[**Materials**]

Development of High Thermal Conducting Insulation Layer for Stator Coil

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Abstract

Because hydro power is a stable and CO2-free clean renewable energy resource, the market demands are increasing. The demands are for the renovation of aged hydropower systems and re-powering them with a higher capacity when the generator is replaced.

Such demand is particularly strong for small and medium capacity hydropower systems since these systems can be qualified as a power source for the Feed-in Tariff (FIT) system in Japan. We have been working on the development of stator coil insulations for generators to realize a higher power output, compact design, and higher efficiency.

Our coil manufacturing technology is based on our thermal analysis technology and evaluation of high thermal conducting materials. We also established an elementary technology for high thermal conducting coil insulation. It features about twice the rate of thermal conductivity from conventional coil insulation and substantially reduced thermal resistance.

1 Preface

We supplied many hydropower systems during the high economic growth period in Japan (1955-1973) and these systems have been operating for more than 50 years. Most of them are approaching the end of their product life and reaching time for renovation. There are increasing market demands for renovation and re-powering for higher capacities when the generator is replaced.

Generally, by increasing the current density of the coil housed in the stator of the generator, and when the output density is increased, it leads to an increase in loss heat generation. Efficiently cooling the stator is, therefore, an issue. **Fig. 1** shows a schematic diagram of the coil cross-section in a stator slot. Stator coils are covered with insulation layers consisting of interlayer insulation, the main insulation, and corona protection layer. The cooling system for the Company's water turbine generator is air cooled. The heat generated by the coil conductor is cooled (1) by heat dissipation (diffusion) of the cooling air passing through the stator duct through the insulating layer and (2) by heat transfer to the stator core.

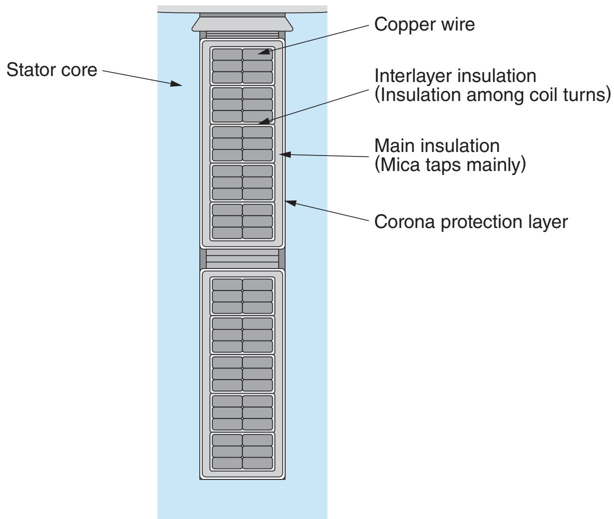


Fig. 1 **Schematic Diagram of Coil Cross-Section in a Stator Slot**

A cross-section of coils inserted in a stator core slot is shown. The coil insulation is mainly composed of interlayer insulation, main insulation, and corona protection layer.

Since the thermal conductivity of the insulation layer is not more than 1/1000 of the stator core, such a physical condition, however, inhibits heat transfer to the coil surface or the stator core. For this reason, if the thermal conductivity of the insulation layer is properly improved, the generated heat in the coil conductors will be transferred to the coil surface or the stator core efficiently.

As a result, the temperature of coil conductors may be lowered. This paper introduces our research program to achieve high thermal conductivity of the generator stator coil insulation. The objectives of this program are to increase output and increase efficiency of water turbine generators.

2 Development of High Thermal Conducting Coil Insulation

Fig. 2 shows a development workflow of high thermal conducting insulation. According to the result of the thermal conductivity measurement for both conventional and new constituent materials, the effect of the new constituent materials was confirmed by using equivalent thermal conductivity calculation and heat conduction analysis. We determined the insulation configuration and coil manufacturing process. As the next step, the thermal conductivity of the insulation layers was checked.

Next, an electrical evaluation was carried out (1) by confirmating the thermal conductivity of the insulating layer, (2) by a quantitative evaluation of heat transfer into the stator iron core by conducting thermal resistance measurement and (3) by the long-term voltage endurance test (V-t test).

