3.3. Results of external heat resistance calculated by finite element method

According to the calculation formula of external thermal resistance, it is necessary to calculate the temperature of the hole position of the cable in the initial unloaded current state and the temperature of the hole position in the cable on-line state. Under the condition of unloaded current, the whole temperature distribution is obtained by finite element analysis as shown in Fig. 5.

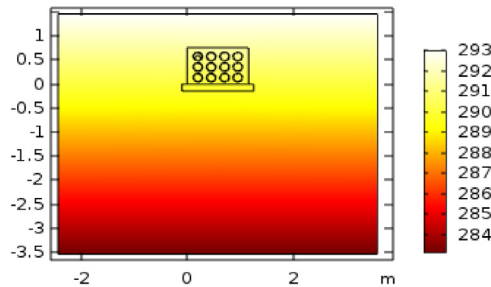


Fig. 5. Overall temperature distribution of model.

In the finite element software, the temperature distribution under these two states is calculated separately as shown in Fig. 6.

Fig. 6 shows the temperature field distribution when the cable is in [1,1] hole position, and calculates the temperature field distribution when the cable is laid in [3,2] hole loading current as shown in Fig. 7.

When the current is not loaded, the initial average temperature of the cable is shown in Table 2. Because of the symmetry of the hole position, only the temperature of the cable with 3 rows × 2 rows of holes on the left side is displayed.

**Table 2.** Temperature of holes without loading current.

Temperature	Row of ductbank	
	291.22 K	291.23 K
Column of ductbank	290.72 K	290.71 K
	290.21 K	290.19 K

After loading the current, the average temperature of the cable during stable heating is shown in Table 3.



Fig. 6. Temperature distribution in two states.

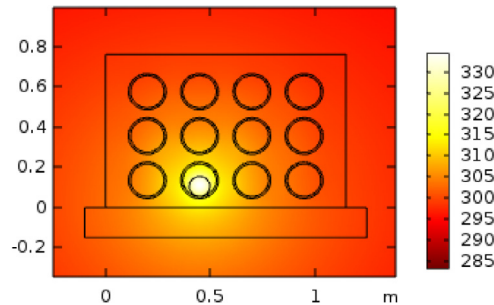


Fig. 7. Temperature field distribution of loading current state of cable in [3,2] orifice laying.

Table 3. Temperature of holes with loading current.

Temperature	Row of ductbank	
	337.49 K	338.46 K
Column of ductbank	339.17 K	340.41 K
	338.22 K	338.90 K

The equivalent thermal resistance of each hole can be obtained from the calculation formula of the external equivalent thermal resistance of the cable as shown in Table 4.

Table 4. Calculated values of equivalent thermal resistance of cable at each hole position.

Equivalent heat resistance	Row of ductbank	
	1.254 K/W	1.280 K/W
Column of ductbank	1.313 K/W	1.347 K/W
	1.301 K/W	1.320 K/W

From Table 4, it can be seen that the equivalent external thermal resistance at [2,2] hole position is the largest, which is 1.347 K/W, while that at [1,1] hole position is the smallest, which is 1.254 K/W, with a difference of 7.4%.

#### 4. Conclusions

The equivalent thermal resistance of each hole in the ductbank is analyzed by finite element method, the basic principle of thermodynamic finite element analysis is analyzed, the finite element model of ductbank with cable is established, and the equivalent thermal resistance of each pipe hole is calculated one by one. The results show that the heat dissipation performance of the hole in the middle of the ductbank is poor. Cables with less heat could be placed in the holes in the middle of ductbank practically. Cables with larger heat could be placed in holes with smaller external equivalent thermal resistance, which is conducive to the increase of the ampacity of cables.



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