Research on the thermal characteristics of steady-state energization of pressure-controlled materials used in transfer fault current limiters

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Abstract. In recent years, there have been more and more researches on fault current limiters. Pressure-controlled materials with piezoresistive effect can be used in current transfer type fault current limiters. Titanium diboride powder is a material with piezoresistive effect, and its resistance is negatively correlated with pressure changes. In the current transfer type fault current limiter, the pressure-controlled materials is the main branch of the current transfer circuit. A large amount of heat will be generated in the steady-state current working state, in turn, the temperature rise in the pressure-controlled materials container continues to increase. On the one hand, excessive temperature rise will affect the resistance of the titanium diboride powder, resulting in the actual flow capacity not reaching the design standard; On the other hand, the accumulation of heat in the material will accelerate the aging of the material and the outer container, thereby reducing the actual service life and even affecting the material's insulation performance and causing safety hazards. This article focuses on the characteristics of the piezoresistive effect of titanium diboride powder, use permanent magnet-repulsive mixing mechanism to provide holding pressure for it. Study the long-term through-flow heat effect with pressure under the cylindrical parallel through-flow container. According to its heating and structural characteristics, several heat dissipation methods are proposed in combination with simulation, and the experiments are carried out. Through simulation and experimentation, The installation of vertical heat sinks and the simultaneous application of industrial fan cooling can effectively reduce the current heating effect. It has important guiding significance for its use in the field of current transfer and current limiting to achieve long-term current flow.

1. Introduction
The regular change characteristic of the resistance value of the material with the change of external pressure is called the piezoresistive effect [1]. In 1856, Kelvin, William Thomson, Baron (1824-1907) first discovered that the impedance of metal changes when a mechanical load is applied; In 1954, the piezoresistive effect of semiconductors was discovered by C.S. Smith [2]. Materials such as semiconductors and metals have been found to have a piezoresistive effect. After the discovery of the piezoresistive effect, it has been widely used in the preparation of various pressure-controlled materials. Mainly used for making various tension meters, torque meters, accelerometers, semiconductor microphones and various pressure sensors [3]. Titanium diboride, as the pressure-controlled materials
whose resistance changes with pressure sensitively, has a strong development and application prospect, its physical properties are shown in Table 1. Xi’an Transportation University proposed in 2005 that pressure-controlled materials can be used for current limiting technology [4], the application prospects of pressure-controlled materials in current limiting technology are pointed out.

Table 1. Physical properties of titanium diboride

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

When pressure-controlled materials are applied to current transfer type fault current limiters, there are two working states. The first is the low resistance state under pressure, and the rated current is passed for a long time; The second is the instantaneous flow of large current during fault current limiting action. In the process of long-term energization of pressure-controlled materials, a large amount of Joule heat will be generated due to the material's own resistance. The generation of heat will cause the temperature of the material to rise, this change may lead to changes in the resistance of the material and a series of physical and chemical changes between the contact surfaces in contact with the material. Therefore, it is necessary to take an effective way to dissipate heat from the flow device. In nature, the transfer of heat is mainly through heat conduction, heat convection and heat radiation. Among them, heat conduction and heat convection are the main heat transfer methods. Currently commonly used cooling methods mainly include natural cooling, forced air cooling, liquid cooling and heat pipe cooling, etc. [5]. Forced air cooling is to add fan equipment near the radiator to increase the speed of air exchange and exchange. It is characterized by simple structure, easy realization and low cost; However, forced air cooling is not as effective as liquid cooling due to the limitation of cooling wind speed; The microchannel liquid radiator was first proposed by Tuckerman and Pease in 1981 [6]. The liquid cooling method is a highly complex cooling method. Its realization method is to pass a certain amount of liquid around the device to be cooled, and realize the flow and heat dissipation of the liquid by means of micropump pipe circulation. During the use of liquid cooling, it is necessary to consider the structure of the equipment, the replacement of the cooling liquid, and the anti-leakage of the cooling liquid. The later maintenance costs are high and the reliability is poor [7]; Heat pipe cooling was invented by George Grover in 1963 [8], it is a cooling method that relies on the phase change of heat absorption and exotherm of the liquid in the heat pipe loop [9]. The heat transfer efficiency of heat pipe cooling is very high, and its relative thermal conductivity can reach hundreds of times that of copper. But it has the characteristics of limited heat transfer limit and complex structure. Table 2 is the performance comparison of the above several common cooling methods. Through the simulation and experimental research on the thermal characteristics of pressure-controlled materials, this paper provides a solution for the long-term heat dissipation reliability of the materials.

