IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 20 June 2023, accepted 30 June 2023, date of publication 4 July 2023, date of current version 11 July 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3292277

RESEARCH ARTICLE

Simulation Study on Surface Temperature Distribution of Collector Strip Material Under Pantograph-Catenary Arc of Urban Rail

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This work was supported in part by the Science and Technology Research and Development Program of China National Railway Group Corporation Ltd. under Grant N2022X009, and in part by the Gansu Provincial Higher Education Innovation Capability Enhancement Project under Grant 2020A-044.

ABSTRACT With the increasing speed of urban rail trains, the vibration between the pantograph collector strip and the contact wire intensifies, and the pantograph-catenary arc occurs frequently, which severely wear the surface materials of the pantograph-catenary. The arc burning strength and arc extinguishing characteristics of the pantograph-catenary arc are affected by the arc temperature parameters. Based on the theory of magnetohydrodynamics, this paper establishes a mathematical model with multi-physical field coupling. According to the mathematical model, apply COMSOL finite element software to establish a simulation model for the arc of the urban rail pantograph-catenary, and simulate and analyze the temperature field about the arc. Use an experimental platform to simulate experiments and verify the feasibility of the simulation model. Based on the simulation model, the surface temperature distribution of different collector strip materials under the action of urban rail pantograph-catenary arc is studied. The research results indicate that there is a positive connection between the arc duration of urban rail pantograph-catenary and the maximum arc temperature; Although the collector strip materials are different, the surface temperature distribution of the collector strip is the same; The surface temperature of the collector strip decreases with the increase of the thermal conductivity of the collector strip material.

INDEX TERMS Collector strip, pantograph-catenary arc, simulation model, thermal conductivity.

I. INTRODUCTION

In recent years, as the rapid growth of China's transportation industry, urban rail transit has developed rapidly in large and medium-sized cities due to its advantages such as large passenger flow, fast speed, safety and stability, green environmental protection, and convenience [1], [2], [3], [4].

Improving the operating speed of urban rail trains has attracted the attention of relevant researchers from various countries. The well touch between the collector strip and the contact wire provides guarantee for the safe operation of urban rail trains. As the development of science and technology, the speed of urban rail train has been continuously improved, the vibration both the collector strip and the contact wire is very severe, leading to a sharp increase in the number of offline pantograph-catenary, and frequent occurrence of pantograph-catenary arc in urban railway, seriously affecting the safe operation of urban railway trains [5], [6], [7]. The essence of urban rail pantograph-catenary arc actually is a gaseous discharge appearance. When the pantograph-catenary is offline, if the voltage between the pantograph-catenary is greater than the arc voltage between the pantograph-catenary, it is going to penetrate the air gap of the pantograph-catenary and generate an arc between the pantograph-catenary [8], [9], [10], [11], [12]. When the arc occurs between the pantograph-catenary, a large amount of heat is generated, which will repeatedly act on the material surface of the pantograph-catenary system, severely wear

The associate editor coordinating the review of this manuscript and approving it for publication was Diego Bellan.

the material of the pantograph-catenary system, affect flow quality of the pantograph-catenary system, shorten the service life of the pantograph-catenary system, and may lead to the breakage of the contact wire, leading to the operation accident of urban rail trains [13], [14]. Therefore, it is essential to study the urban railway pantograph-catenary arc temperature characteristics and distribution, understand the arc generation mechanism, master the influence factors on the arc temperature distribution rule, and provide data for extending the operation life of pantograph-catenary equipment, improving current collection quality, and reducing arc burning times [15], [16], [17], [18].

Arc phenomenon is a process of coupling change of electromagnetic field, thermal field, flow field and other physical fields. An arc is more trouble to crush out than a switching arc because it maintains circuit current [19], [20], [21], [22], [23]. Domestic and foreign scholars have carried out correlations studies on the arc of pantograph-catenary. Hu et al. [24] spectral diagnosis method and infrared camera are used to study the arc temperature of pantograph during pantograph descent. It is concluded that the surface temperature of the contact wire is higher than that of the collector strip, and the rising trend of the temperature of the collector strip and the contact wire slows down. Wang [25] the electric data related to arc that it were collected through DC arc experiments, and the arc burning image of arc was taken by camera, and the related characteristics of arc were studied. It is concluded that the arc in the pantograph system is easy to be generated under the negative power supply. The larger the current between pantograph and catenary, the stronger the arc combustion will be. Reference [26] proposes a calculation model for the wear rate of the pantograph-catenary system, which can approximately predict the wear situation of the pantograph-catenary system, and verifies the calculation model through experiments. The predicted results are consistent with the actual wear, which may provide data reference for extending the operation life of the pantograph-catenary system. Reference [27] studied the position and time of arc root under different air pressure and gas flow rates. It can be concluded that the start time of arc and the existence time of arc root are obviously longer than normal under low pressure, which leads to more serious wear of pantograph-catenary system.

