Research on the material of current-carrying vessel used for current transfer type fault current limiter

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Abstract. In recent years, there has been more and more research on current transfer type fault current limiter. Titanium diboride is used as the pressure-controlled materials in the field of current transfer, which has high application value and research significance. The current transfer type fault current limiter has two working states: when the circuit is operating normally, a certain amount of current passes through the current limiter in a steady state; when a circuit fault occurs, the current transfer type current limiter acts to form a circuit potential difference and promote current transfer to other branches. Titanium diboride, as a material for the normal operation of the transfer fault current limiter access circuit, will produce current heating when it is supplied with current. This phenomenon may affect the entire circuit and the life of the current limiter. This article uses Ansys Simulation analysis to study the thermal phenomenon of titanium diboride passing current has guiding significance for the production and realization of current transfer fault current limiter.

1. Introduction

Wherever there is a temperature difference, there will be heat transfer. In nature, the transfer of heat is mainly through heat conduction, heat convection and heat radiation\cite{1}. Starting from the study of the mechanism of heat transfer is conducive to grasping the main factors affecting heat dissipation, and focusing on this factor. In this article, titanium diboride is a pressure-sensitive material with pressure-sensitive effect, and its resistance changes with pressure. Xi’an Jiaotong University proposed in 2005 that pressure-controlled materials can be used for current limiting technology\cite{2}. Utilizing the characteristic that its resistance changes with pressure, it can be used in current transfer type fault current limiter. When the fault current limiter is connected to the circuit, the long-term current will generate a large amount of Joule heat, which will cause a certain temperature rise of the material. An increase in temperature will affect the performance of the material, and accelerate the aging of the material itself and the external container, and even cause safety hazards and affect the service life. Therefore, analyzing parameters such as the thermal conductivity of the current-carrying container.
material and the commutation coefficient plays a vital role in the realization of the current limiting function of the current transfer fault current limiter.

2. Material characteristics

To study the current characteristics of materials, the characteristics of related materials must first be studied and compared. The material of the container must be a material with high dielectric strength and high expansion coefficient to meet its high voltage and high temperature use environment. Table 1 and Table 2 are the relevant properties and parameters of several alternative materials of titanium diboride and flow vessels. Titanium diboride is the most stable compound of boron and titanium\[3\]. It belongs to the semimetal compound of the hexagonal crystal system\[3\]. This graphite-like layered structure of boron atoms and the outer layer of titanium electrons determine its good conductivity\[4\], its conductivity is similar to that of pure iron and platinum. It is one of the main raw materials of the vacuum coating conductive evaporation boat\[5\].

| Nature                        | Number               |
|-------------------------------|----------------------|
| Resistivity                   | 14.4μΩ·cm            |
| Thermal conductivity          | 25W/(m·K)            |
| Melting point                 | 2980℃                |
| Antioxidant Temperature       | 1100℃                |
| Vickers hardness              | 25~34GPa             |

Table. 2 Comparison of material properties

| Parameter name   | Thermal conductivity w/(m·K) | Bending strength Mp | Impact strength Mpa·m | Dielectric strength Kv/mm | Thermal expansion coefficient ×10⁻⁶/℃ |
|------------------|-----------------------------|---------------------|-----------------------|---------------------------|--------------------------------------|
| Nylon            | 0.5                         | 980-1080            | 5.3-15.9              | 20-26                     | 14-16                                |
| Al₂O₃ ceramic    | 27.5                        | 340                 | 5.1                   | 25                        | 5.4-8.3                              |
| Si₃N₄ ceramic    | 80                          | 1000                | 7                     | 20                        | 3                                    |

3. Finite element simulation modeling analysis

With the continuous development of computer technology, computational fluid dynamics (CFD) has begun to play an important role in fluid mechanics research. It uses computer numerical calculation and image display methods to quantitatively describe the numerical solution of the flow field, thereby simulating and analyzing actual problems. Ansys is an internationally popular commercial CFD software package, which uses a variety of solution methods and multi-grid acceleration convergence technology, so it can achieve better convergence speed and solution accuracy. In this section, through Ansys finite element simulation and related pre-processing software, the heat dissipation model of the titanium diboride current container is constructed, and the influence of different materials and different commutation coefficients of the container on the heat dissipation capacity is studied by computer simulation. This provides direction for the design of better container materials and heat dissipation structures.