Table 2. Performance comparison of several common cooling methods

| Cooling method       | Cooling effect | Complexity | Reliability | Cost       |
|----------------------|----------------|------------|-------------|------------|
| Natural cooling      | Bad            | Very easy  | Very high   | Lowest     |
| Forced air cooling   | Good           | Easy       | High        | Low        |
| Liquid cooling       | Better         | Complex    | Low         | High       |
| Heat pipe cooling    | Best           | Very complicated | Low     | High       |
2. Static pressure-resistance test of titanium diboride

The titanium diboride pressure resistance test is carried out under a static press. The particle size of titanium diboride is 30 μm. The material height of titanium diboride is 36.5mm. The pressure-resistance change curve is shown in Figure 1: When the pressure applied by the press increases, the resistance follows the upper curve, and the resistance drops slowly. When the pressure of the press is released slowly, the resistance changes to the lower curve. When the pressure is reduced to below 500 N, the resistance shows a clear increasing trend.

![Figure 1 Typical pressure-resistance characteristic curve](image)

It can be seen from the upper characteristic curve that when the pressure reaches 4000 N, the change of resistance with pressure slows down significantly. Even if the pressure continues to be applied to reach 8000 N, the decrease in resistance remains basically unchanged. If you want to improve the current passing capacity. At this time, multiple single-tube containers in parallel will be a better choice, so the minimum pressure required for the single-tube test container of titanium diboride is 4000 N.

3. Finite element simulation modeling analysis

When the titanium diboride is connected to the circuit for actual operation, Joule heat will be generated inside due to the passage of a large current, which becomes the main reason for the increase in the internal temperature of the pressure-controlled materials container. The pressure-controlled materials is the main source of heat, and its heat is gradually transferred to the lower temperature direction such as the container shell by heat conduction, and finally the heat energy is released into the air by the shell. In this process, heat conduction and convection heat transfer between the container and the air surface play a major role. Therefore, in this section, through Ansys finite element simulation and related pre- and post-processing software, the heat dissipation model of the pressure-controlled materials container is constructed, and the influence of different heat dissipation methods and different auxiliary heat dissipation equipment on the heat dissipation capacity is studied through computer simulation methods, in order to better choose The heat dissipation material and the heat dissipation structure provide direction.

The model simulation of the current and heat dissipation of the container passes through four steps: geometry drawing, meshing, finite element solution, and post-processing of simulation results. Regarding the domain setting, the internal titanium diboride solid area is used as the heat source in the model. Source Terms need to be added. In this article, it is assumed that the internal heating of the titanium diboride is uniform, and the heat generation power is calculated based on the resistance value of the titanium diboride . The contact and sleeve part are provided with no heat source; Regarding the surface setting, at the interface of two solids, the couple setting is used to couple the temperature field. Outside the sleeve, use it as the interface for convective heat transfer with air to set the surface convective heat transfer coefficient. Adjust the control parameters and convergence factors. After
initialization, set the initial temperature of the area to room temperature (300 K), then the model setting is completed. This article will mainly analyze from the perspective of the steady-state model. The steady-state model mainly studies the steady-state thermal field distribution after the thermal equilibrium is reached. It can be compared with the actual long-term flow situation. We believe that the calculation converges when the residual is less than $1 \times 10^{-9}$. The overall model of the parallel structure of pressure-controlled materials and the geometric model of a single cylindrical sleeve of pressure-controlled materials are shown in Figures 2 and 3.

Figure 2. Pressure controlled material parallel structure

Figure 3. Geometric model of cylindrical sleeve for a single pressure-controlled material

3.1. The influence of industrial fans on heat dissipation capacity

In the simulation, 630 A current is passed for a long time, Three groups of pressure control materials are used in parallel, The sleeve material is silicon nitride with a density of 3.44 g/cm$^3$, Specific heat capacity 0.71 J/(g·K), Thermal conductivity 80 W/(m·K); In practice, the contact is subjected to a pressure of more than 4000 N due to the closing of the permanent magnet-repulsive hybrid mechanism, so the contact material is based on actual use of aluminum alloy. In the simulation, the long-term current and heat of the contact material are considered at the same time; In the case of natural air convection, the surface heat transfer coefficient is 20 W/(m$^2$·K). The starting temperature of the environment is 300 K.

