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Study on Ampacity Calculation of cable in the tunnel Based on Finite Element Method

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***Abstract*—Temperature and ampacity of cables are obtained by calculating the Standard model of IEC 60287 familiarly. However, It is difficult to calculate the ampacity of cable laying in tunnel precisely by using traditional computing model with complex structure, variable environment of cable tunnels. Thence, the paper establishes the calculation model of ampacity of cable in the tunnel based on finite element method, and solved it by Ansys Workbench. According to the calculation results of temperature field of cable tunnel, the ampacity of cable can be estimated. Moreover, the relationship between the convective heat transfer coefficient on cable surface and ampacity of cable is analyzed. This paper is significant to improve the reliability of cable in the tunnel.**

Keywords—finite element method; cable tunnel; ampacity; convective heat transfer coefficient

I. Introduction

Compared with overhead lines, Underground cables used widely in consequence of reliable operation, affected little by external influence, none armored layer, none erection of poles and elegant view etc.[1]. Ampacity is one of important parameters to study by temperature decision, cable's service life and conveying capacity are affected dramatically when cable's temperature higher than the limit or larger ampacity, and smaller ampacity is a waste of resource. Therefore, evaluating cable ampacity accurately is very significant to operate cable reliably, safely and economically.

Currently, the reference of power cable ampacity is calculated commonly by the Standard model of IEC 60287[2-4], and the method applied to simple cable laying, stable environmental conditions, and lower calculation accuracy. Nevertheless, the cable ampacity can't be calculated in the tunnel by the traditional standard model accurately because of complex structure of cable tunnels and change of environment in laying. Thence, this paper establishes the calculation model of ampacity of cable in the tunnel Based on finite element method[5], finite element method belongs to numerical calculation methods[6], and finite difference method, boundary element method, finite volume method, meshless Galerkin method and secant method etc[7-11] included, finite element method is the hybrid of finite difference method and the variation method[12], which has many advantages, for instance, wide adaptability, strong flexibility, high accuracy and solving complex boundaries etc.

In this paper, an ampacity model for cables in the tunnel is established by finite element method and solved by Ansys Workbench. Additionally, the relationship between the convective heat transfer coefficient and ampacity of cable is analyzed with the simulation results. This paper is significant to improve the reliability of cable in the tunnel.

II. Finite Element Model of Cable Ampacity in The TunneL

A. Fundamental of Model

1) Basic Assumptions

a) Simplify cable structure: the shield layer combined into the thickness of insulation layer of conductor, without gradient of temperature in axial of conductor, heat transfer in radial only, besides contact thermal resistance ignored.

b) Steady-state conditions exit.

c) Property parameters are constant, and materials of the cable are homogeneous isotropic media.

d) Ignoring inductive voltage of the shield layer with the lower voltage level, which leads to the loss of the shield layer is negligible.

e) The same species for all of cables, and the electric current of cables are consistent.

2) Mathematical model of heat conduction

The pil differential equations of conductor, which in heat transfer system of 3-D medium, expressed as[13]:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q=0$$

Where Q is heat generation rate per unit volume, W/m^3; T as the temperature of the any point; λ as the thermal conduction coefficient of materials. Heat generation rate per volume Q: $Q=\frac{I^2R}{\pi r_0^2}$, R is resistance of conductor, which considered proximity effect and skin effect.

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3) Mathematical Model Of Heat Convection

The forced convection of air satisfies the N-S (Navier-Stokes) equations (Continuity, Momentum, Energy equations):

$$\nabla\left(\rho\mathbf{u}\right)=0 \tag{2}$$

$$\rho\frac{\partial\mathbf{u}}{\partial\tau}=\mathbf{F}-\nabla P+\mu\nabla^2\mathbf{u} \tag{3}$$

$$\rho C_p\frac{\partial T}{\partial\tau}=\lambda\nabla^2 T \tag{4}$$

Where ρ, $\mathbf{u}$ and $\mathbf{F}$ are the density, vector speed and body force of fluid successively, P is the pressure of fluid field, μ is the dynamic viscosity of fluid, T, λ and C_p are the temperature, convective heat transfer coefficient and specific heat capacity of the fluid.