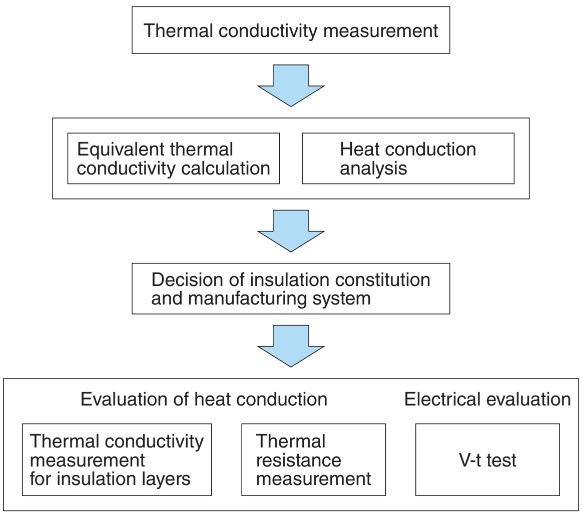


Fig. 2 Development Workflow of High Thermal Conducting Insulation

A development workflow is shown based on (1) the result of thermal conductivity measurements of the materials that compose the insulation layers and (2) the research of the manufacturing method. The insulation configuration was determined by using an equivalent thermal conductivity calculation and heat conduction analysis. Evaluation of heat conduction and electrical evaluation were then carried out.

2.1 Thermal Conductivity and Coil Manufacturing Method

2.1.1 Thermal Conductivity of Constituent Materials

Thermal conductivity was measured for the insulation layer which consists of an interlayer insulation layer, a main insulation (mainly consisting of mica), a corona protection layer, and resin materials used for the impregnation of all of the insulation layers. These data were required for the calculation of the equivalent thermal conductivity and heat conduction analysis. Fig. 3 shows a configuration of the insulation layers and thermal conductivity of resin materials. Thermal conductivity of resin is the lowest and it is only about 1/4 that of the main insulation layer. Since resin is impregnated throughout the insulation layers, we assume such a factor greatly affects the thermal conductivity of the insulation layers. Fig. 4 shows a relationship between the compression ratio of the main insulation layer

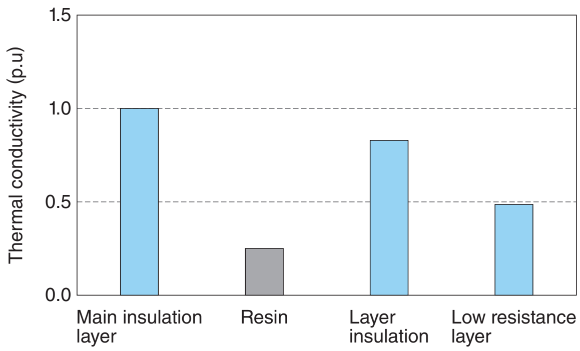


Fig. 3 Configuration of Insulation Layers and Thermal Conductivity of Resin Materials

This data indicates that the thermal conductivity of the resin is lowest among constituent materials and respective layers that compose the insulation layers.

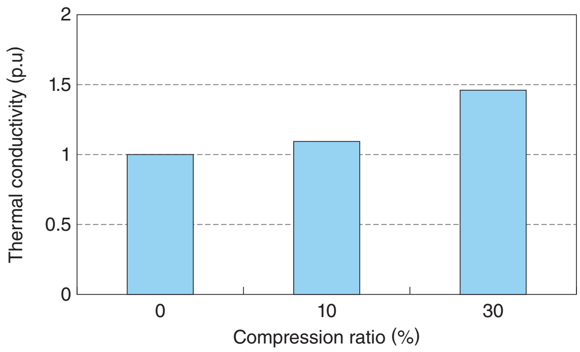


Fig. 4 Relationship between Compression Ratio of Main Insulation Layer and Thermal Conductivity

The higher the compression ratio (resin content low), the higher the thermal conductivity.

and the thermal conductivity. This diagram shows the effect of resin quantity upon the thermal conductivity of insulation layers. The higher the compression ratio (smaller resin quantity), the higher the thermal conductivity. When the compression ratio was raised to 30%, thermal conductivity was improved to approximately 1.5 times. We confirmed that thermal conductivity was improved by reducing the amount of resin contained in the insulation layers.

2.1.2 Manufacturing Method for Generator Stator Windings

The manufacturing method for the generator stator windings is roughly classified into the following two categories:

(1) Full impregnation method

After the stator coils are inserted in the core slots without containing resin, the stator core and coil assembly is impregnated with resin under the vacuum. The stator winding is then fabricated through the processes of heating and hardening for thermal curing.

(2) Press heating method

Each coil containing resin is pressed, heated, and hardened by a press heating machine. The processed coils are assembled to make up a stator winding that is then inserted in the stator core slots.

