Optimization Design of Heater for GIS Circuit Breaker in Alpine Region
Based on Thermal and Flow Field Coupling Simulation

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Abstract. Gas Insulated System (GIS) circuit breaker in the alpine region has the risk of cryogenic liquefaction of SF₆ gas and seriously affects the safe and reliable operation of the electrical equipment. Install the heater can be achieved on the internal gas heating, however, due to the hot gas flow and the complexity of the internal structure of the circuit breaker, it is difficult to accurately predict the overall temperature distribution after heating and ensure the reasonableness of the heater parameter design. In this paper, a temperature distribution model based on the finite volume method of thermal and flow field is established. The temperature distribution law of GIS circuit breaker with different heating power is mastered. Based on this model, the power and structure of GIS circuit breaker heater are optimized reasonably, the power consumption is reduced, gas liquefaction is avoided, and the operation reliability of GIS equipment in alpine region is improved.

Introduction

Outdoor temperatures in alpine regions can reach -40°C and even reach -50°C in extreme conditions. For SF₆ circuit breakers rated at 0.7MPa (absolute pressure) at 20°C, the corresponding gas density is 45kg/m³ and liquefaction begins to occur as the gas temperature decreases gradually to -25°C. If the temperature continues to decrease to -50°C, SF₆ gas density dropped to 20kg/m³, then the gas density is only 44% of the original, significantly reducing the circuit breaker extinguish arc performance and insulation properties [1]. In order to ensure the reliable operation of GIS circuit breaker, the heater is often used to heat the gas. However, the design parameters of the heater often depend on the empirical formula or the low-temperature test due to the differences of different circuit breakers and the complexity of the internal structure [2]. The actual gas flow inside the GIS circuit breaker and the temperature difference away from the heater nearby are difficult to obtain by empirical formula calculation and low-temperature test. Researchers have used the method of coupling electromagnetic field, airflow field and thermal field to analyze the temperature characteristics of GIS busbar when current carrying [3, 4]. The contribution of this paper is to establish the temperature distribution model of the circuit breaker when the heater is operating in the low temperature environment. The model uses the coupling between the flow field and the thermal field to obtain the difference of the overall temperature distribution of the circuit breaker containing the gas. The model provides an important theoretical support for the design of low-temperature circuit breaker heating device.

Simulation Model and Test Verification

Mathematical Model of Thermal and Flow Field

First, establish a set of heat transfer equations that contain conduction, convection, and radiation. In the Cartesian coordinate system, the three-dimensional steady-state heat conduction differential equation is shown in Equation (1)
\[
\frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) = -q_v
\]

where: \( \lambda \) is the thermal conductivity; \( T \) is the absolute temperature; \( q_v \) is the heat generated by the unit volume and time.

The steady-state natural convection of the internal gas of the GIS circuit breaker can be solved by the equations (2) - (5) [5].

Continuity equation:
\[
\nabla \cdot (\rho V) = 0
\]

Momentum conservation equation:
\[
\nabla \cdot (\rho V \otimes V) = \nabla \cdot (-p I + \mu (\nabla V + (\nabla V)^T)) + S
\]

Energy conservation equation:
\[
\nabla \cdot (\rho CTV) = \nabla \cdot (\lambda \nabla T) + Q_v
\]

Ideal gas equation:
\[
\rho = m p / (R_0 T)
\]

where, \( \rho \) is the gas density; \( C \) is the specific heat capacity; \( V \) is the gas velocity; \( T \) is the absolute temperature; \( \lambda \) is the gas thermal conductivity; \( p \) is the gas pressure; \( Q_v \) is volume heat source; \( \mu \) is coefficient of kinetic viscosity; \( m \) is the molar mass of the gas; \( R_0 \) is the universal gas constant.

Due to the relative rule of the shape of the GIS enclosure, the heat transfer coefficient of the enclosure can be calculated by empirical formula (8) and (9) based on the similarity principle.

\[
h_{cov} = N_u \frac{\lambda}{l}
\]

\[
N_u = C (G \cdot P_r)^n
\]

where, \( h_{cov} \) is the surface heat transfer coefficient; \( l \) is the structural characteristics of the length; \( N_u \) is the Nusselt number; \( G \) is the Gravision number; \( P_r \) is the Prandtl number; circuit breaker external convection is a large space natural convection system, according to the reference [6], \( n \) is 1/3; \( C \) is 0.11.

There are two kinds of radiation heat transfer modes in the GIS circuit breaker model, namely, the radiation inside the enclosure and the large space radiation with the outside air of the enclosure. See equation (10), (11) and (12).

The radiation energy \( Q_i \) between different temperature parts is:

\[
Q_i = \sigma \epsilon_i F_{ij} A_i (T_i^4 - T_j^4)
\]

\[
F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} dA_i dA_j
\]

where, \( \sigma \) is the Stefan-Boltzmann constant; \( \epsilon_i \) is the element surface emissivity; \( F_{ij} \) is the radiation angle coefficient; \( A_i, A_j \) is the area of element \( i \) and \( j \); \( T_i, T_j \) is the absolute temperature of element \( i \) and \( j \); \( \theta_i, \theta_j \) is the angle between the normal line of the plane \( A_i \) and \( A_j \); \( r \) is the distance between element \( i \) and \( j \).

