

Temperature Distribution and Current-Carrying Capacity of XLPE High-Voltage Cables under Different Laying Methods

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ABSTRACT: Current research on cable current-carrying capacity mostly focuses on a single laying form and lacks a systematic comparison of temperature-load characteristics under three mainstream laying conditions: direct burial, pipe duct laying, and cable trench laying. This paper takes the YJLW03-64/110 kV single-core high-voltage cable as the research object, develops a two-dimensional electromagnetic-thermal-fluid multi-physics field-coupling model, and determines the carrying capacity by constraining the conductor's maximum allowable temperature to 90°C. The finite element software COMSOL is used to complete the simulation analysis of multiple conditions under the three laying methods. For direct burial laying, the improvement effect of high thermal conductivity sandy soil backfill thickness of 100 mm and 200 mm on heat dissipation is explored; for pipe duct laying, the temperature distribution and carrying capacity differences between air gap and cement-based thermally conductive grout filling are compared; for cable trench laying, the convective heat transfer effect of solid supports and different support opening rates is analyzed. The results show that the improvement measures under the three laying methods can respectively increase the cable current-carrying capacity by varying degrees. The results can provide support and technical reference for selecting high-voltage cable laying methods, as well as expanding and renovating carrying capacity.

1. INTRODUCTION

Cross-linked polyethylene (XLPE) power cables are widely used in power transmission and distribution systems due to their excellent insulation and heat resistance, as well as flexible laying methods [1]. The cable's current-carrying capacity directly determines the heat generated by the conductor. When the heat exceeds the maximum temperature (90°C) which the XLPE insulated cable can withstand under stable operating conditions, the deterioration of the insulation material will be accelerated, shortening its service life. When the cable's current-carrying capacity is too low, it will lead to decreasing transmission capacity and wasting resources. Therefore, under different laying methods, accurately calculating the cable's current-carrying capacity can ensure its economical, reliable, and stable operation [2–4].

At present, the main calculation methods for cable current-carrying capacity include analytical calculation and numerical calculation. The analytical method is based on heat-transfer principles, simplifying the equivalent external environment and cable structure using heat capacity and thermal resistance to obtain an equivalent thermal path and calculate the temperature of each part of the cable through differential equations [5]. Li et al. [6] established a three-core steady-state thermal path model based on different cable structures according to the International Electrotechnical Commission (IEC standard, using the temperature of the outer sheath to infer the temperature of

the cable conductor and verifying it through temperature rise tests, but the error also gradually increased with the increase in current-carrying capacity. Ma and Zhang [7] designed a new cable steady-state thermal path model, and the reason for the lower calculated temperature rise results was that the temperature influence between adjacent cables was not considered. Huang et al. [8] compared the current-carrying capacity and temperature distribution of buried cables with analytical and numerical methods, and concluded that the numerical calculation method can more accurately simulate the cable model under complex laying methods. Numerical calculation mainly includes the boundary element method, finite difference method, and finite element method. Among them, the finite element method is more suitable for solving practical problems with complex laying methods and is widely used in calculating cable temperature fields, fluid fields, and current-carrying capacity [9–11].

Shi et al. [12] used the finite element method to establish a three-dimensional multi-field model for cable laying in tunnels and studied the effects of flow velocity, tunnel temperature, cable spacing, etc. on the cable current-carrying capacity. The results showed that laying spacing in the tunnel and air-flow velocity had a significant impact on the current-carrying capacity. Nie et al. [13] established a simulation model for cable laying in tunnel clusters, and the study indicated that the magnetic field of the cluster-laid cables had a significant impact on the surrounding circulation. Czappand Ratkowski [14] adopted the IEC-60287 analytical thermal circuit formula and

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studied the economic improvement of the thermal backfill size for direct-buried cables, weighing the impact of current capacity increase and engineering investment cost. However, this study was limited to the direct-burying condition and could not handle coupled flow and heat phenomena in pipe and cable trenches. Zhou et al. [15] conducted a comparative study on the materials of tunnel cable supports, such as stainless steel and basalt, and did not make any design improvement for the support structure. Feng [16] built a two-dimensional simulation model for direct-buried power cables and analyzed the effects of current-carrying capacity, laying depth, and environmental factors on the cables' temperature distribution through electrothermal coupling analysis. A large number of studies have also been conducted on factors such as soil temperature and the number of laying circuits during direct-buried cable laying [17, 18]. Liu et al. [19] conducted electromagnetic-thermal coupling simulation for laying medium-voltage cable conduits, analyzed the influence of environmental parameters on current-carrying capacity, and improved the IEC analytical thermal circuit calculation formula based on simulation results. However, this study was limited to the cable conduit laying scenario and did not involve direct-burying or cable trench laying, nor did it conduct quantitative research on the renovation measures for cable conduits. Zhang et al. [20] conducted electro-thermal-flow three-field coupling simulation for forced ventilation cable tunnels, combined with temperature-rise tests to calibrate the convective heat transfer coefficient, and reduced the calculation error of the IEC standard under tunnel laying conditions. However, this study was limited to forced ventilation cable tunnels and did not conduct parametric analysis on renovation measures for the laying structure. Nie et al. [21] conducted cable current-carrying capacity simulations for three laying methods, but this study mainly focused on the comparison of different cable arrangement methods and the impact of cables' placement position under different laying methods on current-carrying capacity and did not conduct research on engineering heat-dissipation renovation measures, nor did it conduct research on the fluid part of pipe trench and cable trench laying. Wang et al. [22] conducted electro-thermal-coupling simulation for submarine cables, studying strategies for current capacity improvement from the perspective of cable body modifications such as changing the armor material and increasing the conductor cross-sectional area. However, this study was oriented towards marine submarine cable scenarios and not applicable to land high-voltage cable lines.