In the full impregnation method, coils are inserted in the stator core before resin impregnation and hardening. If coils are inserted with high pressure, their insulation layers may be damaged. For this reason, the compression force is limited to a few percent at the highest.

Conversely, the press heating method makes the compression and thermosetting on the insulation layers by using a press heating machine. Compared with the full impregnation method, the amount of resin impregnation is reduced because the insulation layers can be highly compressed. Based on the result of thermal conductivity measurement, we decided to adopt the press heating method in order to realize high thermal conductivity for the insulation layers.

2.2 Examination of Insulation Configuration by Equivalent Thermal Conductivity Calculation

After the measurement of the thermal conductivity on constituent materials used for the press heating system, we calculated thermal conductivity of the mica tapes that can achieve two times the thermal conductivity ratio. We calculated by using the equivalent thermal conductivity calculation method.

As a result, it was revealed that more than 2.5 times of the thermal conductivity is needed. It is difficult for conventional mica tapes (conventional mica) to realize this level. Accordingly, we came to realize “high heat conduction mica tapes (high heat conduction mica)” containing high heat conduction inorganic fillers.

Fig. 5 shows a result of the thermal conductivity measurement for conventional mica and high heat conduction mica. **Fig. 6** shows a result of thermal conductivity measurement for conventional mica and high heat conduction mica used as insulation layers. High heat conduction mice showed a heat conductivity about twice that of conventional

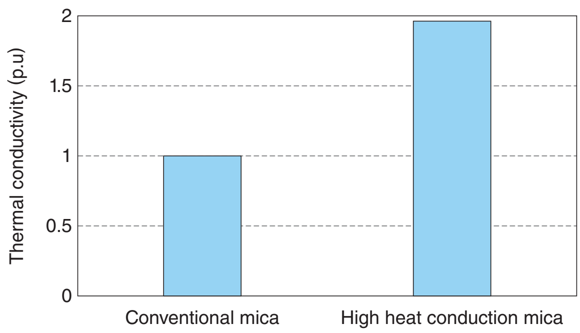


Fig. 5 **Result of Thermal Conductivity Measurement for Conventional Mica and High Heat Conduction Mica**

This diagram indicates that the high thermal conductivity of the developed material is almost twice the thermal conductivity of conventional mica.

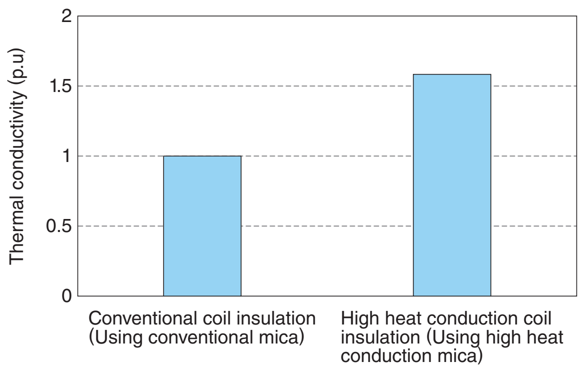


Fig. 6 **Result of the Thermal Conductivity Measurement for Conventional Mica and High Heat Conduction Mica Used as Insulation Layers**

Compared with insulation layers that employ conventional mica, main insulation layers using high heat conduction mica have the thermal conductivity that was about 1.6 times that of conventional one.

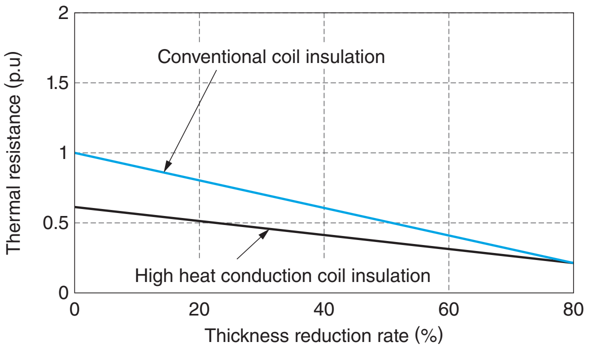


Fig. 7 **Result of the Thermal Resistance Calculation for Insulation Layers by the Equivalent Thermal Conductivity Calculation**

The change in thermal resistance with the main insulation thickness is shown based on the result of the equivalent thermal conductivity calculation.