The radiation energy transfers between the outside of the enclosure and the air is:

\[365\]
\[ Q_t = \sigma \varepsilon_t A_t \left( T_i^4 - T_\infty^4 \right) \]  

(12)

where, \( \varepsilon_t \) is the outer surface emissivity of the enclosure; \( A_t \) is the outer surface area of the enclosure; \( T_i \) is the enclosure temperature; \( T_\infty \) is the ambient temperature. Can be simplified as radiation heat transfer coefficient is as follows:

\[ h_{rad} = \frac{Q_t}{A_t (T_i - T_\infty)} \]  

(13)

Therefore, the integrated heat transfer coefficient of the outer surface of the enclosure is:

\[ h = h_{cov} + h_{rad} \]  

(14)

**Test Verification**

In order to verify the accuracy of the mathematical model, select a section of GIS busbar as the research object to measure and simulate the temperature distribution of the current-carrying test, and obtain the calculation error. The GIS busbar used for testing is shown in Figure 1(a). Busbar shell outer diameter (OD) 332mm, thickness 6mm, conductor OD 90mm, thickness 15mm, SF6 pressure 0.43MPa (absolute pressure), current 4400A, ambient temperature 26.23°C. The temperature measuring point is arranged on the busbar's contactor, conductor and shell.

![Test model](image1)

(a) Test model

![Simulation model](image2)

(b) Simulation model

Figure 1. Test and simulation model of GIS busbar.

Simplified solution domain shown in Figure 1(b), in order to be closer to the experimental model, the simulation model includes the connectors and insulators. And the spring contact finger has been reasonably simplified. The temperature distribution calculation result is shown in Figure 2(a), it can be seen that the upper part of the GIS is higher than the lower part. The highest temperature rise of 56°C, appears in the middle of the conductor. The lowest temperature rises of 12.3°C, appears in the lower part of the enclosure flange. Figure 2(b) shows the velocity distribution of three typical sections, the gas velocity along the conductor surface is large, and the maximum value is 0.34 m/s. Meanwhile it can be found that the velocity in the middle section is the smallest and the heat dissipation efficiency is the lowest, so the highest temperature rise appears in the middle of the conductor.

![Distribution of temperature](image3)

(a) Distribution of temperature

![Velocity distribution at 3 sections](image4)

(b) Velocity distribution at 3 sections

Figure 2. Simulation results.

Table 1 shows the test and simulation results. It can be seen that the relative error of not more than 5%. The accuracy of the simulation model is verified.
Table 1. Comparison of Test and Simulation of Temperature Rise.

<table>
<thead>
<tr>
<th>Test location</th>
<th>Test value/K</th>
<th>Simulation value/K</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer surface of contactor seat</td>
<td>49.1</td>
<td>51.5</td>
<td>4.6%</td>
</tr>
<tr>
<td>Spring contact finger</td>
<td>51.3</td>
<td>52.2</td>
<td>1.7%</td>
</tr>
<tr>
<td>Middle of conductor</td>
<td>54.4</td>
<td>55.2</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

Simulation Model for GIS Circuit Breaker

Heater Structure and Layout

Unlike GIS busbar, the structure of GIS circuit breaker heater is limited by the external support and the mechanism box, and can only be installed in the specified position. As shown in Figure 3, the heater is wrapped by the insulation layer and the stainless steel layer in the circuit breaker outer shell, thermal conductivity of thermal insulation layer is only 0.04W/(m·K), the circuit breaker shell thermal conductivity of 120 W/(m·K). The heater to heat the shell, and through its conduction to the internal gas and other parts of the shell, but due to exposed in cold air, the outer surface without insulation heat dissipation faster.

![Figure 3. GIS circuit breaker heater installation diagram and heater cross section schematic.](image)

Model Simplification and Meshing

The complicated structure inside the GIS circuit breaker affects the gas flow, but it needs to be simplified for the small air gap and the area where the gas does not flow. The simplified model retains as far as possible the external shape that affects the gas flow, as shown in Figure 4 (a), and the grid was subdivided, as shown in Figure 4 (b).

![Figure 4. Simplified GIS circuit breaker internal structure and meshing results.](image)

Simulation Results

The GIS circuit breaker is required to work in the environment of -40°C, the pressure of 0.7MPa, calculated according to empirical formula the total heater power should be 17.6kW, according to the average power arranged in the heater 1 and 2, calculate the temperature distribution shown in Figure 5. It can be seen that the minimum temperature appears at the circuit breaker support because the heat here is easily dissipated through the support, the maximum temperature appears in the upper part of heater because of the hot air flow. From the calculation results, it can be found that the maximum temperature difference after heating reaches 22°C, with a strong non-uniformity, and the minimum
temperature reaches 20°C, while the SF₆ gas liquefaction temperature at this pressure is -20°C, far higher above the liquefaction temperature, waste is created and the temperature difference is increased.

![Temperature distribution](image)

**Optimization Design**

According to the characteristics of gas flow, the heater around the shell is divided into three parts, each part of 2π/3, and in the upper part of the installation of insulation instead of heater. For the heater 1 and 2, divide them into third gear and place the heaters of larger heating power close to the lower temperature parts of the support and the mechanism outlet. The power is reduced to the original 1/2, 9kW, calculate the temperature and flow distribution shown in Figure 6. It can be seen that the minimum temperature at this time is -6°C, the non-liquefaction conditions are still met, and the temperature nonuniformity is improved. The temperature difference is decreased from 22 °C. to 14 °C. Further design can be self-control temperature heaters, according to the ambient temperature to adjust the power put into operation, so as to achieve optimal control.

![Temperature distribution and velocity vector](image)

**Summary**

Through the simulation of thermal and flow field, the temperature distribution of GIS circuit breaker after heating is obtained. This method can display the difference of temperature in different regions after heating, and optimize the heating power and heater arrangement. With the method, the empirical formula to calculate the heater power parameters reduced by 50% and the temperature difference is reduced by 30%. The method provides an important theoretical support for the design of GIS circuit breaker heating device in the alpine region.

**References**