The above study mainly investigated the effects of factors such as tunnel air velocity, laying circuits, soil temperature, cable spacing, and laying depth on temperature distribution and cables' current-carrying capacity. There was relatively little research on the comparison of cable current-carrying capacity and improvement methods for cables laid in direct burial, pipe trenches, and cable trenches. This paper establishes a finite element simulation model for 110 kV power cables. Based on the above research, it supplements the systematic analysis of typical engineering renovation schemes in three types of laying scenarios: the expansion study of the influence law of backfill thickness for direct burial laying; the cement-based thermal conductive grouting filling measure, which proposes a

cooling solution for engineering problems with large air resistance in pipe trenches; the design of opening holes for supports, which proposes a structural change-based cooling solution for the problem of vertical air flow obstruction in cable trenches.

2. PRINCIPLES OF CABLE NUMERICAL CALCULATION

The cables' actual working environment is very complex. The backfilling of the sandy soil used in this study mainly relies on heat conduction, and the current-carrying capacity is calculated in the form of electromagnetic-thermal coupling. For pipe duct laying, due to the presence of airflow, heat convection and heat radiation also need to be considered. For cable trench laying, since there is airflow, multi-field coupling calculations are also required to determine the cables' current-carrying capacity and temperature distribution.

2.1. Electromagnetic Field Model of the Cable

When a transmission line operates, the alternating current flowing through the conductors generates time-varying electromagnetic fields in the surrounding space, inducing electromagnetic losses in each cable layer. These losses primarily occur in the conductor and the metal sheath. To quantitatively describe the above heat sources, the temperature dependence of the electrical conductivity of the conductor and metal sheath is given by Equation (1), and the power loss per unit length in each cable layer is calculated using Equations (2)–(4).

$$\sigma = \frac{1}{\rho_{20} [1 + \alpha_{20} (\theta_c - 20)]} \quad (1)$$

$$\frac{1}{\mu} \nabla^2 A = -J_s + j\omega\sigma A \quad (2)$$

$$J = -j\omega\sigma A + J_s \quad (3)$$

$$P = \sigma^{-1} \int_s J^2 dS \quad (4)$$

In Equations (1)–(4), σ represents the electrical conductivity, S/m; ρ_{20} is the resistivity of the conductor, $\Omega \cdot \text{m}$; θ_c is the temperature of the conductor $^{\circ}\text{C}$; α_{20} is the temperature coefficient of resistivity, K^{-1} ; A represents the vector magnetic potential of each layer, Wb/m; ω is the angular frequency, rad/s; μ is the magnetic permeability, H/m; J is the current density of each layer, A/m²; J_s is the source current density, A/m²; P is the power loss per unit length of each layer, W/m; S is the cross-sectional area, m².

2.2. Cable Temperature Field Model

The cable's axial length is much larger than its cross-sectional size, and the axial heat conduction can be neglected. The directly buried cable is simplified to a two-dimensional model for analysis. The losses at each part of the cable can be regarded as heat sources in the temperature field. The regions with heat sources include the wire core and metal shielding, whose steady-state thermal conduction differential equation is

TABLE 1. Comparison of methods.

Comparison dimension	IEC analysis method	Existing numerical studies	The method presented in this article
Principle	Equivalent thermal resistance	Numerical solution	Numerical solution
Air convection	Empirical heat transfer coefficient	Empirical heat transfer coefficient	CFD Coupled Calculation
Scope of Application	Direct burial	Single laying method	Three laying methods
Limitations	Poor accuracy	No standard verification	Considerable computational load

shown in Equation (5), while the regions without heat sources include an insulation layer, an outer sheath, and soil (as shown in Equation (6)).

$$\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q_v = 0 \quad (5)$$

$$\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = 0 \quad (6)$$

In Equations (5)–(6), q_v represents the heat source, in units of W/m^3 , and λ is the material's thermal conductivity, in units of $W/(m \cdot K)$.

For conduit laying and cable trench laying methods, radiation heat transfer occurs between the cable surface and the inner wall of the conduit or trench, as described by Equation (7).

$$Q_1 = \varepsilon_1 A_1 \sigma_0 (T_1^4 - T_{s2}^4) \quad (7)$$

In Equation (7), Q_1 represents the radiative heat transfer rate, in W; ε_1 is the effective emissivity of the object; A_1 is the radiation area, in m^2 ; σ is the Stefan-Boltzmann constant; T_1 and T_2 are absolute temperatures of the two surfaces, in K.

Solving the temperature-field governing equation requires well-defined boundary conditions. In accordance with heat transfer theory, boundary conditions are classified into three types: the first type prescribes the temperature on the boundary of the solution domain, as given by Equation (8); the second type specifies the normal heat flux density on the boundary, as shown in Equation (9); and the third type defines the convective heat transfer coefficient and the temperature of the adjacent fluid at the boundary, as expressed in Equation (10).

$$T|_r = T_w \quad (8)$$

$$\lambda_s \frac{\partial T}{\partial n} \Big|_r + q_w = 0 \quad (9)$$

$$-\lambda_s \frac{\partial T}{\partial n} \Big|_r = \alpha (T - T_f) \Big|_r \quad (10)$$

In Equations (8)–(10), T represents the temperature variable, in K; T_w represents the temperature of the object surface, in K; λ_s represents the soil thermal conductivity, in $W/(m \cdot K)$; q_w represents the heat flux density, in W/m^2 ; α represents the convective heat transfer coefficient, in $W/(m^2 \cdot K)$.