B. Judgment of the Boundary Conditions

It is necessary for determining the boundary conditions of parts to establish the calculation model of ampacity of cable in the tunnel based on finite element method. Three common categories exist in heat transfer system and the control equations as follows[14]:

$$\begin{cases}\dfrac{\partial^2 T}{\partial x^2}+\dfrac{\partial^2 T}{\partial y^2}+\dfrac{\partial^2 T}{\partial z^2}=0\\ T(x,y,z)\big|_{\Gamma_1}=f(x,y,z)\big|_{\Gamma_1}\end{cases} \tag{5}$$

$$\begin{cases}\dfrac{\partial^2 T}{\partial x^2}+\dfrac{\partial^2 T}{\partial y^2}+\dfrac{\partial^2 T}{\partial z^2}=0\\ \lambda\dfrac{\partial T}{\partial n}\bigg|_{\Gamma_2}=q_2\end{cases} \tag{6}$$

$$\begin{cases}\dfrac{\partial^2 T}{\partial x^2}+\dfrac{\partial^2 T}{\partial y^2}+\dfrac{\partial^2 T}{\partial z^2}=0\\ -\lambda\dfrac{\partial T}{\partial n}\bigg|_{\Gamma_3}=h(T-T_f)\big|_{\Gamma_3}\end{cases} \tag{7}$$

Where q_2 is density of heat flow rate, T_f is the temperature of fluid, Γ is the integral boundary, h is the thermal conduction coefficient.

The laying pattern of cable tunnel of the closed domain model is shown as Figure Ⅰ; generally, the temperature gradient of horizontal direction of cables is zero, and belongs to the second boundary condition. The internal media of tunnel is air, and the thermal conduction coefficient and the temperature of air are known, is the third one. The lower border is deep soil, and the temperature is constant for the first boundary condition.

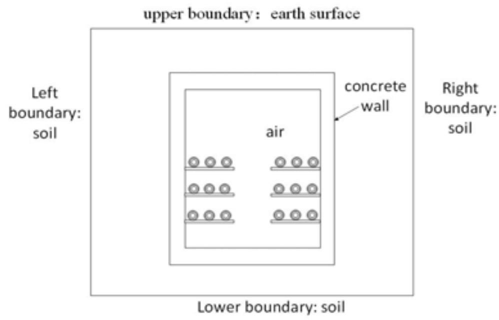


FIGURE I. SCHEMATIC DIAGRAM OF CABLE TUNNEL

C. Meshing

Meshing is the pivotal section of finite element method, generally speaking, the smaller grids are divided, the more precise calculation results, but the slower to calculate. Therefore, this paper divides the model by uneven triangle meshing with 422836 nodes and 215660 elements, the elements around the cable are denser due to severe changes of the temperature and the other parts are sparse, which shorten calculation time and improve calculation accuracy. The single core cable meshing and cable tunnel meshing show as Figure II and Figure III.

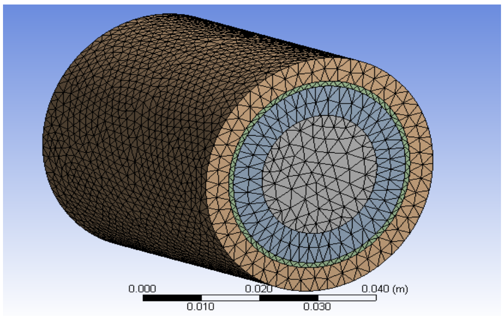


FIGURE II. SINGLE CORE CABLE MESHING

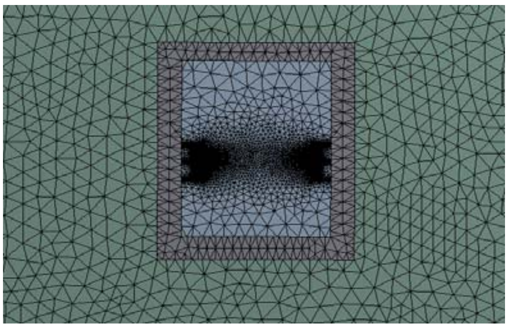


FIGURE III. CABLE TUNNEL MESHING

III. RESULTS AND ANALYSIS OF SIMULATION

A. Validation of Finite Element Method's Effectiveness

To validate the correctness of calculation results of the simulation model, 8.7/15 kV YJV 1*400 mm^2 cables as an object used for it. Ansys Workbench is used to obtain the ampacity of single core cable, meshing shows as Figure II, the structural and physical parameters of cables and initial environment parameters in Table I and Table II. The core of cables is Cu, by physical characteristics of materials and relevant national regulations, the temperature limit of AC XLPE cables is 90℃ in long-term operation, cable ampacity, is the current value at the temperature. The currents are converted into heat generation rate and through into the cable core, and the temperature distribution of the entire cable tunnel is got, based on that, using dichotomy to determine the heat generation rate at 90℃, corresponding ampacity obtained eventually. As a comparison, cable ampacity is calculated by the Standard model of IEC 60287 by writing programs in MATLAB and setting the same parameters.