Based on the previous research on pantograph-catenary arc, the pantograph-catenary arc in urban railway transit is studied in this paper. Firstly, the assumptions related to the physical characteristics of the urban railway pantograph-catenary arc simulation model are proposed, and a mathematical model with multiple physical field coupling is established. The COMSOL finite element software is used to solve the arc mathematical model, establish the urban rail pantograph-catenary arc simulation model, and output the arc temperature distribution cloud diagram. Collect the maximum arc temperature and arc duration data, and use the DC offline pantograph-catenary arc platform to obtain pantograph-catenary arc test data. Based on the simulation and experimental data of the pantograph-catenary arc, a curve diagram of the maximum temperature and duration of the arc was drawn, and the feasibility of the simulation model was verified through comparative analysis. According to the simulation model, the surface temperature distribution of collector strip made of different materials under the affection of urban rail pantograph-catenary arc is studied.

II. ESTABLISH MATHEMATICAL MODEL

The physical and chemical changes during the occurrence of pantograph-catenary arc are very complex. The temperature characteristics pantograph-catenary arc of urban rail are studied, the mathematical calculation process is simplified, and the following assumptions are put forward for the establishment of pantograph-catenary arc model system.

(1) It is believed that when calculating the pantograph-catenary arc temperature, the pantograph-catenary arc exists stably.

(2) When pantograph-catenary arc occurs, the material physical parameters of the pantograph-catenary system change less.

(3) The flow characteristics of arc plasma are equivalent to laminar flow.

(4) The plasma permeability is considered to be constant.

(5) The pantograph-catenary arc flow field of the arch grid satisfies the local thermodynamic equilibrium.

A. MATHEMATICAL MODEL OF PANTOGRAPH-CATENARY ARC

Magnetohydrodynamics is a theory that combines traditional fluid mechanics with electromagnetism [28], [29], [30]. The mathematical model of pantograph-catenary arc with Multiphysics coupling shall include Navier-Stokes equations, Maxwell electromagnetic equations and thermal radiation equations. Source terms are added to the momentum equation and energy equation to ensure strong coupling between the equations, as shown in Fig. 1.

1) NAVIER-STOKES EQUATIONS

a: MASS CONSERVATION EQUATION

In any material system (isolated system) that is isolated from its surroundings, the total mass remains unchanged no matter what changes occur. The change in mass per unit time is mean to the mass inflow per unit time minus the mass outflow per unit time, so the following is mass conservation equation:

$$\frac{\partial \rho}{\partial t} + div(\rho v) = 0 \tag{1}$$

In this formula, ρ is the fluid density, kg/m^3; v is the velocity vector.

b: MOMENTUM CONSERVATION EQUATION

For the whole closed system, which is not acted upon by external forces, or the sum of external forces is zero, then the momentum of the whole system is conserved, so the