2.3. Cable Flow Field Model

According to fluid mechanics principles, when power cables are installed in conduits or cable trenches, the natural convection of the internal air is governed by the conservation laws of mass, momentum, and energy. The corresponding governing equations are given by Equations (11)–(13).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (11)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} - \frac{\lambda_a}{\rho c_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = 0 \quad (12)$$

$$\begin{cases} \rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \eta \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\ \quad + \rho g \beta (T - T_r) \cos \theta \\ \rho \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \eta \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \\ \quad + \rho g \beta (T - T_r) \sin \theta \end{cases} \quad (13)$$

In Equations (11)–(13), u and v are the velocity components in the x and y directions, respectively, in m/s; λ_a is the air thermal conductivity, in $W/(m \cdot K)$; ρ is the air density, in kg/m^3 ; c_p is the specific heat capacity at constant pressure, in $J/(kg \cdot K)$; p is the air's static pressure, in Pa; η is the air dynamic viscosity, in Pa·s; g is the gravitational acceleration, in m/s^2 ; β is the air's volumetric expansion coefficient, in K^{-1} ; T_r is the reference temperature, in K; θ is the angle between the coordinate axis and the gravity vector, in rad.

2.4. Method Comparison

At present, the calculation of the current-carrying capacity of high-voltage cables mainly falls into two categories: the equivalent thermal path analysis method as per IEC 60287 and the finite element numerical simulation method. Table 1 shows the comparison between these two methods and the method proposed in this paper.

3. CONSTRUCTION OF SIMULATION MODEL

3.1. Establishment of Cable Geometric Model

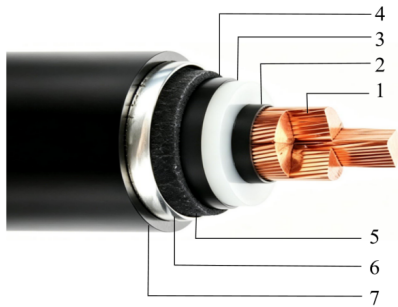
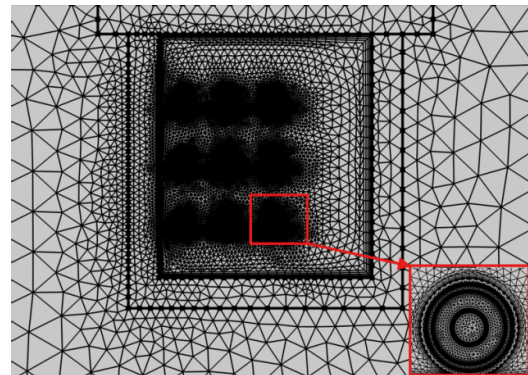
This paper takes the YJLW03-64/110 kV $1 \times 630 \text{ mm}^2$ type cable as the research object. Figure 1 shows the cable structure diagram.

TABLE 2. Cable structural parameters.

Structure Name	Thickness (mm)	Outer diameter (mm)
Copper conductor	/	30.0
Conductor semiconducting screen	1.5	33.0
XLPE insulation	16.5	66.0
Insulation semiconducting screen	1.2	68.4
Semiconducting buffer layer	4.5	77.4
Corrugated aluminum sheath	2	81.4
Polyethylene outer sheath	4.5	90.4

TABLE 3. Electrical and thermal parameters.

Structure Name	Relative permittivity	Density (kg/m ³)	Electrical conductivity (S/m)	Thermal conductivity [W/(m·K)]
Copper conductor	1	8900	5.96×10^7	400
Conductor semiconducting screen	22	1150	0.1	0.35
XLPE insulation	2.25	930	1×10^{-15}	0.29
Insulation semiconducting screen	22	1150	0.1	0.35
Semiconducting buffer layer	12.5	700	0.01	0.20
Corrugated aluminum sheath	1	2700	3.77×10^7	237
Polyethylene outer sheath	2.30	950	1×10^{-16}	0.42
Soil	4	1800	1×10^{-4}	0.8
Concrete	6	2400	1×10^{-6}	1.5

**FIGURE 1.** Structure of the YJLW03-64/110 kV $1 \times 630 \text{ mm}^2$ cable. 1 — Copper conductor; 2 — Conductor semiconducting screen; 3 — XLPE insulation; 4 — Insulation semiconducting screen; 5 — Semiconducting buffer layer; 6 — Corrugated aluminum sheath; 7 — Polyethylene outer sheath.**FIGURE 2.** Grid division diagram.

3.2. Cable Simulation Parameters

Table 2 shows structural dimensions of each part of the cable. Table 3 presents laying conditions and electrical-thermal characteristic parameters, and Table 4 gives boundary condition parameters.

To ensure the calculation accuracy, distances from the lower, left, and right boundaries of the computational domain to the cable are set to 20 m. The soil's upper boundary is exposed to air for convective heat transfer.

3.3. Model Validation

3.3.1. Verification of Grid Independence and Numerical Convergence

To eliminate the influence of grid density on the calculation results, three different grid density schemes were set up for grid

independence verification. The maximum conductor temperature was taken as the evaluation index, and the cable trench laying case was adopted for analysis. Figure 2 shows the grid discretization, and Table 5 presents grid independence verification results. When the number of grids reaches 225,000, the conductor temperature difference from the finer mesh scheme was less than 0.1°C . Further grid refinement produced no significant improvement in calculation accuracy. Therefore, the grid discretization scheme selected in this paper satisfies the grid independence requirement.