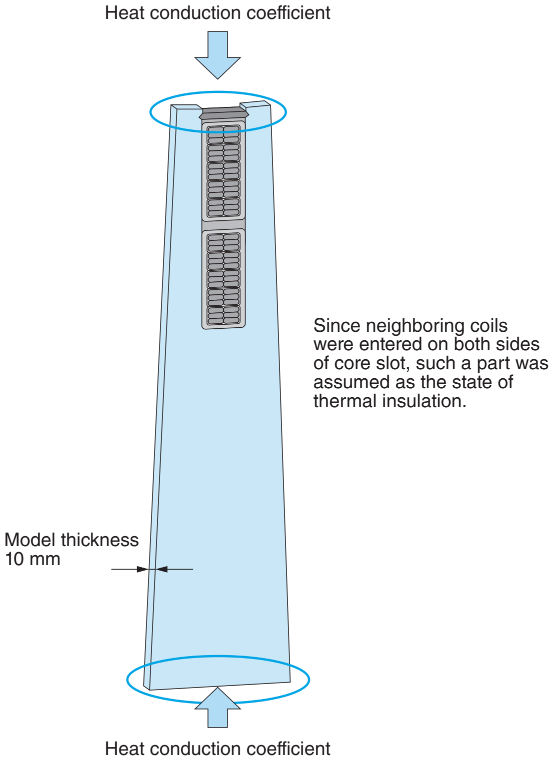


Fig. 8 **Heat Conduction Analytical Model**

A single slot of the stator core was put into a model for analysis.

mica when used for the main insulation layers. For the insulation layers, thermal conductivity is about 1.6 times that of conventional mica. Thermal resistance attributable to insulation thickness was obtained based on the thermal conductivity calculated for insulation layers.

Fig. 7 shows a result of the thermal resistance calculation for insulation layers by the equivalent thermal conductivity calculation. Compared with conventional coil insulation, high heat conduction coil insulation assures a 40% reduction of thermal resistance with the same insulation thickness as a conventional one. If the insulation thickness is further reduced by 30%, thermal resistance will be reduced by 50% or more. For conventional coil insulation in comparison, thermal resistance is merely reduced by 30% even though the insulation thickness is reduced by 30%.

2.3 Effect of Coil Temperature Reduction by Heat Conduction Analysis

By the thermal conductivity measurement, we obtained the thermal conductivity of each insulation material needed for heat conduction analysis. Further, we conducted heat conduction analysis on a partial model of the stator to confirm the effect of coil temperature reduction when a high heat conduction coil insulation was applied. **Fig. 8** shows a heat conduction analytical model. At the time of the heat conduction analysis, a single slot was put into an analytical model and a heat conduction coefficient was applied to the inner and outer diameter surfaces of the stator core. Since the neighboring coils kept contact with each other in a radial direction, we assumed that they were in the state of thermal insulation. Analysis was carried out on the following four models:

(1) Fully impregnated coils
(2) Conventional press-heated coil insulation
(3) High heat conduction press-heated coil insulation
(4) High heat conduction press-heated coil thin insulation (insulation thickness reduced by 30%)

Table 1 shows a result of heat conduction analysis. Compared with conventional coil insulations, high heat conduction coil insulation showed about 10°K reduction, and high heat conduction coil thin insulation showed about 12°K reduction. Apparently, we expected sufficient effects.

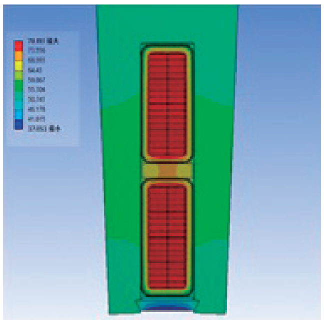
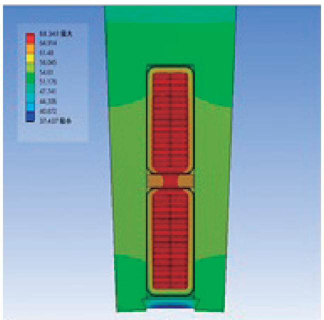
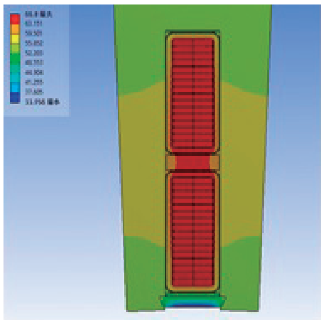
2.4 Measurement of Insulation Layer Thermal Conductivity

In order to compare thermal conductivity between high heat conduction mica tapes and conventional mica tapes, we measured the thermal conductivity of the constitution of each coil insulation.

