Temperature Rise Analysis of Vacuum Circuit Breaker (VCB) in Consideration of Thermal Resistance

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Abstract

Our company is developing a vacuum circuit breaker (VCB) that uses dry air (GWP100 = 0) as the insulating gas, instead of sulfur hexafluoride (SF_6), which has a global warming potential (GWP100) of 23,900 times.

Because dry air has a lower thermal conductivity than SF_6, the temperature rise when current is passed through it becomes more severe. If the temperature rise value does not meet the specifications, the conductor diameter and product volume will need to be redesigned, which could affect the development schedule.

Studying the accuracy of temperature rise analysis at the initial design stage is important, and improving analysis accuracy is essential. We suspected that the thermal resistance characteristics of the vacuum interrupter electrodes and conductor contact points were insufficient to improve analysis accuracy. Therefore, we measured the thermal resistance characteristics of the main components constituting the circuit breaker and performed thermal fluid analysis using these measured values.

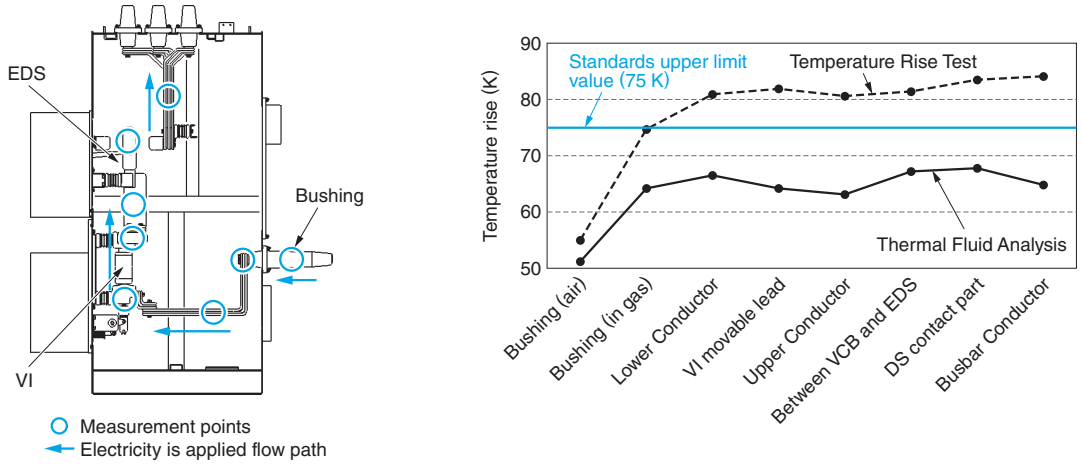
1 Preface

Our company is working on developing vacuum circuit breakers (VCBs) that use dry air as the insulating gas, instead of sulfur hexafluoride (SF_6), which has a global warming potential (GWP100) 23,900 times that of carbon dioxide. The insulating performance of dry air is approximately 1/3 that of SF_6. To obtain equivalent performance, it is necessary to increase the gas pressure or enlarge the external dimensions. Furthermore, because dry air has a lower thermal conductivity than SF_6, the temperature rise when the same amount of current is passed through it will be higher. While these technical challenges exist, we also want to minimize the external dimensions of the equipment we develop, considering the replacement of equipment already in operation. However, if the analysis accuracy at the initial design stage is low due to the desire to reduce the external dimensions, and the temperature rise when current is passed through it does not meet the standard values, redesign such as increasing the conductor diameter or equipment volume will be necessary. If redesign is required, it will not only affect the development schedule but also potentially impact other product development plans.

Temperature rise analysis is crucial during the initial design phase, and improving analysis accuracy is essential. This paper introduces our efforts to improve the accuracy of thermal fluid analysis.

2 Issues in Thermal Fluid Analysis

Fig. 1 shows a comparison of the temperature rise test and thermal fluid analysis results. Comparing the temperature rise test results and the thermal fluid analysis results, there was a tendency for the temperature rise to be larger in the VI periphery and conductor contact areas. Considering that there were challenges in setting the thermal resistance characteristics of the components constituting the VI periphery shown in Fig. 2 and the contacts shown in Fig. 3, we focused on these components and measured their thermal resistance.



