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NUMERICAL ANALYSIS ON THE LOW TEMPERATURE FIELD OF AEROSPACE ELECTRICAL CONNECTORS

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Abstract. *Numerical analysis is used to study the influence of low temperature environment on the performance of electrical connectors, which is one of harsh working conditions severely affecting the reliability. The three-dimensional analysis model of the electrical connector is built by ANSYS functional module, which is imposed by the reasonable loads and boundary conditions with the consideration of the heat conduction and convection cooling. The temperature field distribution characteristics of different type spectrums of electrical connectors at different low temperature environments are analyzed by the thermoelectric coupling simulation. The results show that the abrupt changes of low temperature conditions have a big impact on the outer insulator. The type spectrum of electrical connector has a great influence on the temperature field distribution. The region of the maximum temperature gradient and the overlap region of temperature change alternately may be the weakness of performance degradation of the insulator. Finally, the simulation result is compared with the theoretical value, which has a good consistency.*
Keywords: Low temperature field, Electrical connectors, Thermoelectric coupling

1. **Introduction.** The electrical connector is a kind of fundamental electromechanical components which is widely applied to realizing electrical connection and signal transmission among the components, devices and systems in the field of aviation, aerospace, electronics and communication. The reliability and security of the whole control system are dominated by the quality and reliability of electrical connectors [1].

The working condition of aerospace electrical connectors is complex and harsh, among which the ambient temperature is one of the important factors affecting the reliability of electrical connectors [2]. The ambient temperature of military electrical connector commonly ranges from −55°C to 125°C, even from −65°C to 200°C [3]. Under the low temperature conditions, there may be the following appearances for the electrical connector. 1) Contact pairs and insulator of electrical connectors become crisp [3-5]. 2) From high temperature to low temperature, the surface coating of electrical connectors may fracture due to the changes of the linear expansion coefficient [6]. 3) Low temperature may lead to the mechanical failure, brittle fracture of non-metallic and the seal damages [7-9]. Based on the above, the failure modes of materials in low temperature condition were studied. However, the failure mechanism of performance degradation for connectors caused by low temperature need further theoretical research. So, in order to investigate the weak areas of performance degradation for aerospace electrical connectors, the FEM model is built and the temperature fields of connectors with different type spectrums under different low temperatures are analyzed.

2. **Problem Statement and Preliminaries.** Some researches on the material properties of electrical products working at low temperature have been done. In [6], the linear

expansion coefficients of several typical alloy and glass commonly used in electrical connector are measured in several different low temperature zones. The fracture mechanism of rubber in low temperature condition is studied in [10,11] and a stress wave transmission model is created to describe fracture procedure of rubber particle. In [12], the rigidity of cryogenic elastic element, such as spring and bellow of valve for space, is studied under low temperature conditions. However, little research on the low temperature field of electrical connector has been done in spite of many researches on the temperature field of electrical connector [2,13-16]. In [13], the temperature field of the connector under different high temperature conditions is analyzed and the change rule of the maximum temperature under different high temperature zones is obtained. In [14], the mathematical model of temperature rise for connector is built according to the theory of heat conduction, convection and radiation. The temperature field distribution of the connector under different tightening torques caused by vibration is analyzed. In [15], the simulation analysis of temperature field has been done for electrical connectors by the introduction of the equivalent resistance. In [16], the 3-D coupled field finite-element method model has been developed for analyzing the electrical, thermal, and mechanical behaviors of a plug-in connector under steady and short circuit condition, the validity of the calculation model is demonstrated by temperature rise experiment.

The difference of temperature field simulation between the low temperature and the high temperature is the heat transfer coefficient which is changed from high temperature condition to cryogenic state. In this paper, the work is based on the prior results of the research group. Luo et al. [17] simulated the high temperature field of the electrical connector and the simulation results are consistent with the experimental results. Luo et al. [18] proposed a thermal fatigue test scheme, and a test circuit is designed for the experiment. The thermal fatigue failure mechanism of electrical connectors is analyzed.