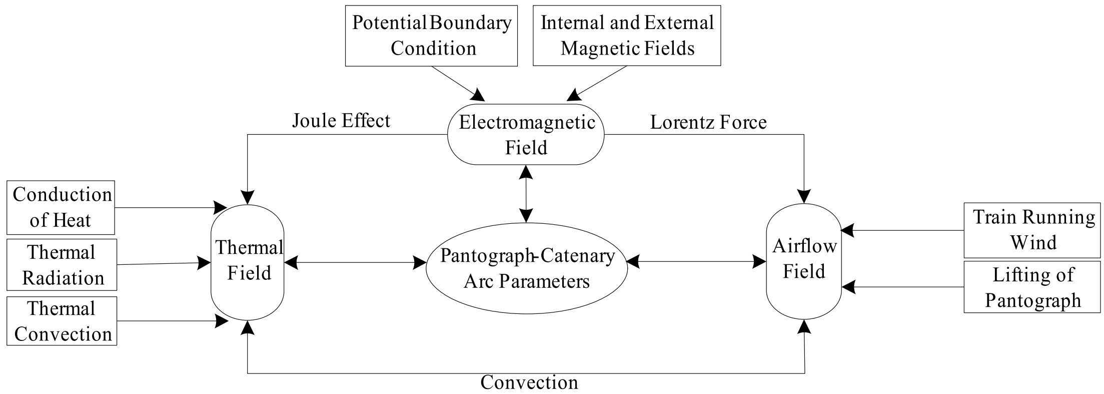

FIGURE 1. Relationship between multiple physical fields of pantograph-catenary arc.

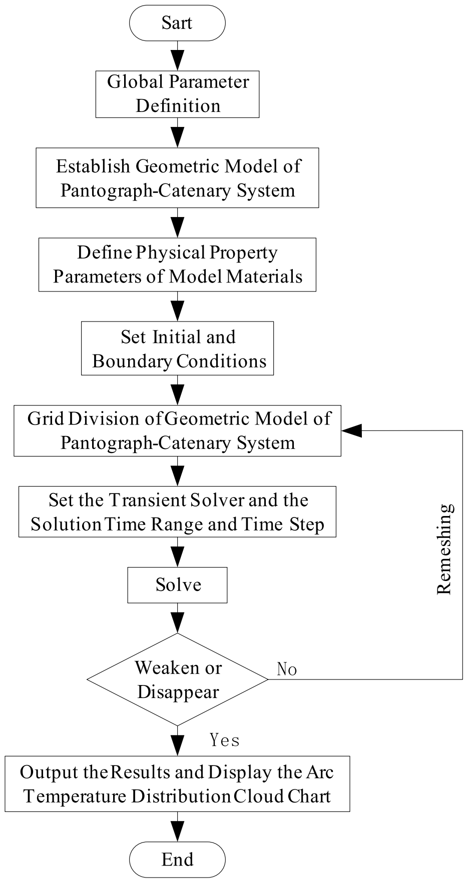

FIGURE 2. Solve process of the mathematical model of the pantograph-catenary arc.

following is momentum conservation equation:

$$\frac{\partial(\rho v_i)}{\partial t} + div(\rho v v_i) = div(\eta grad v_i) - \frac{\partial p}{\partial x_i} + S_{vi} \tag{2}$$

In this formula, v_i is the velocity component at different coordinates, m/s; η is the viscosity coefficient, kg/(m·s); p is the fluid pressure, P_a; S_{vi} is the source term of the equation.

Arc plasma is electrically neutral, and the effect of electric field on arc fluid is negligible. The main factor affecting arc fluid is electromagnetic force, so the following is source term

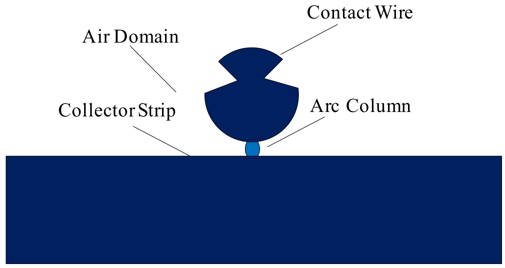

FIGURE 3. Geometric simplified model of the pantograph-catenary system.

in the momentum conservation equation:

$$S_{vi} = (J \times B)_i \tag{3}$$

In this formula, J is the current density, A/m^2; B is the magnetic induction strength.

c: ENERGY CONSERVATION EQUATION

Energy does not appear out of thin air, nor does it suddenly disappear. It only transforms from one form of energy to another, and the aggregate energy of the system remains unchanged. The following is the energy conservation equation:

$$\frac{\partial(\rho T)}{\partial t} + div(\rho v T) = div(\frac{\lambda}{C_p} grad T) + S_T \tag{4}$$

In this formula, T is the temperature, K; λ is the thermal conductivity, W/(m·K); C_p is the specific heat capacity of the fluid at normal temperature and pressure, J/(kg·K); S_T is the energy source term.