(a) Developer internal structure

(b) Comparison of test and analysis results

Fig. 1 **Comparison of Temperature Rise Test and Thermal Fluid Analysis Results**

When comparing the Temperature Rise Test and analysis results, there was a tendency for the difference between the VI periphery and the Conductor contact part to be large.

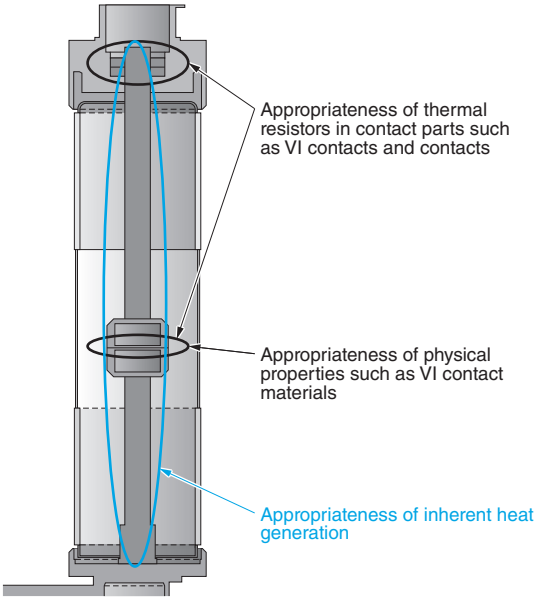
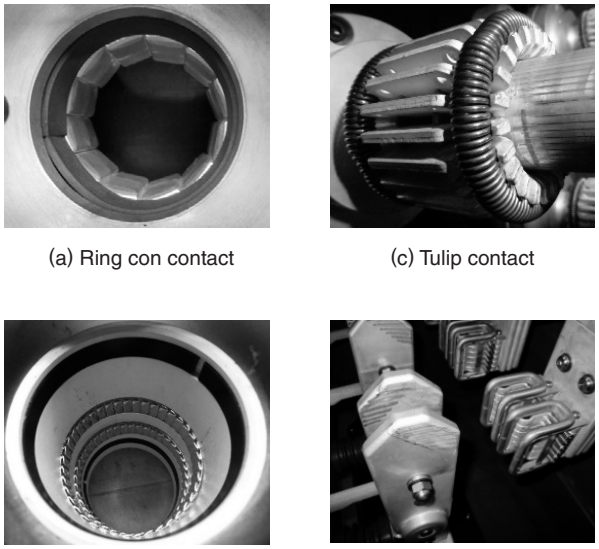


Fig. 2 **VI Peripheral Configuration**

Characteristics were obtained by focusing on places where parts come into contact with each other.



(a) Ring con contact

(c) Tulip contact

(b) Multi-contact

(d) Finger contact

Fig. 3 **Contact**

Typical contacts used in Conductor contacts are shown. Contact is the part where Conductor are pressed against each other with the force of a Springs to conduct Electricity is applied.

3 Acquisition of Thermal Resistance Characteristics of Major Components

3.1 Thermal Conductivity Measurement Device

Measuring the thermal resistance of components such as VI electrodes and silver-plated conductors in their original shapes is difficult. Therefore, we used a device that can cut out cylindrical test pieces from the components and measure their thermal resistance using the temperature gradient method.

3.2 Temperature Gradient Method

Fig. 4 shows a schematic of the temperature gradient method. The measurement principle is as follows: The sample is placed between jigs, and heat is applied from the top of the jigs to create a temperature gradient in the thickness direction. Thus, the thermal resistance can be calculated using the following formula:

Thermal Resistance
= Temperature Difference
÷ Amount of Heat Passing Through the Sample

In this measurement, contact thermal resistance was obtained by changing the contact pressure.

3.3 Measurement of Contact Thermal Resistance

The thermal resistance of the contact was measured under the same conditions as in product use. Fig. 5 shows a schematic of the measurement. A resistor, which is a heat-generating element, was placed in the center, and the voltage was adjusted using a DC stabilized power supply and power meter so that the amount of heat generated in the resistor was an arbitrary value.