After performing steady-state simulation of the temperature field under natural convection conditions on the original model in Figure 2, the temperature cloud map distribution in Figure 4 is obtained. The figure shows the temperature distribution at the vertical section of the center of the three pressure-controlled materials sleeves. It can be found that the highest temperature rise in the center reaches 184.30 K and reaches 211.30 °C during long-term flow. The temperature at the edge of the pressure-controlled materials sleeve reached 206.20 °C. Long-term high temperature may cause irreversible damage to the pressure-controlled materials and the properties of the sleeve material. Therefore, we plan to use an external fan to enhance gas convection to enhance heat dissipation. Use the surface heat transfer coefficient to be 50 W/(m$^2$·K) for steady state simulation of the original device, and the other conditions remain unchanged to obtain the temperature cloud distribution as shown in Figure 5. It can be found that the maximum temperature rise of the inner core temperature of the pressure-controlled materials is 96.60 K, and the temperature drop rate reaches 47.5%.
3.2. The influence of the vertical heat sink on the heat dissipation capacity

In order to further enhance the heat dissipation capacity of the original device, reduce the temperature rise inside the material caused by long-term current flow, reduce the oxidation of the material and the sleeve container, and maintain the stability of the performance and structure. The four device heat dissipation measures in this article are: the upper end cover is equipped with 30 mm aluminum heat sink, the lower part is equipped with 30 mm aluminum heat sink, the lower part is equipped with 60 mm aluminum heat sink, and the lower part is equipped with 60 mm copper heat sink. In the case of strong convection, the four kinds of heat dissipation devices are simulated and analyzed, and the vertical section is taken at the center of the pressure-controlled materials, and the temperature cloud distribution as shown in Figures 6-9 are obtained. The temperature rise and temperature at the recording center are shown in Table 2.

Figure 4. Temperature distribution at the central section of the original pressure control material under natural convection

Figure 5. Temperature distribution at the central section of the original pressure control material under strong convection

Figure 6. Temperature distribution at the central section of pressure control material with aluminum heat sink (30mm long) on the upper end cover
Figure 7. Temperature distribution at the central section of pressure control material with aluminum heat sink (30mm long) at the lower part

Figure 8. Temperature distribution at the central section of pressure control material with aluminum heat sink (60 mm long) at the lower part

Figure 9. Temperature distribution at the central section of the pressure control material with a copper heat sink (60 mm long) at the lower part

Table 3. Steady state of the temperature of the pressure-controlled material under different devices

| Device structure                                      | Temperature rise at the center of the material | Temperature at the center of the pressure-controlled material | Temperature at the center edge of the sleeve |
|-------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|---------------------------------------------|
| The original device adds a fan                        | 96.60 K                                       | 123.60°C                                                   | 115.00°C                                    |
| The upper part of the original device with 30mm Aluminum heat sink | 87.00 K                                       | 114.00°C                                                   | 106.50°C                                    |
| The lower part of the original device with 30mm Aluminum heat sink | 73.50 K                                       | 100.50°C                                                   | 90.90°C                                     |
| The lower part of the original device with 60mm Aluminum heat sink (no fan) | 113.60 K                                      | 140.60°C                                                   | 132.50°C                                    |
| The lower part of the original device with 60mm Aluminum heat sink (with fan) | 65.80 K                                       | 92.80°C                                                   | 84.20°C                                     |
| The lower part of the original device with 60mm Copper heat sink (with fan) | 63.70 K                                       | 90.70°C                                                   | 82.60°C                                     |

It can be seen from the steady-state temperature cloud diagram in Figures 3.5-3.8 that heat is transmitted outward through the contacts and the upper and lower fixed end caps. When a 30 mm
aluminum heat sink is installed on the upper end cover, the temperature rise at the center of the pressure-controlled materials can be reduced by about 4.66 K, which is much smaller than the 18.16 K when a 30 mm aluminum heat sink is installed at the bottom. After observing the temperature Figures 3.5 and 3.6, it can be found that when the upper end cover is equipped with a heat sink, the temperature rise at the lowest temperature of the heat sink is only 17.1 K, which is lower than the temperature rise of 28.4 K when the heat sink is installed at the end. This is because the installation of the heat sink on the upper end cover is farther away from the heat source, so that the heat dissipation efficiency is greatly reduced after the heat is transferred to the heat sink. Therefore, the installation of the heat sink below is a better choice for this mechanism. Furthermore, when a 60 mm aluminum heat sink is installed in the lower part, the temperature rise of the center of the pressure-controlled materials is lower by 7.7 K than when a 30 mm aluminum heat sink is installed in the lower part, which indicates that increasing the height of the heat sink can effectively improve the heat dissipation capacity. Taking into account the space of the actual device, the use of a 60 mm heat sink can make full use of the distance between the device and the lower overtravel spring. Due to the limitation of the thermal conductivity of the contact material and the overall structure of the heat sink, the heat dissipation effect of adding a 60 mm copper heat sink to the lower part is only 2.1 K lower than that of a 60 mm aluminum heat sink, so the use of a copper heat sink is of little significance. Taking into account the actual cost, weight and other comprehensive factors, the use of aluminum heat sinks can basically meet the demand.