Because the viscous dissipation term does not generate additional energy in practice, it can be negligible. So the following is the source term in the energy equation above:

$$S_T = \frac{\partial \rho}{\partial t} + \frac{1}{\sigma} J^2 - Q_R \tag{5}$$

In this formula, σ is the electrical conductivity, S/m; Q_R is the radiation loss of energy.

TABLE 1. Physical standard of the pantograph-catenary system.

Material	Density/(kg/m³)	Specific heat/(J/(kg·K))	Thermal conductivity/(W/(m·K))
Pure copper contact wire	8960	385	400
Graphite collector strip	2400	710	151

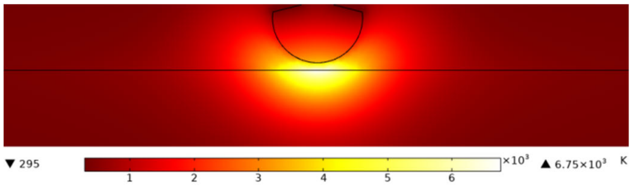

FIGURE 4. Cloud atlas of temperature profile of the pantograph-catenary arc.

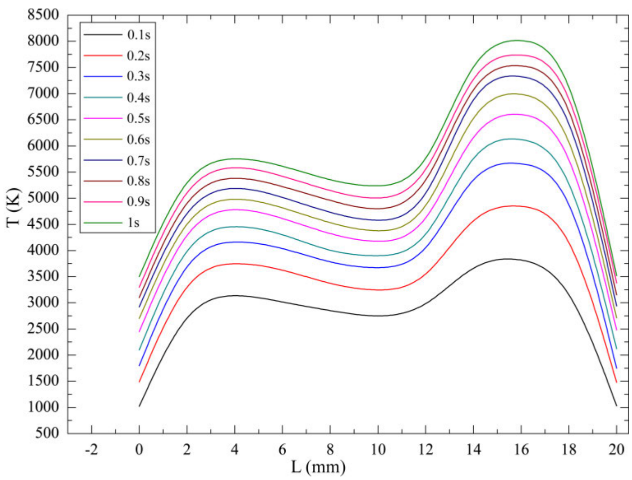

FIGURE 5. Temperature curve on arc center axis.

2) MAXWELL ELECTROMAGNETIC EQUATIONS

From the momentum and energy equations of the Navier-Stokes equations, it can be seen that to solve the source term. Therefore, the current density J and magnetic field strength B in the electromagnetic field should be obtained. On the ground of Maxwell's equations, so the following are the current density solution equations:

$$\nabla \times E = 0 \tag{6}$$

$$div(\sigma\, grad\varphi) = 0 \tag{7}$$

$$J = -\sigma\, grad\varphi \tag{8}$$

In this formula, E is the electric field, φ is the potential.

In order to simplify the calculation, the magnetic induction intensity is solved using a magnetic vector position:

$$\nabla^2 \times A = -\mu_0 J \tag{9}$$

$$div(gradA) = -\mu_0\, J \tag{10}$$

$$B = \nabla \times A \tag{11}$$

In this formula, μ_0 is the vacuum permeability, and A is the magnetic vector position.

3) THERMAL RADIATION EQUATIONS

Due to the complexity of the radiation heat dissipation and absorption process, so as to simplify the radiation calculation process, every fluid element is considered as a separate radiation source for calculation. Unit volume dV at wavelength interval $d\lambda$ the radiation energy of is $dQ_{R,\lambda}$, so the following is the thermal radiation equation set:

$$dQ_{R,\lambda}dV = 4k(\lambda)M_{Q,\lambda}(\lambda)d\lambda dV \tag{12}$$

$$M_Q = \int_0^{\infty} M_{Q,\lambda}(\lambda)d\lambda = \alpha T^4 \tag{13}$$

$$Q_R = 4\alpha T^4 \tag{14}$$

In this formula, $M_{Q,\lambda}$ is the spectral emissivity; k is the absorption coefficient, at 1 atm standard atmospheric pressure, $k = 13$ (m^{-1}); $\alpha = 5.67057$ (W/m^{2}K) is the Stefan Boltzmann constant.