The simulation of the heat dissipation model of the vessel with current flows through four steps: geometry drawing, meshing, finite element solution, and post-processing of simulation results. The inner diameter, wall thickness, and height of the vessel simulation model are set to 32 mm, 4 mm, and 100 mm, respectively. The upper and lower contacts are made of aluminum alloy, and the height of titanium diboride is 36.5 mm. The geometric model of the titanium diboride cylindrical sleeve is shown in Figure 1 below. The top and bottom of the titanium diboride are metal electrodes that compress the titanium diboride. The grid division of the cylindrical current-carrying container is
shown in Figure 2, and the number of grids is above 400,000. When the initial temperature of the container and the environment is room temperature (300 K), the pressure-controlled materials in a single sleeve has a long-term current of 210 A, and the resistance of the pressure-controlled materials is set to 16 mΩ. The steady-state model mainly studies the steady-state thermal field distribution after reaching the thermal equilibrium. When the residual error is less than $1 \times 10^{-9}$, it is regarded as the calculation convergence. The transient model is mainly to observe the temperature distribution at a certain moment in the process of reaching equilibrium.

![Figure 1](image1.png)
Figure. 1  Geometric model of cylindrical sleeve for a single pressure-controlled materials

![Figure 2](image2.png)
Figure. 2  Cylindrical sleeve meshing

### 3.1 Thermal conductivity of container material.

The heat transfer between solids is mainly through heat conduction. Thermal conductivity is the main influencing parameter of heat conduction. When the convection heat transfer coefficient is 20 W/(m²·K) under the condition of natural air convection, the sleeves are made of nylon, alumina ceramics and silicon nitride ceramics respectively, that is, the thermal conductivity of the corresponding external container is respectively 0.5 W/(m·K), 27.5 W/(m·K) and 80 W/(m·K) for simulation analysis. The steady-state temperature distribution cloud chart is shown in Figure 3. Create a horizontal section at the midpoint of the upper and lower aluminum alloy contacts, and you can get the temperature. The temperature distributions of the three stable horizontal sections are shown in Figure 4.

![Figure 3](image3.png)
(1) Steady-state temperature cloud diagram when the container is a nylon
Figure 3 Contour of temperature distribution in the steady state of the sleeve when using different materials

(1) Cross-section temperature distribution when using nylon sleeve

(2) Cross-section temperature distribution when using alumina ceramic sleeve

(3) Steady-state temperature cloud diagram when the container is silicon nitride ceramic

(2) Steady-state temperature cloud diagram when the container is alumina ceramic
(3) Cross-sectional temperature distribution when using silicon nitride ceramic sleeve

Figure 4  Temperature distribution at the center section of the dynamic and static contacts in the steady state under different material sleeves

According to the simulation results of the steady-state model of the cylindrical container under three different container thermal conductivity, the temperature at the center of the titanium diboride, the temperature at the outer edge of the container bottom and the center section of the upper and lower contacts in the steady state were measured. The temperature at the edge is shown in Table 3.

Table. 3  Temperatures at different measurement points of a cylindrical vessel steady state model under different thermal conductivity

| Sleeve material | Temperature at the center of titanium diboride | Temperature at the outer edge of the bottom of the container | Temperature at the edge of the center section of the upper and lower contacts |
|-----------------|-----------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------------|
| Nylon           | 431.5 K                                       | 374.1 K                                                     | 411.0 K                                                            |
| Al₂O₃ ceramic   | 426.8 K                                       | 392.8 K                                                     | 425.3 K                                                            |
| Si₃N₄ ceramic   | 424.1 K                                       | 393.6 K                                                     | 422.4 K                                                            |

Use the cylindrical container for transient simulation, use a time step of 0.01 s, calculate 6000 time steps, a total of 60 s of heat dissipation time, the rest of the conditions are the same as the previous simulation, and the three different surface heat transfer coefficients are simulated separately. At t=60 s, the temperature at each point is obtained by the same method as shown in Table 4.