To ensure the stability and reliability of steady-state simulation iterative calculation results, a numerical convergence test was conducted for cable trench laying. The convergence criterion was set as follows: the residuals of continuity, momentum, and energy equations should drop below 10^{-6} , and at the same time, the maximum temperature of the cable conductor

TABLE 4. Boundary condition parameters.

Name	Numerical value	Unit
Environmental temperature	20	°C
Direct burial depth	1.0	m
Emissivity of cable outer sheath	0.90	—
Emissivity of the pipe inner wall	0.88	—
Emissivity of concrete wall surface	0.92	—
Soil surface convective heat transfer coefficient	5.0	W/(m ² ·K)
Air Prandtl number	0.71	—
Current frequency	50	Hz
Conductor temperature criterion	90	°C

TABLE 5. Verification results of grid independence.

Total number of grids	Minimum unit size (m)	Maximum unit size (m)	Maximum temperature of the conductor (°C)	Deviation from the 90°C rated temperature (°C)
62510	0.0019	0.15	89.28	0.62
123988	0.0014	0.10	89.76	0.24
225374	0.0011	0.07	89.99	0.01

TABLE 6. Comparison of Nu values for two types of natural convection benchmark cases.

Rayleigh number	Horizontal concentric annular cavity			Square closed cavity		
	Literature benchmark	This article presents a simulation.	Relative error	Literature benchmark	This article presents a simulation.	Relative error
10 ⁴	2.28	2.32	1.75%	2.24	2.28	1.79%
10 ⁵	4.72	4.81	1.91%	4.51	4.59	1.77%
10 ⁶	10.30	10.52	2.14%	8.92	9.08	1.79%

should be monitored. After continuous iterations for 50 steps, if the temperature fluctuation of the cable conductor is less than 0.05°C, the calculation has reached convergence.

3.3.2. Verification of Natural Convection Base Case Calculation

To verify the computational accuracy of the non-isothermal flow CFD solver presented in this paper for natural convection in enclosed cavities, two types of engineering air domain characteristics, namely the rectangular cavity of the cable trench and the circular air gap between the cable's outer surface and the inner wall of the cable duct, were matched. Two classic benchmark examples, horizontal concentric circular cavities [23] and square closed cavities [24], were selected for verification. The inner radius of the circular cavity was 45.2 mm, and the outer radius was 100 mm; the side length of the square cavity was 0.5 m. The cavities were all filled with air, and the Boussinesq approximation was adopted. The heating wall was maintained at a constant temperature of 323.15 K and the cooling wall at 293.15 K.

Three sets of typical Rayleigh numbers were selected, and the average Nu values of the cavity wall surfaces were extracted for comparison with benchmark values from the literature. Ta-

ble 6 shows the results, and Figure 3 depicts velocity distributions under typical conditions.

The results show that the maximum relative error between simulation values of the two benchmark examples and the literature benchmark values is 2.14%, which verifies the computational accuracy of the fluid-thermal coupling solution in this paper and can provide algorithm support for fluid-field simulation.

4. SIMULATION RESULTS AND ANALYSIS

4.1. Analysis of Cable Current Capacity and Temperature Field in Direct Burial Installation Method

In actual engineering, for cost-saving purposes, the original soil is often backfilled during direct burial. For the direct burial model, the center spacing of the cable conductors is set at 250 mm, and the burial depth is 1 m. With the constraint that the highest temperature of the cable conductors reaches 90°C, the calculated load current is 952 A. The temperatures of the conductors on both sides are 85.6°C. Based on this simulation condition, the cable load current is calculated using the IEC 60287 standard analytical method and is 931 A. Comparing the

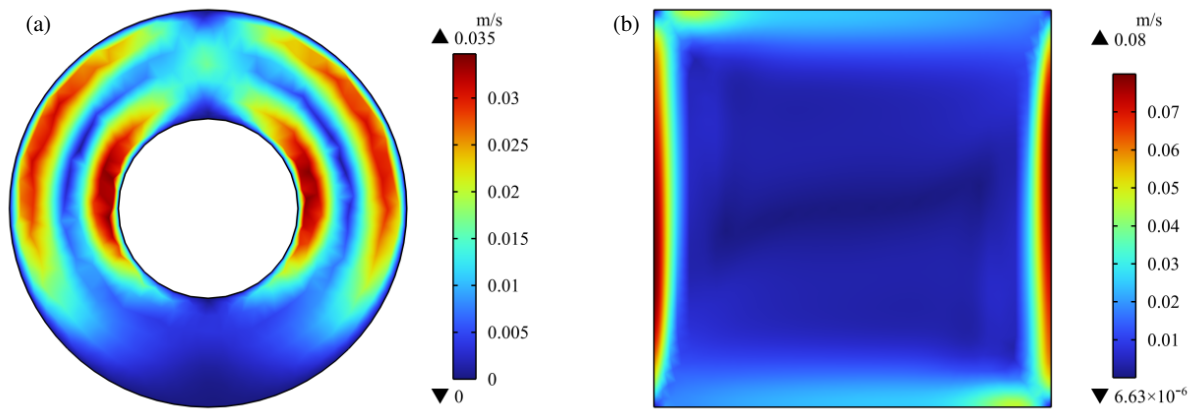


FIGURE 3. Velocity distribution of natural convection in two cavities. (a) Uniform annular cavity velocity distribution and (b) square cavity velocity distribution.