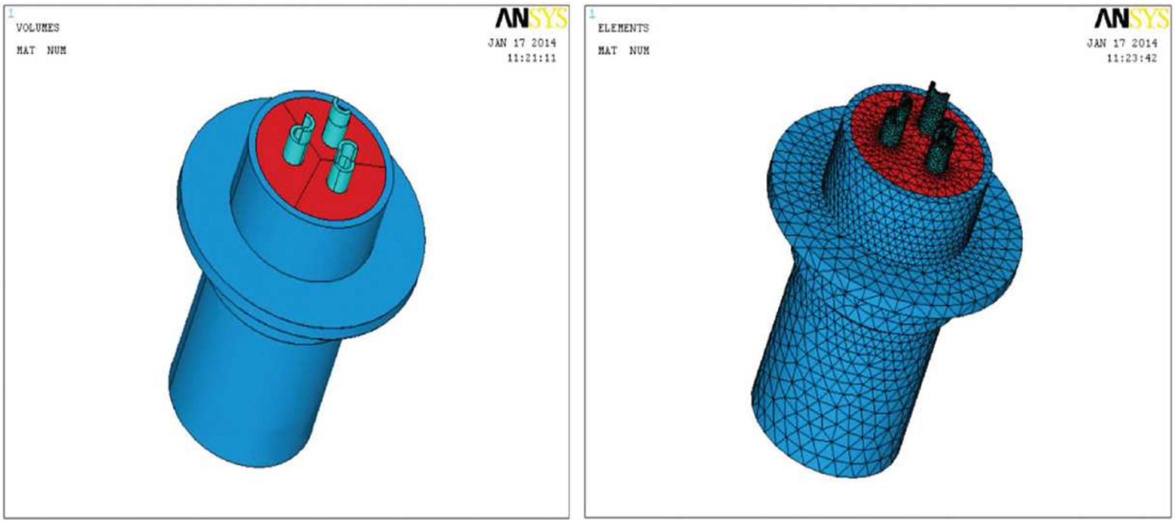
3. Numerical Analysis for Electrical Connectors.

3.1. **Establishment of the finite element model.** In order to meet the calculation accuracy requirements and improve the calculation speed, appropriate simplifications for certain components in the structure of electrical connector are made during the modeling process. 1) The spring washer which barely contributes to the thermal analysis of the system is removed. 2) All screw threads are revised as smooth curved surfaces. 3) Regard the contact between pin and jack as a surface contact. 4) Detail features, e.g., chamfers and tiny apertures or small lugs are ignored. The simplified solid model of three-pin (3P) electrical connector and its FEM are shown in Figure 1. Figure 1(a) shows the 3-D solid model, which is built by using modeling function of ANSYS. Figure 1(b) shows FEM, which is generated by free meshing of the 3-D solid model. The material properties of the electrical connector model at the room temperature are shown in Table 1.

Aerospace electrical connector is mainly composed of contact pairs (pin and jack), insulator (pin socket and jack socket) and outer casing. The only source of heat is contact pairs carrying the load current. The heat dissipates through natural convection and thermal radiation by insulator and outer casing. So, the SOLID227 tetrahedron elements with thermoelectric coupling analysis functions are used for analysis of contact pairs, and the SOLID87 tetrahedron element with the thermal analysis functions is used for analysis of the insulator and outer casing.

The main load imposed on contact pairs is current. The natural convection coefficient and thermal radiation coefficient are imposed on the surface of electrical connector. We define the sum of them as the integrated heat transfer coefficient. The natural convection coefficient h_f can be calculated by using the empirical formula:

$$h_f = 3.25 \times (T_S - T_B)^{0.25} \tag{1}$$



(a) Model of the electrical connector

(b) FEM of the electrical connector

FIGURE 1. The simplified model of 3P electrical connector

TABLE 1. Material properties of the electrical connector at the room temperature

Component	Material composition	Electrical resistivity [Ω]	Thermal conductivity [W/(m$^2 \cdot$°C)]
Pin	Brass	$7.1 * 10^{-8}$	108
Jack	Tin bronze	$8 * 10^{-8}$	83.7
Insulator	Phenolic resin	/	0.029
Outer casing	Aluminium alloy	/	156