To measure the thermal resistance of the contact, it is important to apply heat transfer concentrically to the resistor. If heat is dissipated in the upward or downward direction, the thermal resistance of the contact cannot be measured accurately. Therefore, the thermal conductivity of the upper and lower insulation materials was made sufficiently low compared to the side insulation material to prevent heat transfer between the upper and lower parts. Table 1 shows the characteristics of the insulation materials used. Furthermore, by measuring the thermal resistance in a constant temperature bath, changes in ambient temperature were avoided.

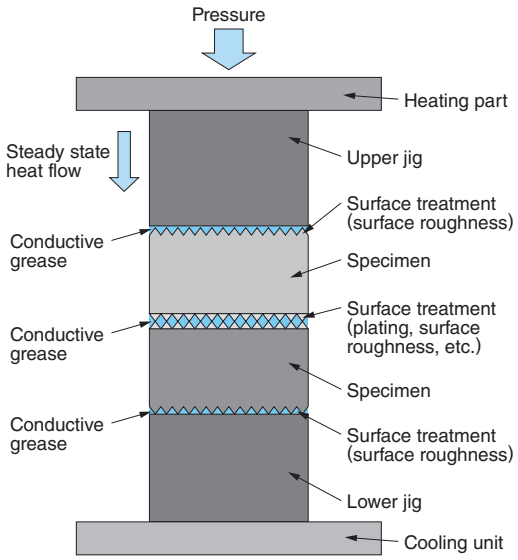


Fig. 4 Overview of the Temperature Gradient Method

By heating the upper jig, a thermal gradient is generated to obtain thermal resistors.

3.4 Method for Calculating Contact Thermal Resistance

Fig. 6 shows the method for calculating thermal resistance. If all heat moves concentrically, the

Table 1 Characteristic of the Insulation Material Used in the Measurement

The characteristics of the three types of insulation materials used are shown.

Insulation	Specifications location	Transfers internal heat [W/(m·K)]
Insulation 1	Top and bottom insulation	0.046
Insulation 2	Side insulation	0.8～1.0
Insulation 3	Side insulation	0.24

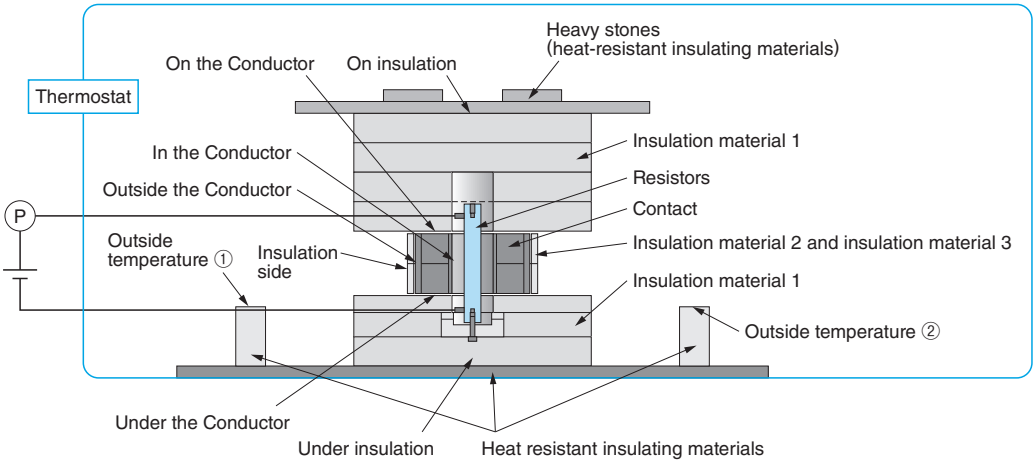


Fig. 5 Measurement Summary

By using an insulating material, we devised ways to improve measurement accuracy.

amount of heat Q passing through the sample can be expressed as follows.