Table. 4  Temperature at different measuring points of different transient thermal conductivity models of cylindrical vessels at t = 60s

| Sleeve material | Temperature at the center of titanium diboride | Temperature at the outer edge of the bottom of the container | Temperature at the edge of the center section of the upper and lower contacts |
|-----------------|-----------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------------|
| Nylon           | 354.3 K                                       | 309.3 K                                                     | 332.9 K                                                            |
| Al₂O₃ ceramic   | 348.7 K                                       | 316.7 K                                                     | 347.0 K                                                            |
| Si₃N₄ ceramic   | 346.8 K                                       | 317.6 K                                                     | 344.7 K                                                            |
According to the temperature distribution cloud diagram of the container, it can be seen that titanium diboride is the main heat source and the highest temperature gathering place. The container sleeve and the moving and static contacts will be the main heat dissipation channels, and the temperature will be gradually transferred from the center of the material to everywhere. According to the cross-sectional temperature cloud diagram at the center of the upper and lower contacts in Figure 4, it can be found that the temperature decreases from the center to the edge, and the heat is transferred to the container sleeve through the material, and finally escapes from the sleeve to the air. The isotherm at the cross section is not a regular circle, because the contact adopts a five-finger contact finger structure, and the contact as a good heat conductor also plays an important role in the heat dissipation of the material.

According to Table 3, when the inside and outside of the container reach the energy balance (steady state), the center point temperature of the titanium diboride has an important relationship with the container material, and it decreases with the increase of the thermal conductivity of the material. The maximum temperature rise of the material is 131.5 K is reduced to 124.4 K, indicating that the increase in thermal conductivity increases the heat conduction capacity of the container, so that the heat reaches the interface between the container and the air faster, thereby reducing the accumulation of internal temperature of the material, and allowing better heat dissipation. effect. At the same time, it can be seen that the temperature of the center section edge of the nylon material container is lower than that of the silicon nitride material container. This also reflects that the thermal conductivity is too small, which will cause the temperature to be stored inside the material. Will fundamentally limit the heat dissipation capacity.

According to the results in Table 4, after 60 s of heat generation, using a silicon nitride container, the temperature at the center of the titanium diboride is lower, the temperature rise is 46.8 K, and the temperature at the edge of the center section of the upper and lower contacts is also lower.

3.2. Surface heat transfer coefficient of container material.

The external surface of the container is exposed to the external environment, and the heat transfer between it and the ambient gas or liquid is mainly carried out by thermal convection. The surface heat transfer coefficient is an important parameter that determines the process speed. Different heat dissipation methods are used, such as adding Installing a fan to form strong gas convection or adding a liquid cooling device can greatly increase the surface heat transfer coefficient.

In the steady-state model of the cylindrical container, the outer container uses silicon nitride material, that is, the thermal conductivity is 80 W/(m·K), respectively for natural convection, fan forced convection, and under liquid-cooled (water-cooled) convection conditions, that is, the surface heat transfer coefficient Simulation analysis is performed for the situations of 20 W/(m²·K), 50 W/(m²·K) and 200 W/(m²·K) respectively. The three temperature distribution cloud diagrams that reach the steady state are shown in Figure 5. The temperature distribution of the horizontal cross-section between the contacts under three different surface heat transfer coefficients is shown in Figure 6.