4) THERMAL FLUX EQUATIONS

When the pantograph-catenary arc occurs, the urban rail train is in operation, and the pantograph-catenary arc is in a complex air flow field with a high surrounding air velocity. Therefore, it is necessary to consider the heat flux issue of the pantograph-catenary system during the operation of urban rail trains. So list the equations related to heat flux.

$$-\mathbf{n}q = d_z q_0 \tag{15}$$

$$q_0 = h \cdot (T_{ext} - T) \tag{16}$$

In the equation of heat flux, $-\mathbf{n}$ is the normal vector of heat flux in fluid heat transfer, h is the heat transfer coefficient in convective heat flux, and T_{ext} is the external temperature.

III. ESTABLISHMENT OF SIMULATION MODEL

Based on the mathematical model established by the pantograph-catenary system, the mathematical model of the pantograph-catenary arc is solved using COMSOL Multiphysics finite element software, and a two-dimensional pantograph-catenary arc simulation model is established. Specific simulation model solve process is shown in Fig. 2.

A. ESTABLISHMENT OF GEOMETRIC MODEL OF PANTOGRAPH-CATENARY

COMSOL Multiphysics software actually converts a two-dimensional model into a three-dimensional model and then performs calculations. A two-dimensional geometric simplification model is adopted for simulation modeling of arc in the pantograph-catenary, and a longitudinal cross-section of the arc along the contact wire is established, as shown in Fig. 3. In this figure, the size parameters of the

TABLE 2. Simulation data of maximum arc temperature and arc duration.

Time(s)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Temperature(K)	4520	5030	5870	6390	6750	7120	7390	7630	7850	8100

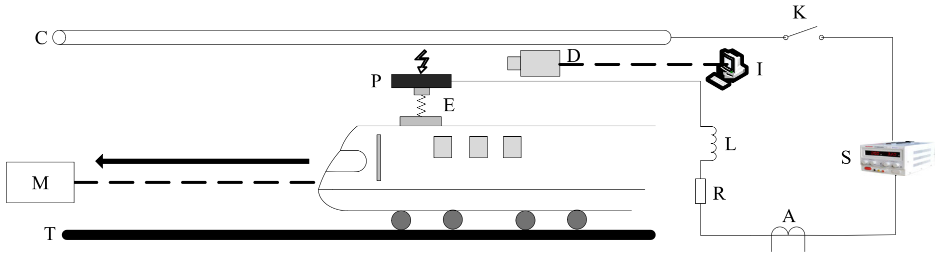

FIGURE 6. Schematic diagram of DC offline arc experimental device.

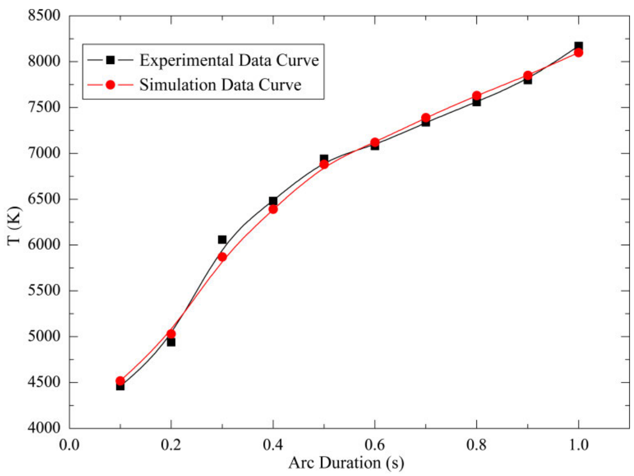

FIGURE 7. Comparison curve of simulation and experiment.

contact wire are set with reference to the actual situation of the urban rail pantograph-catenary system, and the diameter of the contact wire is 14.4 mm. Simplify the collector strip into a rectangular body with a geometric dimension of 200 $\times$ 20 mm. The contact wire is made of pure copper and the collector strip of the pantograph is made of graphite. The related physical property standard of the pantograph-catenary system are shown in Table 1.

B. INSTALL OF STARTING CONDITIONS

In order to solve the mathematical model of arc, the boundary conditions of arc simulation model were set in finite element software. The energy conservation of the entire pantograph-catenary arc system is achieved, and the initial temperature of the system is set to 295 K. In the arc simulation system, the thickness of the air solution domain is set to 500 mm, and the pressure of the system fluid is set to 1 atm. Due to the fast speed of urban rail trains and the relatively fast air flow speed, the air flow speed cannot be ignored in the simulation calculation. The boundary conditions for the wall surface and air convective heat transfer of the pantograph-catenary system are set as the forced convection mode, so the convective heat transfer coefficient of the pantograph-catenary arc system is set as 100 W/(m^2·K). The pantograph-catenary arc heat flux density is set as 10^{10} W/m^2. Set the off-line air gap of the pantograph-catenary to 2 mm, the maximum arc duration to 1 s, and the time step length to 0.1 s.