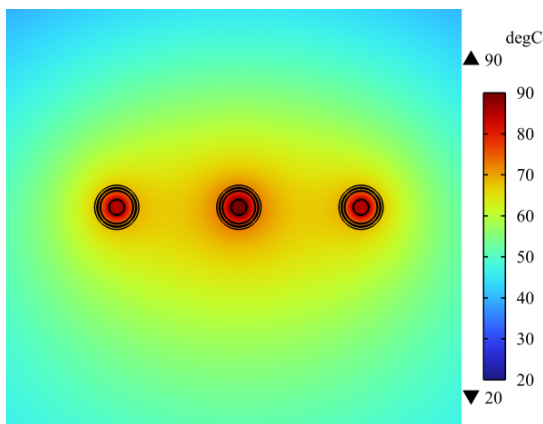


FIGURE 4. Temperature field distribution of cables in direct-buried laying.

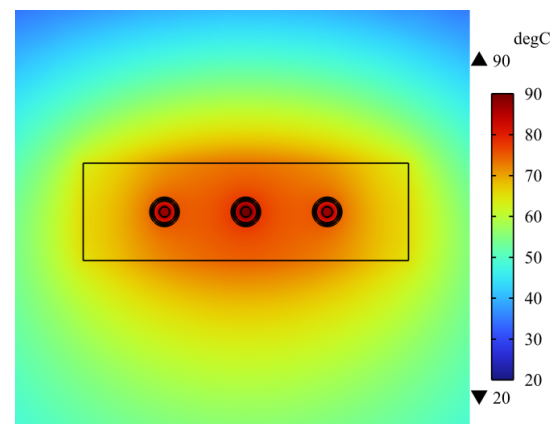


FIGURE 5. Temperature distribution of direct-buried laying with 100 mm thick sandy soil backfill.

two, the relative error between the simulated result and the IEC standard analytical value is approximately 2.26%. The error's main sources are geometric simplification and setting boundary conditions. Figure 4 shows the temperature field distribution.

As shown in Figure 4, the middle cable experiences the highest temperature rise due to the combined heat effect of the two side cables. The heat gradually decreases from the cable conductor to the outside. The temperature gradient distribution in the soil is continuous and smooth, consistent with the heat-transfer law for solid conductors.

According to the relevant provisions of the “Power Engineering Cable Design Standard” [25], soft soil or sand layers should be laid above and below the cables, with a thickness of no less than 100 mm. There is no limit on the maximum thickness. We now explore the influence of backfill thickness on the current-carrying capacity of directly buried cables. In this paper, 100 mm- and 200 mm-thick sand layers are laid closely on both sides of the cables, meeting the standard's minimum thickness requirements. The study was conducted when the thermal conductivity of the sandy soil was set at 1.5 W/(m·K) (with a moisture content of 10%) [26]. Figures 5 and 6 show temperature distribution maps for the two thicknesses of the filled sandy soil.

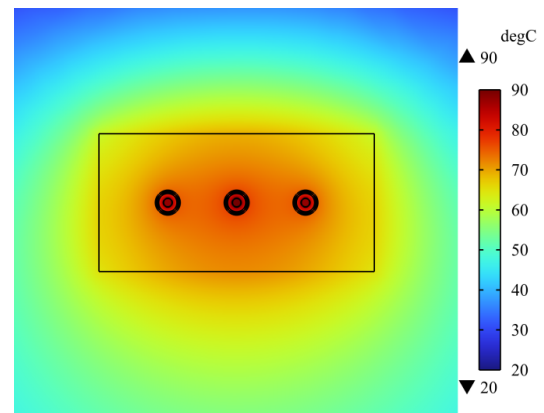


FIGURE 6. Temperature distribution of direct-buried laying with 200 mm thick sandy soil backfill.

In Figures 5 and 6, the rectangular areas represent the back-filled sandy soil. When filling with 100 mm and 200 mm thicknesses, the cable current-carrying capacity was 985 A and 993 A, respectively. Compared to the original soil condition, the current-carrying capacity increased by 3.5% and 4.3%, respectively. Compared to the 100 mm condition, the internal

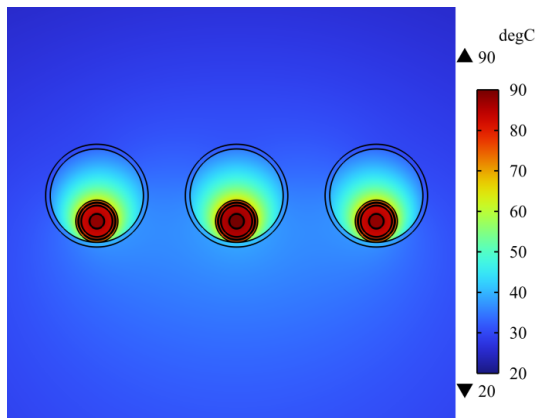


FIGURE 7. Temperature distribution map of cables in conduit laying.

temperature gradient in the 200 mm-thick sandy soil backfill area was alleviated. Therefore, using sandy soil backfill can effectively reduce the equivalent thermal resistance of the cable outside. This change pattern is consistent with the external thermal resistance calculation principle in the IEC 60287 standard.

4.2. Analysis of Cable Current Capacity and Temperature Field under Conduit Laying Configuration

To address the issue that 110 kV high-voltage cables are prone to corrosion by the soil and thus affect their operational reliability, the engineering design adopts buried laying in pipes to construct a physical protective barrier. In this paper, modified polypropylene power pipes are selected to replace the traditional polyvinyl chloride sleeves, which can meet the long-term operation requirements of the cables due to their excellent heat resistance and corrosion resistance. The pipe's inner diameter is 200 mm; the outer diameter is 220 mm; and the wall thickness is 10 mm. According to "Standard for Cable Design in Power Engineering" [25], the inner diameter of the protective pipe should not be less than 1.5 times the cable's outer diameter to reserve sufficient space for cable insertion operations and radial heat dissipation channels. This model's inner diameter meets the requirements. A three-phase horizontal arrangement thermal conduction model with a conductor center spacing of 300 mm is established, and Figure 7 shows the temperature distribution.