(1) Steady-state temperature cloud map under natural air convection
(2) Steady-state temperature cloud diagram under forced air convection

(3) Steady-state temperature cloud diagram under water-cooled natural convection

Figure 5  steady state temperature distribution with different surface heat transfer coefficients

(1) Temperature distribution of cross-section between contacts when air is convective in steady state

(2) Temperature distribution of cross-section between contacts when air is forced convection in steady state
Temperature distribution of cross-section between contacts under water-cooled natural convection in steady state

Figure 6  Temperature distribution at the center section of moving and stationary contacts under different surface heat transfer coefficients at steady state

According to the simulation results of the steady-state model of the cylindrical vessel under three different thermal conductivity of the vessel, the temperature at the center of the pressure-controlled material, the temperature at the outer edge of the bottom of the vessel and the edge of the central section of the upper and lower contacts were measured in the steady state. The temperature is shown in Table 5.

| Cooling method                        | Temperature at the center of titanium diboride | Temperature at the outer edge of the bottom of the container | Temperature at the edge of the center section of the upper and lower contacts |
|---------------------------------------|-----------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------|
| Natural air convection                | 424.1 K                                       | 393.6 K                                                     | 422.4 K                                                                  |
| Forced air convection                 | 403.1 K                                       | 374.5 K                                                     | 401.1 K                                                                  |
| Water-cooled natural convection       | 358.9 K                                       | 334.6 K                                                     | 356.0 K                                                                  |

The transient simulation was also carried out using this model. The temperature values of the above three positions of the cylindrical vessel transient model under three different thermal conductivities are shown in Table 6.

| Cooling method                        | Temperature at the center of titanium diboride | Temperature at the outer edge of the bottom of the container | Temperature at the edge of the center section of the upper and lower contacts |
|---------------------------------------|-----------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------|
| Natural air convection                | 346.8 K                                       | 317.6 K                                                     | 344.7 K                                                                  |
Forced air convection & 345.6 K & 316.9 K & 343.4 K \\
Water-cooled natural convection & 340.4 K & 313.7 K & 337.7 K \\

Combining the steady-state temperature cloud diagrams in Figures 5 and 6 and the temperature data of different measurement points in Table 5, when the inside and outside of the container reach energy balance (steady state), the temperature of the center point of titanium diboride decreases with the increase of the surface heat transfer coefficient. Under the condition of strong air convection, the temperature of the center point of the pressure-controlled materials is lowered by 21 K than under the condition of natural air convection. When water cooling is used, water cooling under natural convection alone is much better than forced air convection, and the center temperature of titanium diboride decreases by 44.2 K, and the temperature at the edge of the center section of the upper and lower contacts also decreases, indicating that the increase of the surface heat transfer coefficient can increase the surface temperature dissipation and facilitate heat dissipation. According to the results in Table 6, after 60 s of heat generation, under the condition of strong air convection, the temperature rise at the center of the pressure-controlled materials is 45.6 K, and under the condition of water-cooled natural convection, the temperature rise at the center of the pressure-controlled materials is 40.4 K. In general, strong air convection and water-cooled natural convection, that is, increasing the surface heat transfer coefficient are beneficial to the improvement of heat dissipation capacity, and it is more beneficial to the long-term operation of the material. From the simulation results, the effect of using water cooling is extremely excellent.

4. Conclusion
This paper uses Ansys simulation to study the effect of material thermal conductivity and surface heat transfer coefficient on heat dissipation capacity. It can be obtained by comparing steady-state and transient model simulations. The increase of material thermal conductivity and surface heat transfer coefficient can effectively improve the heat dissipation capacity of the pressure-controlled materials sleeve, and the internal temperature rise of the pressure-controlled materials will decrease significantly with the increase of these two parameters. In general, increasing the thermal conductivity and surface heat transfer coefficient is beneficial to the heat dissipation of the container when the internal heat source starts to generate heat until the temperature dynamic equilibrium is formed. Therefore, comparing several materials, choose a relatively good silicon nitride ceramic material to obtain better heat dissipation effect. From the perspective of simulation results, water cooling is better than air cooling, which can be used as a reference for selection in actual working conditions.

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