IV. ANALYSIS OF SIMULATION RESULTS AND EXPERIMENTAL VERIFICATION

Through the arc mathematical model, the COMSOL Multiphysics finite element software is used to output the temperature distribution cloud diagram, so as to study the arc generation mechanism and the arc temperature distribution. The temperature data of DC arc were obtained by the experimental equipment of DC arc, and the reliability of the simulation model was verified.

A. ANALYSIS OF SIMULATION RESULTS

The temperature profile of arc was analyzed in the arc simulation model with the contact wire as anode and collector strip as cathode.

(1) In the range of arc duration, take any time to output the temperature distribution cloud diagram of pantograph-catenary arc, as shown in Fig. 4.

According to the Fig. 4, the temperature of urban rail pantograph-catenary arc can reach more than 6000 K, and the closer to the two poles of pantograph-catenary arc, the more obvious the arc column shrinkage. The temperature field of the pantograph-catenary arc is symmetrically distributed along the central axis of the arc.

(2) In COMSOL Multiphysics simulation software, define a two-dimensional cross-section as the arc center axis, and use COMSOL Multiphysics simulation software to collect 10 duration temperature curves with a step length of 0.1 s within 0 s to 1 s, as shown in Fig. 5.

According to the Fig. 5, the temperature curve on the central axis of the arc that the observed trend of the arc temperature curve is roughly the same in different duration.

(3) Collect the maximum arc temperature and arc duration data, as shown in Table 2.

According to the analysis in Table 2, as the arc duration increases, the arc temperature gradually increases.

TABLE 3. Physical properties parameters of carbon slides made of different materials.

Material	Density/(kg/m^3)	Specific heat/(J/(kg·K))	Thermal conductivity/(W/(m·K))
Pure copper collector strip	8960	385	400
Copper impregnated collector strip	2320	478	6
Copper based powder metallurgy collector strip	8100	376	80

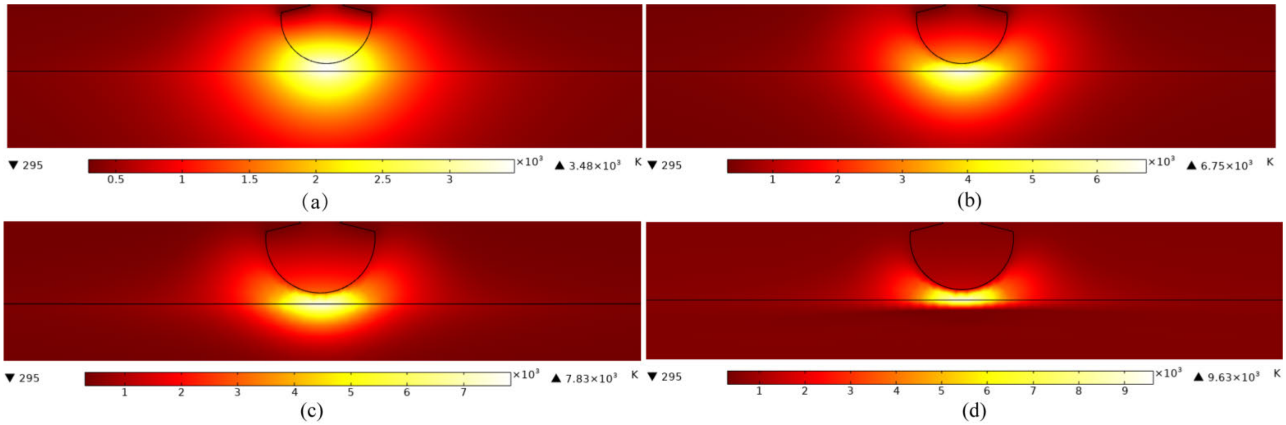

FIGURE 8. Temperature distribution cloud chart of collector strip made of different materials: (a) Cloud atlas of arc temperature profile in pure copper collector strip material, (b) Cloud atlas of arc temperature profile under graphite collector strip material, (c) Cloud atlas of arc temperature profile under copper based powder metallurgy collector strip material, (d) Cloud atlas of arc temperature profile under copper impregnated collector strip material.