Figure 7 shows that when a current of 845 A is applied, the conductor temperature reaches 90°C, and the temperature field on the soil side shows a roughly elliptical pattern of attenuation outward, consistent with the typical heat-transfer law for multiple heat sources. Due to the introduction of an air layer and additional thermal resistance between the cable and the pipe wall in the pipe arrangement, under the condition of maintaining the same external parameters such as burial depth, soil thermal properties, and environmental temperature, with the original soil direct burial arrangement having a current-carrying capacity of 952 A as the benchmark, the allowable current-carrying capacity for the pipe arrangement is 845 A, representing a relative decrease of 11.24% in current-carrying capacity.

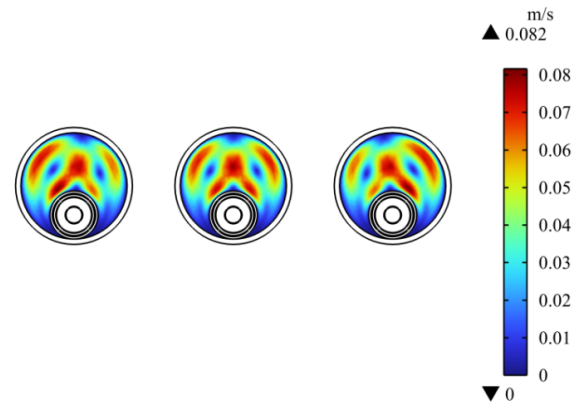


FIGURE 8. Distribution map of fluid flow in pipelines under conduit laying.

Figure 8 shows the fluid distribution when an 845 A current is passed through the pipe under laying conditions.

As shown in Figure 8, the maximum air-flow velocity within the pipe is 0.082 m/s, and the overall flow is in a laminar flow range, which is consistent with the classic natural convection flow pattern of the annular closed cavity. This flow field is driven by the thermal buoyancy generated by the heat on the cable surface. The hot air flows upward at an angle along both sides of the cable, and after being constrained by the top wall of the sleeve, it flows downward along the inner wall to complete the circulation. The air layer limiting heat dissipation is the main reason for the significantly lower current-carrying capacity compared to direct burial laying.

Therefore, high thermal conductivity materials are filled into the internal air of the conduits to enhance the heat dissipation of the cables. Now, the three-phase conduits are filled with cement-based thermal conductive grout, which, after curing, has a thermal conductivity of 1.5 to 2.5 W/(m·K). The filling density, heat-dissipation durability, and long-term stability of thermal properties are even better [27]. With a thermal conductivity of 2.0 W/(m·K) of the cement-based thermal conductive grout as the filling medium inside the conduits, Figure 9 shows the steady-state temperature field distribution of the conduit laying.

As shown in Figure 9, filling the air layer can effectively enhance the cable's radial heat transfer. When the temperature of the cable conductor stabilizes at 90°C, the current-carrying capacity of the pipe arrangement filling condition is 948 A, which is 12.2% higher than 845 A when the cable is laid in the pipe without filling. The cable's current-carrying capacity significantly increases when filled with cement-based thermal grout.

4.3. Analysis of Cable Current Capacity and Temperature Field under Cable Trench Installation Method

To address the issue that 110 kV high-voltage cables are prone to being submerged by water and thus affecting their operational reliability, a physical protective barrier was constructed using the cable trench laying form. Hot-dip galvanized steel cable supports were selected to replace traditional concrete supports. Their excellent impact resistance and convenient con-

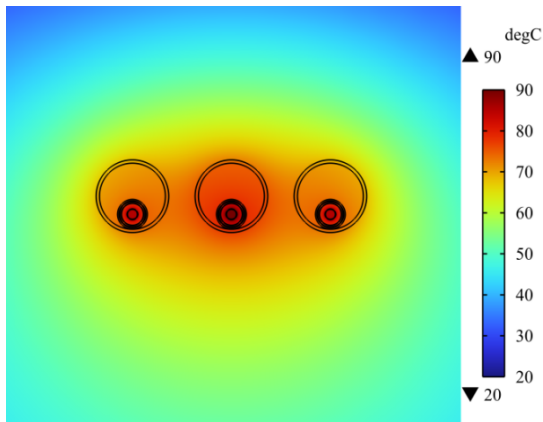


FIGURE 9. Temperature distribution map of cement filling for cables in pipeline installation.

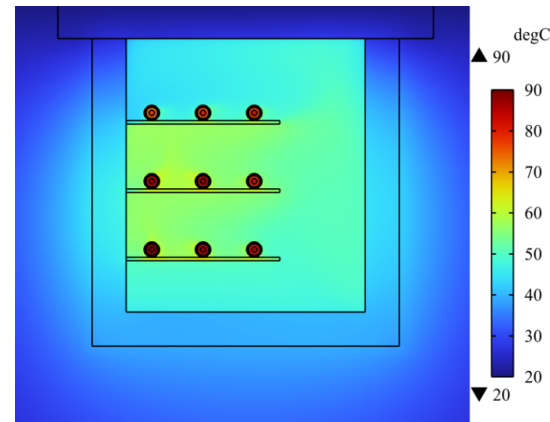


FIGURE 10. Temperature distribution map of cables in a cable trench.