TABLE 2. Coefficient of heat transfer under different low temperature conditions

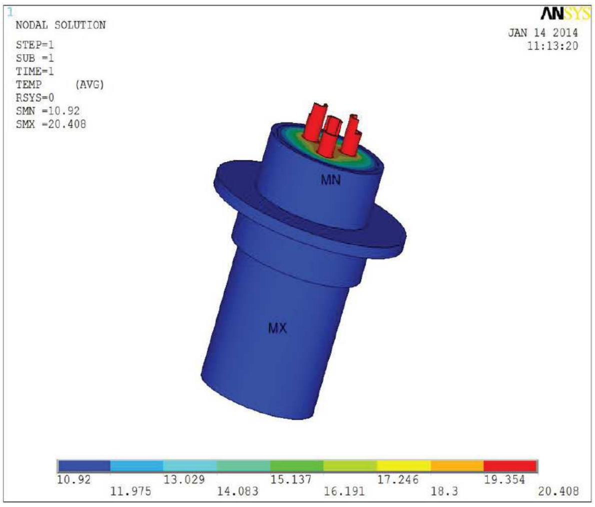
Ambient [°C] temperature	Natural convection coefficient [W/(m$^2 \cdot$°C)]	Thermal radiation coefficient [W/(m$^2 \cdot$°C)]	Integrated heat transfer coefficient [W/(m$^2 \cdot$°C)]
5	6.4	4.76	11.16
−5	7.27	4.52	11.79
−10	7.61	4.41	12.02
−20	8.17	4.18	12.35
−30	8.64	3.97	12.61
−40	9.05	3.77	12.82
−50	9.4	3.58	12.98
−65	9.87	3.33	13.20

Thermal radiation is another form of heat loss, and thermal radiation coefficient P_{fs} can be expressed by:

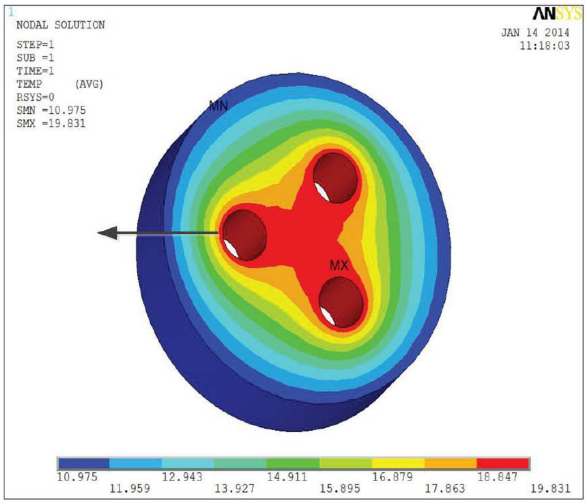
$$P_{fs} = \sigma\varepsilon_f \left(T_S^4 - T_B^4\right) \tag{2}$$

where the σ is Pan-oersted Boltzmann constant, and the value of σ is 5.67×10^{-8} W/(m^{2}K^4). The T_S and T_B are solid surface temperature and ambient fluid temperature, and the unit is °C. The ε_f is the emissivity which is set as 0.9, and the shape coefficient is 1. The natural convection coefficient, thermal radiation coefficient and integrated heat transfer coefficient under different low temperature conditions are shown in Table 2.

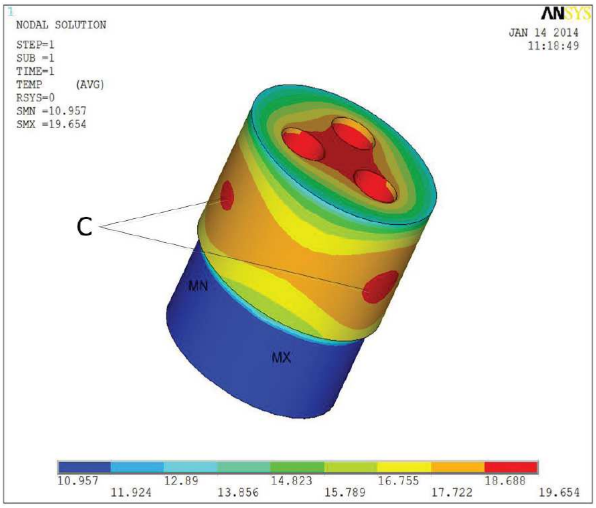
3.2. **Simulation result.** In order to completely analyze the temperature field distribution of electrical connectors taking the 3P electrical connector as an example, these temperature field distributions under the ambient temperature 5°C, such as the pin socket, jack socket, the whole connector and its axial section, are computed, which are shown in Figure 2.