TABLE I. STRUCTURAL PARAMETERS OF CABLE

Physical quantities（mm）	Parameters
Conductor radius	11.9
Insulation largest radius	17.8
Shielding layer largest radius	18.1
Protective covering largest radius	20.4
External diameter of the cable	41

TABLE II. STRUCTURAL PARAMETERS OF CABLE

Physical quantities of material and environment	Parameters
Copper core thermal conductivity (W/m·K)	377
Insulation thermal conductivity (W/m·K)	0.285
Shielding thermal conductivity (W/m·K)	377
Protective covering thermal conductivity (W/m·K)	0.132
Air convection heat transfer coefficient (W/m^2·K)	11
Air temperature (℃)	20

The temperature distribution of single core cable shows as Figure IV, the corresponding ampacity value is 1011A; the ampacity calculated by the Standard model of IEC 60287 is 1000A. The result of them, deviation only 1.1%, which satisfies error requirement. Thence, the effectiveness of the model is validated.

B. Calculation Result and Analysis of the Ampacity Model

The 8.7/15 kV YJV 1*400 mm^2 cables still used as research object here, based on the temperature field of cable tunnel, to reckon the ampacity of cable tunnel. Default size of the cable tunnel in Figure I, which set by relevant national standard[15-16], as follows: space between single core cables is 90mm and the interval of layers is 300mm, 2.5m wide, 3m height, thickness of concrete wall is 0.3m, top of the wall to earth surface is 1m and the thickness of soil is 3m. The structural sizes and the laying conditions as Table I and Table III.

TABLE III. LAYING CONDITIONS

Physical quantities	parameters
Copper core thermal conductivity (W/m·K)	377
Insulation thermal conductivity (W/m·K)	0.285
Shielding thermal conductivity (W/m·K)	377
Protective covering thermal conductivity (W/m·K)	0.132
Air convection heat transfer coefficient (W/m^2·K)	11
Air temperature (℃)	20
Soil thermal conductivity (W/m·K)	1
angle iron thermal conductivity (W/m·K)	240
Concrete thermal conductivity (W/m·K)	0.5
Deep soil temperature (℃)	10
Air temperature of earth surface (℃)	6

Cables of two sides in the tunnel are arranged in three layers, and the temperature field of the tunnel model in this case showed as Figure V, and corresponding ampacity value is 1019A. The result indicates that the model has the advantages: ease of operation, computing efficiency and can obtain the temperature distribution and ampacity of tunnel cables easily, and more convenient and effective compares with the traditional model, a basis for a real project provided.

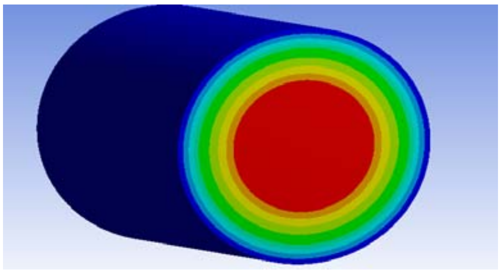


FIGURE IV. TEMPERATURE DISTRIBUTION OF SINGLE CORE CABLE

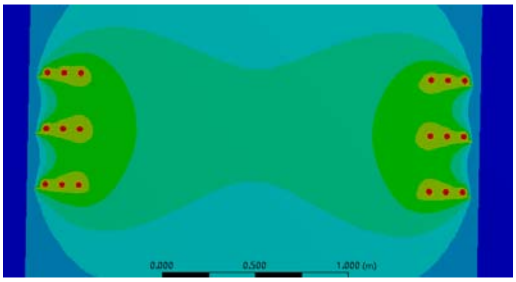


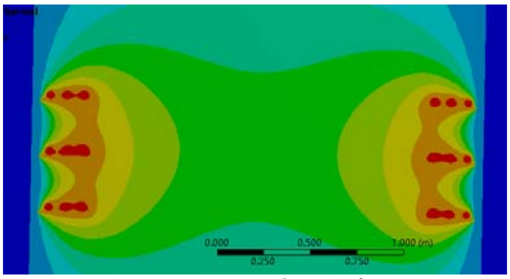
FIGURE V. TEMPERATURE DISTRIBUTION OF CABLE TUNNEL

C. The Correspondence Of Convective Heat Transfer Coefficient And Cable Ampacity

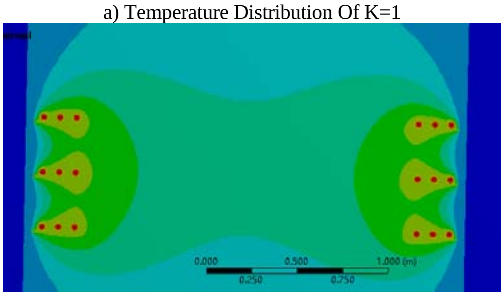
To study the correspondence of convective heat transfer coefficient and cable ampacity, the single variable principle used; based on the real project, convective heat transfer coefficients select by a gradient. Simulation results and correspondence showed as Table IV and Figure VII. Several temperature distribution diagram in different convective heat transfer coefficient showed Figure VI.