B. EXPERIMENTAL VERIFICATION

The simulation experiment of urban rail pantograph-catenary arc is carried out by using DC power to simulate pantograph-catenary arc through laboratory arc experiment platform. Use a spectrometer to collect the plasma radiation spectrum information of the pantograph arc, to calculate the temperature change data of the pantograph arc, and use a data acquisition device to gather current and voltage fluctuation data when the pantograph-catenary arc is generated for subsequent comparative analysis with the pantograph-catenary arc simulation experiment.

1) DC OFFLINE ARC EXPERIMENT PLATFORM

Utilize a pantograph-catenary arc experimental generator to verify the accuracy of the arc simulation model on output parameters. The material settings, initial conditions and parameters of the simulation experiment are unanimous with those of the simulation experiment. The sketch map of the pantograph-catenary arc experimental equipment is shown in Fig. 6. The pantograph electrical contact experimental equipment uses the DC motor to drag the train to simulate locomotive operation, and simulates the phenomenon of pantograph-catenary separation by controlling the expansion and contraction of the DC electromagnet.

According to the Fig. 6, S-DC Power Supply; K-Circuit Changer; A-Current Transformer; I-IPC; L, R-Analog System Load Impedance; D-Spectrometer; E-DC Electromagnet; P- Collector Strip of Pantograph; M-DC Motor; T-Rail; C-Contact Wire. In the pantograph catenary electrical contact experimental device, single-phase AC is converted into DC to supply power to the system. R, L simulates the resistance and inductance of the system. Use a current transformer to record current changes. The optical system is used to collect the radiation spectrum information of the arc plasma of the pantograph-catenary, and the plasma temperature is calculated using Boltzmann mapping method.

2) COMPARATIVE VERIFICATION

Using the established DC offline arc experimental platform to simulate the process of arc occurrence, the alteration of the maximum arc temperature with time is calculated. According to simulation data and experimental data, draw a comparison curve of arc temperature, as shown in Fig. 7.

According to Fig. 7, both simulation and experimental arc temperature curves show that with the increase of arc duration, the arc temperature gradually rises. It is concluded that the simulated arc temperature curve is basically unanimous with the experimental arc temperature curve, and the results are basically unanimous within the error range, which verifies the correctness of the output parameters of the arc simulation model.

V. TEMPERATURE EFFECT OF PANTOGRAPH-CATENARY ARC ON CARBON SLIDES MADE OF DIFFERENT MATERIALS

A. PHYSICAL PARAMETERS OF CARBON SLIDES MADE OF DIFFERENT MATERIALS

In order to realize the reliable current collection of urban rail trains, the collector strip material of pantograph shall have the characteristics of high temperature resistance. Currently, the

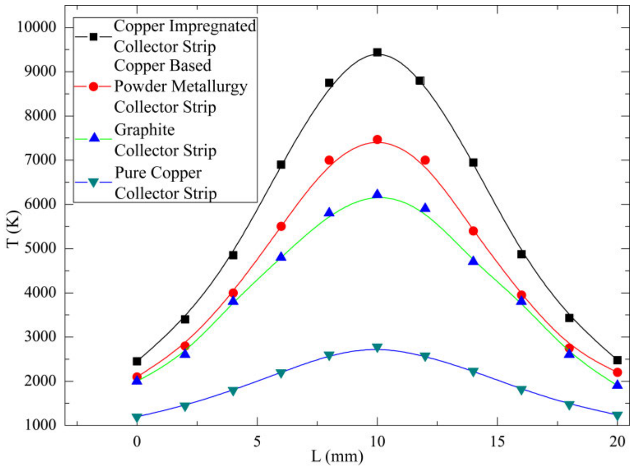

FIGURE 9. Surface temperature distribution curve of collector strips under different materials.