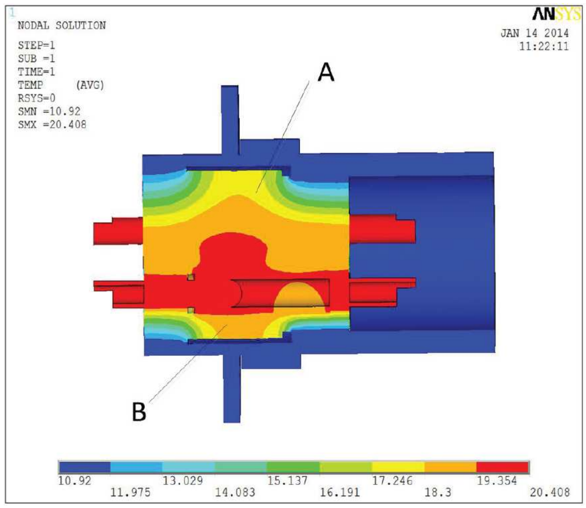
(a) Temperature field of whole connector



(b) Temperature field of pin socket



(c) Temperature field of jack socket



(d) Temperature field of the axial section

FIGURE 2. (color online) Temperature field of 3P electrical connector under the ambient temperature 5°C

As shown in Figure 2(a), the contact pairs have the highest temperature up to 20.408°C and the temperature rise is 15.408°C at 5°C. The temperature of the outer casing is the lowest, which is 10.92°C. This is because the contact pairs of the electrical connector are the sole heat source and the outer casing directly touches the air outside with a strong heat dissipation capacity.

Figures 2(b) and 2(c) show the temperature field distributions of a cross-section of pin socket and jack socket, respectively, which show basically the same except that the highest temperature of the pin socket is slightly higher than that of the jack socket. The temperature field distributions can be obviously divided into three temperature regions: high-temperature region, mid-temperature region and low-temperature region. The characteristics of three temperature regions are as follows. 1) High-temperature region includes the circle regions of each pin/jack periphery and the band region from the pin/jack to the center of pin/jack socket. 2) Mid-temperature region is a family of isothermal layers with gradually decreasing temperature. 3) Low-temperature region is an annular region near the outer casing. It can be seen in Figure 2(b), the width of isothermal layers with the same temperature at different parts of the insulator is also different. For instance, the width of isothermal layers near pin/jack is minimum following the direction of the arrow, which illustrates that the temperature gradient is the largest. In Figure 2(c), there are three high-temperature regions (marked as point C) where the pins join jacks.

From the direction of the axial section shown in Figure 2(d), the temperature distributions of the high-temperature region, mid-temperature region and low-temperature region are irregular. 1) Taking the contact pair as a core, high-temperature region shows a glyph symbol of "ㅑ" (color online). 2) Mid-temperature region consists of a family of isothermal layers with gradually diminishing temperature. The width of isothermal layers with different temperatures is different (marked as point A and point B). 3) Low-temperature region mainly distributes at the four corners of the insulator. So, the characteristics of the uneven distribution of temperature field need the higher requirements on the performance of insulators.

In [19], the research shows that the temperature gradient has an impact on the number and orientation of orientation spherulite. The greater the temperature gradient is, the more wafer layers of orientation spherulite along the gradient direction will damage on the microscopic, which is affected by the tangential stress. On the macroscopic view, the performance of resistance of slow crack degrades. Therefore, it can be inferred that, under different ambient temperatures, the weakness of the insulator may be the position of the highest temperature, the lowest temperature or the maximum temperature gradient except for internal defects of the insulator.

4. Results Analysis.

4.1. The influence of ambient temperature on the temperature field.

The temperature field of electrical connectors is simulated under the ambient temperature of 5°C, −5°C, −10°C, −20°C, −30°C, −40°C, −50°C and −65°C. The maximum temperature, the minimum temperature and the temperature rise of the electrical connector under different low temperatures are shown in Figure 3.