In summary, choosing to install a 60 mm aluminum heat sink at the lower part of the overall device, and installing a fan on the outside to achieve strong convection can achieve a better level of heat dissipation. In a room temperature environment, the center temperature of the pressure-controlled materials is approximately 90.8 ℃ when the current through the current reaches a steady state for a long time. The heat dissipation capacity of the two methods used at the same time is 28.21% higher than that of the original device under strong convection and 64.3% higher than that of the original device under natural convection.

4. Test verification

As shown in Figure 10 a 60 mm aluminum heat sink is made. The external current excitation source of the pressure-controlled materials adopts a large current generator, and its output current is adjusted to 630 A. It is connected to the pressure-controlled materials in the closed state through a flat copper bar. Stabilize the flow for 1 minute, measure the temperature distribution with an infrared thermal imager, and use a high-power industrial fan to simulate a surface heat transfer coefficient of 50 W/(m²·K). In order to get closer to the simulation, thermal grease was applied to the contact surface of the heat sink and the device in the experiment to increase the contact and reduce the heat conduction error of the device due to the processing accuracy.

![Thermal Imager](image1)
![Industrial Fan](image2)
![Aluminum Heat Sink](image3)

**Figure 10.** Temperature rise and heat dissipation test equipment

When the whole device is not equipped with heat sink, the temperature rise is higher, as shown in Figure 11. In the figure, the cross star is marked as the highest temperature of the thermal imager, its value is displayed in the upper right corner, the green box is positioned at the current center position of the handheld device, and its temperature is displayed in the upper left corner.
It can be seen from the figure that the highest temperature point is concentrated in the pressure-controlled materials itself and the silicon nitride container closely connected to it. The lower contact and the disk surface have higher temperatures, which is consistent with the finite element calculation results. The upper contact is closer to the material. The temperature is higher, and the upper end face is far away, so the temperature rise is not high, and the maximum temperature of the device reaches 235.1 ℃. A fan is applied outside the device to simulate the increase of the air circulation coefficient. The result is shown in Figure 12.

The fan enhances the convection heat dissipation, so that the maximum temperature is reduced to 157.3 ℃, the temperature rise of its bottom plate is still relatively serious, and the overall temperature is still high. A heat sink is installed at the bottom of the bottom panel, and the heat dissipation effect without industrial fans is shown in Figure 13.

The installation of a heat sink effectively reduces the overall temperature of the device. As can be seen from the figure, the heat sink conducts the heat transferred from the bottom plate surface, increases the heat dissipation area, and reduces the maximum temperature to 122.2 ℃. On this basis, an external fan is applied for air blowing. The heat dissipation effect is shown in Figure 14.
Figure 14. The temperature distribution with fan and heat sink

The application of heat sinks and fans not only increases the overall heat dissipation area of the device, but also increases the heat convection efficiency on the surface of the device, and finally reduces the temperature to 93.4 °C, which is 159.7 °C lower than the original 235.1 °C, which effectively improves safety and service life of steady-state current.

When the heat sink and the fan are applied at the same time, the final measured temperature on the surface of the current-carrying container is close to 93.4 °C, which is different from the simulation corresponding to 84.2 °C. The main reason for the difference is that on the one hand, although the upper surface of the additional heat sink and the lower surface of the container are made of the same aluminum material, due to the limitation of processing accuracy, there is a small air gap on the surface. Although the thermal grease is used, the heat is transferred by the thermal grease. The coefficient is lower than that of aluminum material, so there are differences; On the other hand, there are also certain differences in using industrial fans to simulate the increase in the circulation coefficient of air.

5. Conclusion
Based on the theoretical analysis of the heat dissipation mechanism, a heat dissipation model of the pressure-controlled materials container with the same test structure was constructed. Through the steady-state simulation analysis of the model, it can be obtained that the increase of the heat transfer coefficient of the material surface can effectively improve the heat dissipation capacity of the pressure-controlled materials sleeve. Through the heat dissipation simulation of the entire device of the pressure-controlled materials container, it is found that the method of adding a heat sink to the upper end of the device only brings a temperature drop of 4.66 K to the entire device, and the effect is not obvious. With the addition of 60 mm aluminum heat sink and 50 W/(m²·K) forced air cooling at the lower part, the center temperature rise of the pressure-controlled materials was reduced by 70.7 K and 87.7 K, respectively. The effect is obvious and easy to achieve.

The comparison of simulation and test results shows that the addition of vertical heat sink and air cooling is effective. When the two heat dissipation methods are used at the same time, the detectable temperature on the surface of the container drops to 93.40 °C, and the temperature drops significantly. This program provides a solution for the application of pressure-controlled materials in the field of current transfer and current limiting.

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