TABLE 7. Ampacity under different opening ratios of support brackets.

Supporting condition	Maximum flow rate (m/s)	Current-carrying capacity (A)	Compared with solid brackets, the ampacity increases (%)
Solid support (0% porosity)	0.17	822	—
20% opening rate	0.18	873	6.2
40% opening rate	0.21	898	9.3
60% opening rate	0.22	905	10.1
80% opening rate	0.23	909	10.6

struction and assembly characteristics are suitable for the long-term operation requirements of the cables. A three-phase horizontal arrangement with a conductor center spacing of 300 mm was established. The geometric dimensions of the air space in the trench were $1.4 \text{ m} \times 1.6 \text{ m}$; the thickness of the concrete and cover plate was 200 mm; and the thickness of the support was 20 mm. This size design complies with the provisions of the “Standard for Cable Design in Power Engineering” [25]. Figure 10 shows the temperature distribution.

As shown in Figure 10, when the conductor temperature is 90°C , the current flow is 822 A, and a significant vertical temperature stratification is formed within the channel. The cable areas in the middle and lower layers have severe heat accumulation. The cable’s average temperature in the bottommost support layer is 55°C , and the average temperature in the middle support layer is 57°C . Microscopic cross-layer heat exchange is achieved through the narrow gaps at the ends of the supports, and the air convective heat resistance increases significantly. Figure 11 shows the velocity distribution.

In Figure 11, the air in each layer can only exchange through the gap at the end of the support. A single-sided vertical circulation is formed within the channel, and the peak flow velocity of the main flow channel along the wall surface is 0.17 m/s.

Since supports significantly hinder the heat dissipation of the cables, a uniform hole design is now implemented for three-layer supports, with hole areas being 20%, 40%, 60%, and 80% of the total support area. Changes in current-carrying capac-

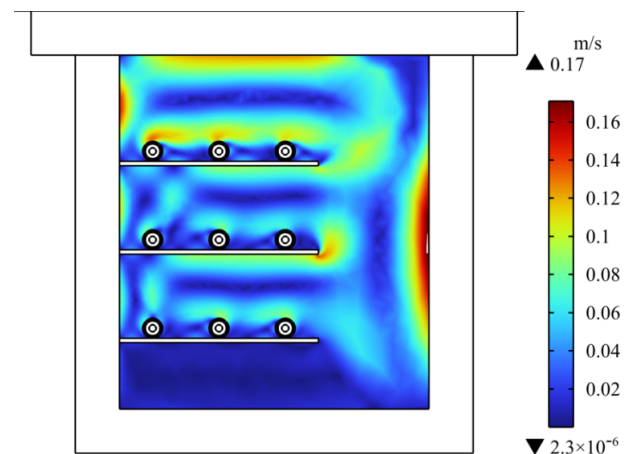


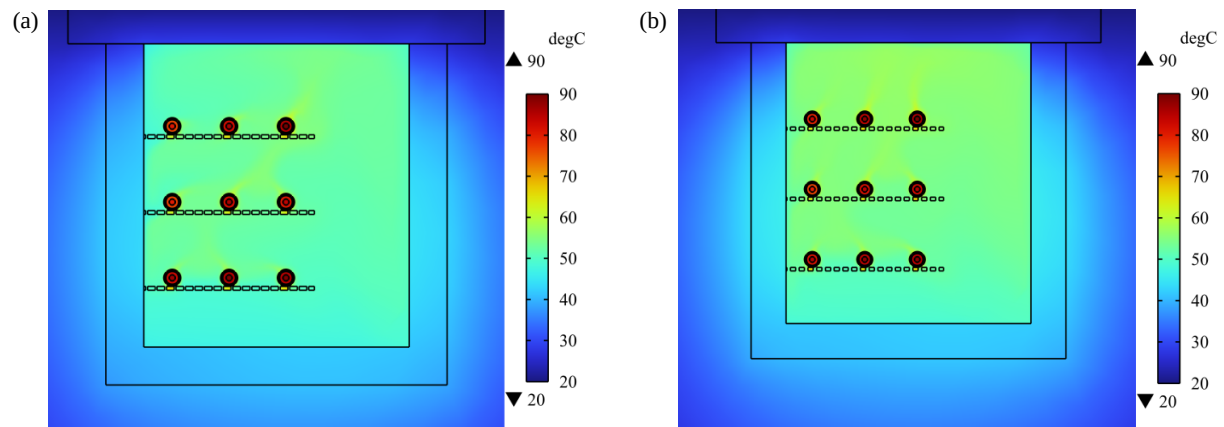
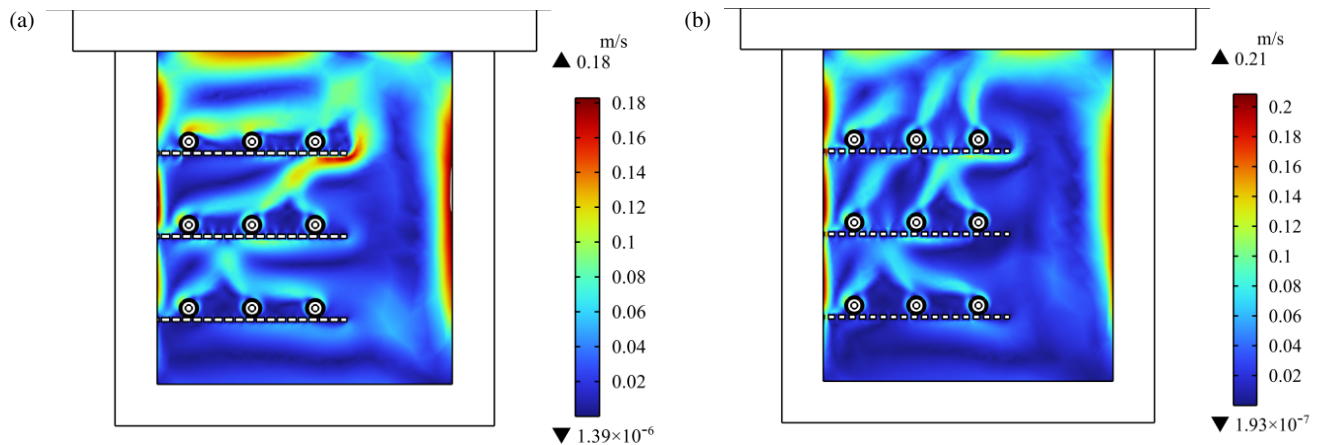
FIGURE 11. Distribution map of fluids in cable trench.