Figure 3 shows that the maximum and minimum temperatures become lower along with the decline of the ambient temperature, but the temperature rise basically remains

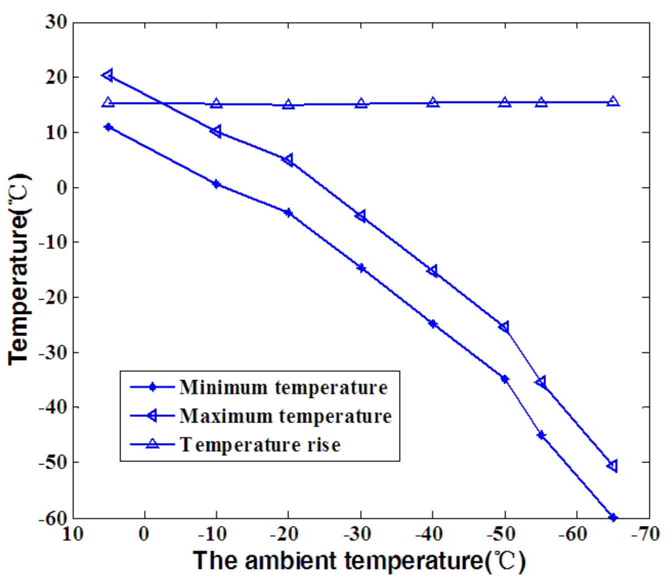


Figure 3. Temperature rise of 3P electrical connector along with ambient temperatures

constant. This is mainly because the heat produced by the current is the same, although integrated heat transfer coefficient gets bigger with the decline of the ambient temperature, which has little influence on temperature rise.

The temperature field distribution characteristics of the insulator are slightly different under different ambient temperatures. Following the direction of the arrow in Figure 2(b), the width of isothermal layers of pin socket for 3P connector is shown in Table 3. For the high-temperature region and mid-temperature region, the area and the width of isothermal layers are almost the same under different ambient temperatures. For the low-temperature region, the changes are mainly concentrated at the width of the outer two isothermal layers near the outer casing. The width of the outermost isothermal layer becomes wider and the other becomes narrower along with the decline of ambient temperature. Therefore, the overlap region of the outer two isothermal layers may be the weaknesses of insulator when the external environment changed.

Table 3. The width of isothermal layers of pin socket for 3P connector

Ambient	The width of isothermal layers of pin socket [mm]								
temperature [°C]	1 (red)	2	3	4	5	6	7	8	9 (blue)
5	0.325	0.329	0.333	0.331	0.335	0.335	0.336	0.338	0.338
−5	0.325	0.328	0.333	0.331	0.335	0.335	0.336	0.338	0.339
−10	0.325	0.328	0.333	0.331	0.335	0.335	0.336	0.338	0.339
−20	0.325	0.328	0.333	0.331	0.335	0.335	0.336	0.338	0.339
−30	0.325	0.327	0.333	0.331	0.335	0.335	0.336	0.337	0.34
−40	0.325	0.328	0.333	0.331	0.335	0.335	0.336	0.336	0.341
−50	0.325	0.327	0.333	0.331	0.335	0.335	0.336	0.336	0.342
−65	0.325	0.327	0.333	0.331	0.335	0.335	0.335	0.336	0.344

4.2. **The influence of type spectrum on the temperature field.** Table 4 shows the structure parameters and simulation results of different type spectrums of electrical connectors.