TABLE IV. CABLE AMPACITY IN DIFFERENT CONVECTIVE HEAT TRANSFER COEFFICIENTS

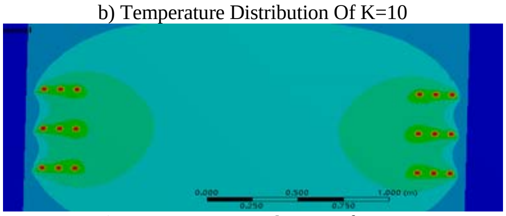
Results	convective heat transfer coefficient K(W/m²*℃)					
	0.5	1	5	10	15	20
Cable ampacity(A)	376.5	464	806.5	997	1104	1174
Results	**convective heat transfer coefficient K**(W/m²*℃)					
	25	30	40	60	80	100
Cable ampacity(A)	1224	1261	1313	1371	1403	1425



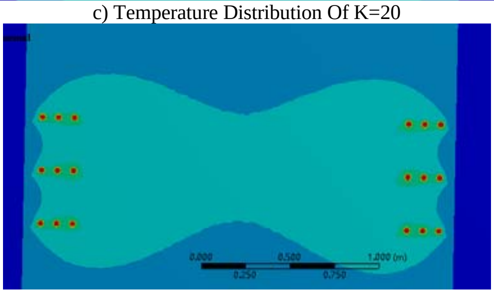
a) Temperature Distribution Of K=1



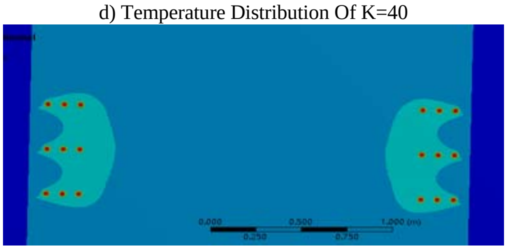
b) Temperature Distribution Of K=10



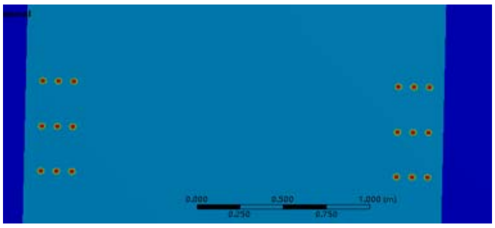
c) Temperature Distribution Of K=20



d) Temperature Distribution Of K=40



e) Temperature Distribution Of K=80



f) Temperature Distribution Of K=120

FIGURE VI. TEMPERATURE DISTRIBUTION OF DIFFERENT CONVECTIVE HEAT TRANSFER COEFFICIENTS

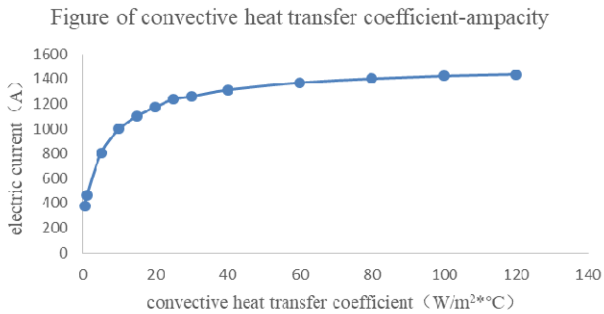


FIGURE VII. CORRESPONDENCE OF CONVECTIVE HEAT TRANSFER COEFFICIENT AND CABLES AMPACITY

As can be seen from Table IV and Figure VII, the cable ampacity increases with the increasing of the convective heat transfer coefficient, which causes of remarkable effect for the heat dissipation of cables surface. The larger convective heat transfer coefficients, the faster heat dissipation of cables, and the cable ampacity improved. However, the ampacity no longer increases and tends to be stable when convective heat transfer coefficient is large enough, the limit of heat dissipation attained. Therefore, the cable ampacity can be improved by changing the convective heat transfer coefficients, besides the delivery enhanced capacity and the heat loss reduced.

IV. CONCLUSION

a) According to heat transfer theory, the calculation model of cable ampacity in the tunnel established based on finite element method, and three common categories boundary conditions summarized. Comparing with the Standard model of IEC 60287, the effectiveness of the model is validated.

b) Modelling the six loop cable tunnel in enclosed area, and 8.7/15 kV YJV 1*400 mm² cables as the research object, the temperature distribution and cables ampacity can be obtained effectively and quickly by the finite element method simulation, verifying the analytical ability of cable temperature distribution and cable ampacity.

c) The correspondence of convective heat transfer coefficient and cables ampacity is verified: the cable ampacity increases with the increasing of the convective heat transfer coefficient. The innovative study of the paper is promising for cable tunnels in a certain extent.

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