$$Q=\frac{T_1-T_2}{\frac{1}{2\pi L}\left(\frac{1}{\kappa_1}\ln\frac{r_2}{r_1}+\frac{1}{\kappa_2}\ln\frac{r_3}{r_2}+\frac{1}{\kappa_3}\ln\frac{r_4}{r_3}\right)+\frac{1}{nN}(R_{in}+R_{out})} \quad \cdots\cdots (1)$$

$$R=R_{Con}+R_{Ctt} \quad \cdots\cdots (2)$$

$$R_{Con}=\frac{1}{2\pi L}\left(\frac{1}{\kappa_1}\ln\frac{r_2}{r_1}+\frac{1}{\kappa_2}\ln\frac{r_3}{r_2}+\frac{1}{\kappa_3}\ln\frac{r_4}{r_3}\right) \quad \cdots\cdots (3)$$

$$R_{Ctt}=\frac{1}{nN}(R_{in}+R_{out}) \quad \cdots\cdots (4)$$

T : Temperature
L : Conductor height
κ : Thermal conductivity
r : Conductor diameter
n : Number of contact pieces
N : Number of contact links
R : Thermal resistance
R_{in} : Thermal resistance per piece on the inside of the contact piece
R_{out} : Thermal resistance per piece on the outside of the contact piece
R_{Con}: Thermal resistance of the component
R_{Ctt} : Thermal resistance of the contact part

If R_{Con} is sufficiently smaller than R_{Ctt} ($R_{Con} \ll R_{Ctt}$), $R \cong R_{Ctt}$, and R_{Ctt} can be calculated from the following equation.

$$R_{Ctt} \cong \frac{T_1-T_1}{Q} \quad \cdots\cdots (5)$$

3.5 Measurement Results

As an example of the measurement results of the measured thermal resistance, Fig. 7 shows the contact thermal resistance of sample A.

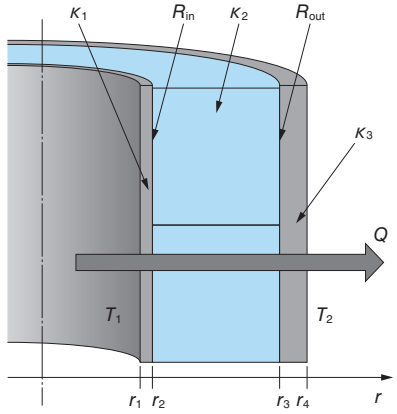


Fig. 6 How to Calculate Thermal Resistors

Thermal resistors was calculated as a model in which heat moves in concentric circles.

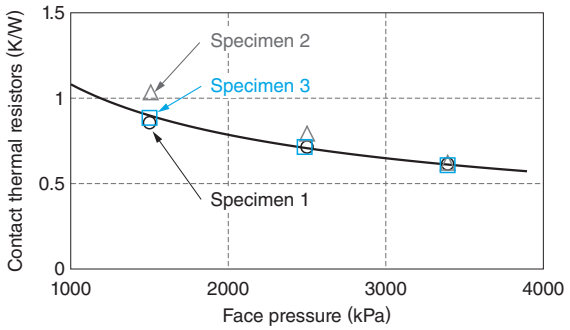


Fig. 7 Sample A Contact Thermal Resistors Curve

The contact thermal resistors curve in sample A is shown. An approximate curve is obtained from the acquired values.