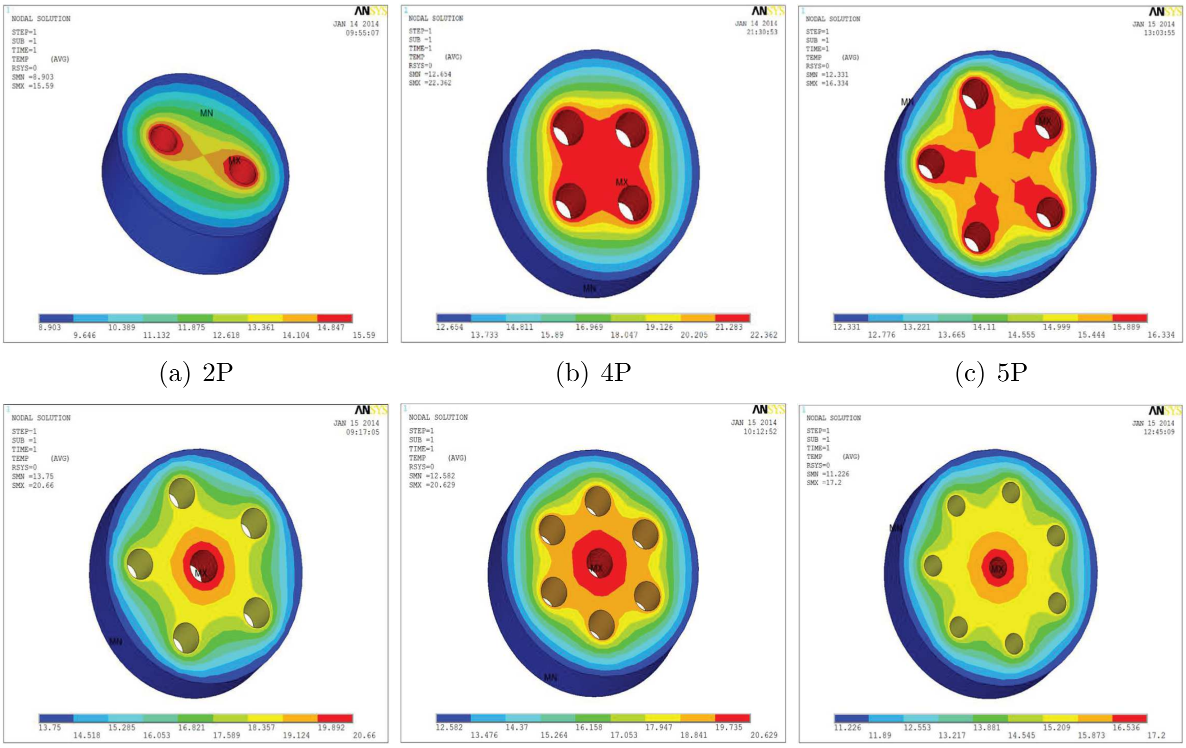
Table 4. Structure parameters and simulation results

Number of pins	Rated current [A]	Diameter of the pin/jack [mm]	Center distance of pin and pin socket [mm]	Temperature rise [°C]
2P	15	3.43/4.94	5.2	11.161
3P			4.84	15.408
4P			5	17.894
5P	12	2.92/4.48	7.25	11.623
6P			7.23	17.487
7P	10	2.92/4.40	6.08	16.006
8P	7	2/3.48	7.3	12.487

As shown in Table 4, several conclusions can be obtained.

1) Under the same rated current and the same diameter of pin/jack, the amount of heat rises with the increase of the number of pins, which causes the increase of temperature rise of the electrical connector. This is because the current is the main factor affecting the temperature rise.

2) The type spectrum of electrical connector, referring to the permutation of the contact pairs, has a big impact on the temperature field distribution, which is shown in Figure 4. The temperature distribution of the insulator for the 4P electrical connector is basically



(a) 2P (b) 4P (c) 5P

(d) 6P (e) 7P (f) 8P

FIGURE 4. (color online) Temperature distribution of pin socket for different type spectrums

the same as that of the 3P electrical connector. However, the area of the high-temperature region for the 4P electrical connector is bigger than that of the 3P connector, which is mainly due to the fact that the 4P electrical connector generates more heat than the 3P connector and the strong thermal coupling effect between the pins causes the difficulty in intermediate heat lost.

3) The temperature distribution of 6P and 5P electrical connector is very different due to the different permutation of the contact pairs. The high-temperature region of the 6P connector is mainly concentrated on the middle contact pair, and the temperature of the other five contact pairs is lower than that of the middle one. The temperature distribution of the 8P and 7P connector is basically the same as that of the 6P, while the highest temperature of the 8P and 7P connector is lower than that of the 6P connector, because the rated current input is relatively small.