ity are analyzed. Figures 12 and 13 show the temperature and fluid distribution after the holes are made, and Table 7 presents current-carrying capacities for each hole ratio.

From Figures 12 and 13, it can be seen that heat accumulation between support layers after the holes are made has been significantly alleviated. The airflow can effectively weaken the thermal stratification phenomenon. As the opening rate increases, the overall temperature distribution inside the cable trench becomes more uniform. After the holes are made, the supports create a large number of channels for air inside the trench, and

TABLE 8. Comparison of current carrying capacity under three installation methods.

Laying method	Condition category	Specific condition	Current-Carrying Capacity (A)	Ampacity improvement (%)
Direct burial	Baseline	Direct burial in undisturbed soil	952	/
	Comparison	200 mm thick sand backfill	993	4.3
Duct laying	Baseline	Empty duct laying	845	/
	Comparison	Filled with grout	948	12.2
Trench laying	Baseline	Solid bracket laying	822	/
	Comparison	40% open area bracket laying	898	9.3

**FIGURE 12.** Temperature distribution map of the cable trench after the support opening. (a) 20% opening rate cable trench temperature distribution map and (b) 40% opening rate cable trench temperature distribution map.**FIGURE 13.** Fluid distribution map of the cable trench after the support opening is made. (a) 20% opening rate cable trench velocity distribution map and (b) 40% opening rate cable trench velocity distribution map.

airflow no longer relies solely on the ports for exchange. According to Table 7, with the highest conductor temperature of 90°C as the constraint, the current-carrying capacity significantly increases for different opening rates of supports. When the opening rate exceeds 40%, further increasing the opening rate has limited effect on the increase of the current-carrying capacity.

4.4. Comparison of Current-Carrying Capacity under Different Operating Conditions

Table 8 summarizes calculated results of the current-carrying capacity for the three cable-laying methods under base conditions and comparison conditions. The percentage increase in current-carrying capacity represents the relative increase of the same laying method compared to base conditions in this group.

5. CONCLUSION

This paper takes 110 kV XLPE high-voltage power cables as the research object, builds electromagnetic-thermal-flow coupled simulation models under different laying methods, and solves the long-term allowable current-carrying capacity of the cables under the constraint of conductor temperature rise of 90°C. The COMSOL finite element software is used to complete the simulation calculations for three typical laying conditions (direct burial, pipe laying, and cable trench laying), systematically revealing the regulation laws of different laying methods on the temperature field and current-carrying capacity of the cables, and drawing the following conclusions:

(1) The main heat dissipation bottleneck in direct burial is the external soil's thermal conductivity resistance. Using high thermal conductivity sandy soil for backfilling can reduce surface thermal resistance to some extent and smooth the temperature gradient. Under a 200 mm-thick sandy soil backfill condition, the current-carrying capacity increases by 4.3% compared to the original soil condition, but the overall improvement is limited. In engineering applications, simply relying on thickening the sandy layer is not sufficient to significantly increase the cable's current-carrying capacity. Expansion and renovation should prioritize reducing the main heat resistance path.

(2) During pipe laying, the core thermal resistance comes from the sealed air layer inside the pipes. Filling the pipes with cement-based thermal grout can directly replace the high-resistance air medium and enhance radial heat transfer. A simulation was conducted using the typical value of 2.0 W/(m·K) from the commonly used thermal conductivity range. The current-carrying capacity increased by 12.2% compared to the benchmark condition of the empty pipes. In engineering design, grouting filling is an effective method for expanding the capacity of pipe cables. The selection should take into account material cost, construction feasibility, and heat dissipation requirements.

(3) The main limitation on heat dissipation in cable trenches is caused by thermal stratification between layers and the obstruction of solid supports to the vertical airflow. Using perforated supports can open the airflow channels between layers and weaken the thermal stratification effect. Under a 40% perforation rate, the current-carrying capacity is increased by 9.3% compared to solid supports. However, further increasing the perforation rate significantly reduces the improvement in current-carrying capacity, and heat gain shows a marginal decreasing trend. This change pattern can provide a thermal-performance-based reference for the structural design of cable trench supports.

In conclusion, the potential for heat dissipation improvement of the three laying schemes is determined by their respective dominant thermal resistance bottlenecks; the improvement effect of replacing the high-resistance medium (pipe grouting) on the current-carrying capacity is the best, followed by the method of using hole openings on the supports to enhance natural convection, while external backfill soil thermal conductivity improvement yields the lowest gain. The model and conclusions of this paper can provide theoretical references for select-

ing laying schemes and capacity expansion and renovation of 110 kV XLPE cables.

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