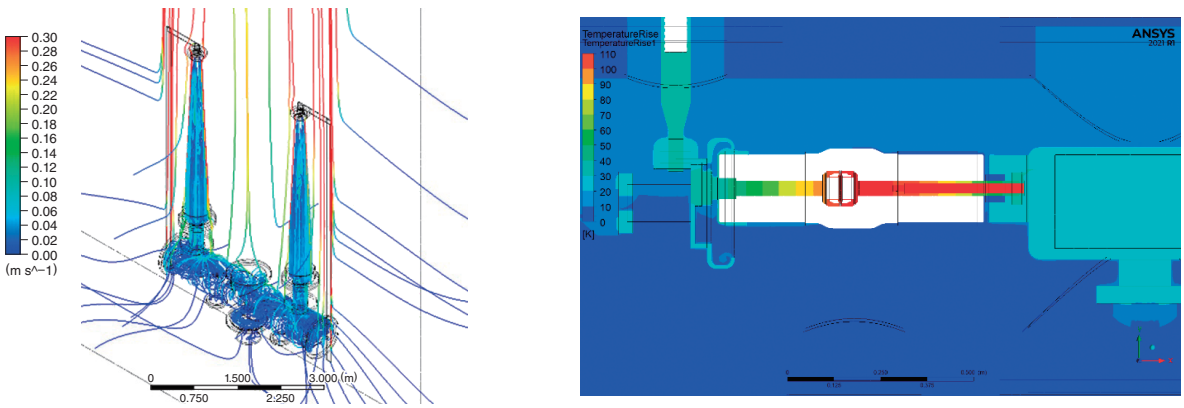


Fig. 8 Thermal Fluid Analysis Results

Thermal fluid analysis results are shown using 240 kV tank type VCB unit as an example.

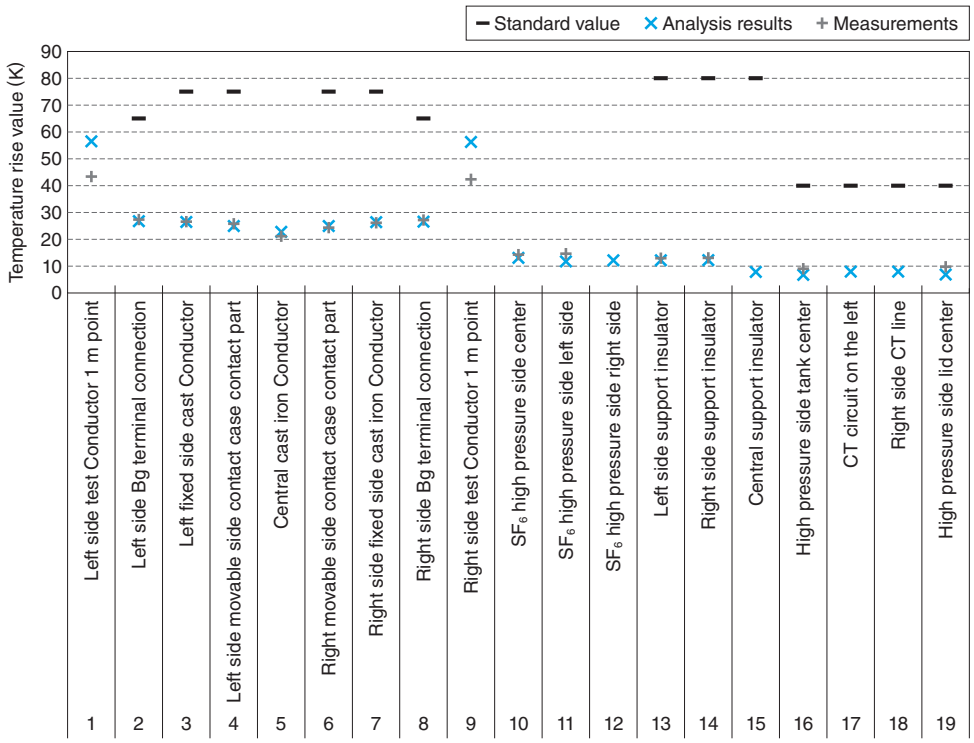


Fig. 9 **Thermal Fluid Analysis Temperature Rise Result**

The analysis result was an accuracy of ±1 K at the thermocouple measurement point.

4 Thermal Fluid Analysis

Using the measured thermal resistance characteristics, a thermal fluid analysis was performed. The model analyzed was a 240 kV tank-type VCB. Fig. 8 shows the thermal fluid analysis results, and Fig. 9 shows the temperature rise results. An improved accuracy result was obtained, with the thermocouple measurement point within ±1 K.

5 Postscript

To improve the accuracy of thermal fluid analysis of vacuum circuit breakers, contact thermal resistance was measured, and an analysis was performed using the measured value.

This time, a single circuit breaker was introduced, but in the future, we aim to apply this to switchgear products such as cubicle-type gas-insulated switchgears (C-GIS), and to streamline product development.

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