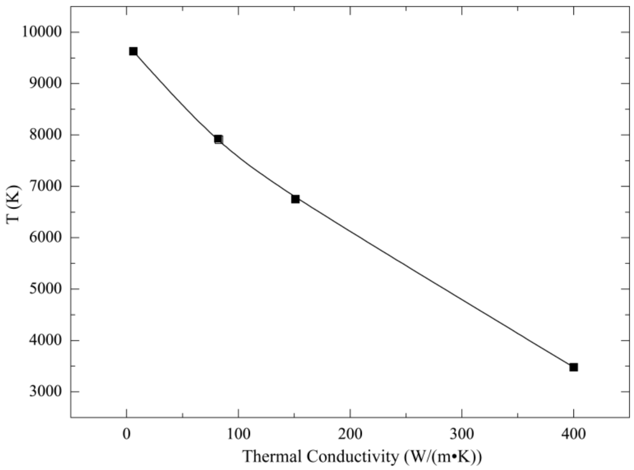

FIGURE 10. Curve chart of material thermal conductivity and maximum surface temperature of collector strips.

commonly used collector strip materials at home and abroad mainly include pure copper collector strip, graphite collector strip, copper based powder metallurgy collector strip, and copper impregnated collector strip. Graphite collector strip is used in both arc simulation experiments and arc simulation experiments, and the specific parameters are shown in Table 1. Other physical arguments of various collector strip materials are shown in Table 3.

B. TEMPERATURE DISTRIBUTION LAW OF CARBON SLIDING

(1) According to Table 3, set different collector strip parameters in the simulation model, set the arc duration as 0.5 s, and keep other parameters unchanged. Output the temperature distribution nephogram to study the temperature distribution of collector strips of different materials under the action of urban rail pantograph-catenary arc, as shown in Fig. 8.

According to Fig. 8, under the action of pantograph arc, distinct materials of collector strip and distinct temperature profile rules of collector strip surface also affect the temperature profile of arc region.

(2) In the simulation software COMSOL Multiphysics, the two-dimensional transversal was defined as the central axis along the plane direction of the collector strip, and the temperature profile of the collector strip surface of distinct materials was obtained when the pantograph arc occurred, as shown in Fig. 9.

From Fig. 9, it can be seen that although the materials of collector strips are different, the distribution of arc temperature on the surface of collector strips is basically consistent, the middle temperature is high and gradually decreases towards the periphery. According to the material characteristics of the pantograph-catenary in Table 1 and Table 3, under the affection of arc, the surface temperature of the collector strip decreases gradually with the increase of thermal conductivity of the collector strip material.

(3) The temperature fluctuation data of collector strip surface under the action of arc were collected, and the correlation curve between thermal conductivity and collector strip surface temperature was drawn by computer software, as shown in Fig. 10.

According to Fig. 10, when the arc occurs, the temperature of the collector strip surface decreases with the increase of the coefficient of heat conductivity of material. Due to the fact that the surface temperature of collector strip is a major factor in wear collector strip materials, selecting collector strip materials with high thermal conductivity can help improve the extent of arc erosion on collector strips.

VI. CONCLUSION

In this paper, the pantograph-catenary arc simulation model of urban rail is established by COMSOL Multiphysics. The accuracy of the simulation model is verified through experiments. Based on the simulation model, the physical parameters of collector strips of different materials are changed under the action of the arc of pantograph-catenary, and the surface temperature distribution of collector strips is studied, and the following conclusions are drawn.

(1) In the range of arc duration, the arc temperature increases gradually with the increase of arc duration. Therefore, the arc duration is positively correlated with the arc temperature.

(2) Different materials of collector strip not only affect the surface temperature distribution of collector strip, but also affect the temperature distribution of the entire arc region; Although the materials of the collector strip are different, the surface temperature distribution of the collector strip is basically the same, and the middle temperature gradually decreases to the surrounding; The maximum surface temperature of the collector strip is inversely proportional to its thermal conductivity. Choosing collector strip material with high thermal conductivity can help improve the extent of arc erosion on the collector strip by arc temperature.

The research conclusion of this paper has practical engineering meaning for the normal operation and maintenance of urban rail trains and the selection of collector strip materials.

ACKNOWLEDGMENT

The authors are very grateful to Liu Yijuan for her help with the grammar of this article.

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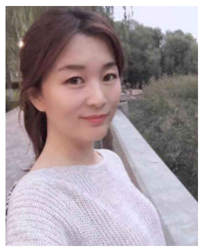

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