4.3. **Comparative analysis of the simulation results and the calculation results.** On the assumption that the distribution of contact elements of round electrical connector is symmetrical and the current-carrying capacity of contact elements is the same, it can be deduced that the highest temperature of electrical connector is at the center of cross-section shown in Figure 5. The highest temperature can be estimated by Formulas (3)-(5), which is deduced in [2]:

$$T_c = {}^{q}\!/_{4\pi lk} + T_S \tag{3}$$

$$q = I^2 RN[1 + \alpha(T_c - 20)] \tag{4}$$

$$T_S = T_a + {}^{q}\!/_{\pi Dlh} \tag{5}$$

where the I is the current of per contact pair (A). R is the contact resistance at 20°C (Ω). The α is the coefficient of resistance. N is the number of contact pairs. The l is the length of the connector (m). The k is thermal conductivity of insulators. T_S is the surface temperature of electrical connector (°C). D is the diameter of the electrical connector (m).

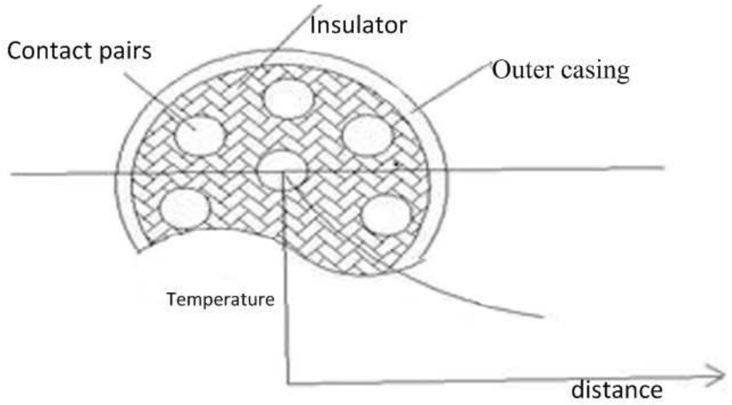


Figure 5. Curve of temperature rise of parts of circular electrical connector

Table 5. Comparison between the simulation results and the calculation results

Number of pins	Temperature rise [°C]		Deviation [%]
	Simulation results	Calculation results	
2P	11.161	11.9262	6.42
3P	15.408	15.5724	1.06
4P	17.894	19.3493	7.52
5P	11.623	16.3171	28.8
6P	17.487	18.7360	6.67
7P	16.006	15.9855	0.13
8P	11.487	11.0067	4.30

The h is the integrated heat transfer coefficient. The T_a is the environment temperature (°C).

Taking 3P connector as an example, the relevant parameters at 5°C are: $R = 0.0006$ Ω, $l = 0.05$ m, $D = 0.025$ m, $h = 11.16$, $k = 0.23$, $N = 3$, $I = 15$ A. The highest temperature of 3P electrical connector is 20.5724°C according to Formulas (3)-(5), so the temperature rise is 15.5724°C in theory. The error between the simulation results and calculation results is 1.06%. The temperature rise of electrical connector in theory for different type spectrums is estimated, which is shown in Table 5.

It can be seen in Table 5, the 5P electrical connector has the maximum deviation because the maximum temperature is not at the center of the connector (seen in Figure 4). The deviation of 2P electrical connector is not very big because of the smaller diameter although the temperature distribution characteristic of the 2P electrical connector is the same as that of the 5P electrical connector. The other errors between the simulation results and the theoretical calculation value range from 0.13% to 7.52%, which has a good consistency.

5. **Conclusions.** Based on the study, the following conclusions can be obtained.

1) The temperature field of electrical connectors can be simply divided into three regions: high-temperature region, mid-temperature region and low-temperature region. The highest temperature for the same type spectrum of the connector is dropping along with the decline of ambient temperature while the temperature rise remains basically constant. Convection and radiation heat have a little impact on the temperature rise of the electrical connector.
2) The type spectrum of electrical connectors has a big difference on the temperature rise and temperature distribution. The number of contact pairs affects the temperature

rise under the same rated current. The permutation of the contact pairs has a big impact on the temperature field distribution.

3) The simulation result is in basic accordance with the theoretical estimation result, which verifies the feasibility of numerical analysis method for thermal analysis of the electrical connector.

There is an issue for future work. The issue is that the temperature cycling test needs to be carried out to verify the views proposed in this paper because the degradation characteristics of insulator are studied only in theory.

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