For this thermal conductivity measurement, thermal conductivity was evaluated in the state of the generator in practical operation. As such, a sta-

Table 1 **Result of Heat Conduction Analysis**

The result of the heat conduction analysis on conventional coil insulation and high heat conduction coil insulation is shown.

Insulation configuration	Conventional coil insulation	High heat conduction coil insulation	High heat conduction coil thin insulation (30% reduction)
Contour diagram			
Coil temperature (℃)	78.1	68.3	66.8
Coil temperature difference (℃)	—	9.8	11.3

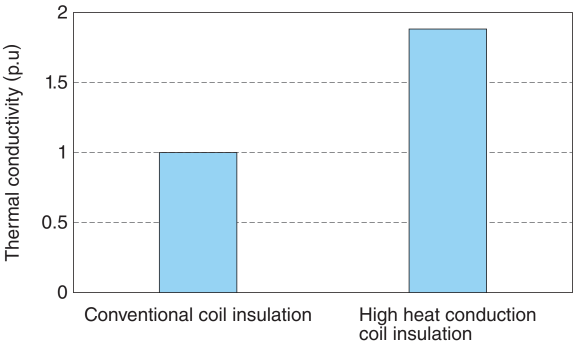


Fig. 9 **Result of Thermal Conductivity Measurement for Insulation Layers**

This diagram shows that the high heat conduction coil insulation has a thermal conductivity about 1.9 times that of the conventional coil insulation.

tionary method was adopted. Fig. 9 shows a result of thermal conductivity measurement for insulation layers. The test piece simulated the actual layer structure. As the result of the test measurement, we confirmed that the high heat conduction coil insulation has a thermal conductivity about 1.9 times that of a conventional coil insulation.

2.5 Measurement of Thermal Resistance

Simulating the state of stator coils inserted in the stator, a quantitative evaluation was carried out on the cooling performance of the high heat conduction coil insulation by measuring the thermal resistance between the coil's conductors and the stator core. Thermal resistance is given by Expression (1) below.

$$R_{th} = \frac{1}{K \times A} \quad \cdots\cdots (1)$$

Thermal resistance is classified into thermal resistance inside the body and contact thermal resistance between the bodies. Contact thermal resistance is calculated by Tachibana's equation[1], i.e. Expression (2) below, which is applicable to metallic materials. Insulation materials are composed of high molecular resin and inorganic materials. Since we considered that the physical condition of contact is not so different from that of metals, this equation was adopted.

$$K = \frac{1.7 \times 10^5}{\frac{\delta_1 + \delta_0}{\lambda_1} + \frac{\delta_2 + \delta_0}{\lambda_2}} \times \frac{0.6 \times P}{H} + \frac{1 \times 10^6 \times \lambda_f}{\delta_1 + \delta_2} \quad \cdots\cdots (2)$$

Where,

R_{th} (K/W): Thermal resistance
K (W/m^2·K): Contact thermal conductance
δ_1, δ_2 (μm): Surface roughness
δ_0 (μm): Equivalent length of contact
λ_1, λ_2 (W/m·K): Thermal conductivity of respective materials
λ_f (W/m·K): Thermal conductivity inside the gap
P (MPa): Contact pressure
H (HB): Brinell hardness of a softer material

Fig. 10 shows an outline diagram of a thermal resistance measuring device. Fig. 11 shows a mimic core (temperature measuring section). Fig. 12 shows a schematic diagram of the inside of mimic core interior. When a current is carried through strands,

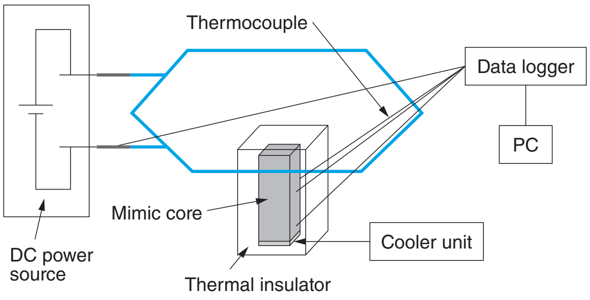


Fig. 10 **Outline Diagram of Thermal Resistance Measuring Device**

An outline diagram of a thermal resistance measuring device is shown. A mimic iron core embedded with a thermocouple is set in the coils and the coils are heated by a DC current. In this setting, the temperature difference between coils and core can be measured.

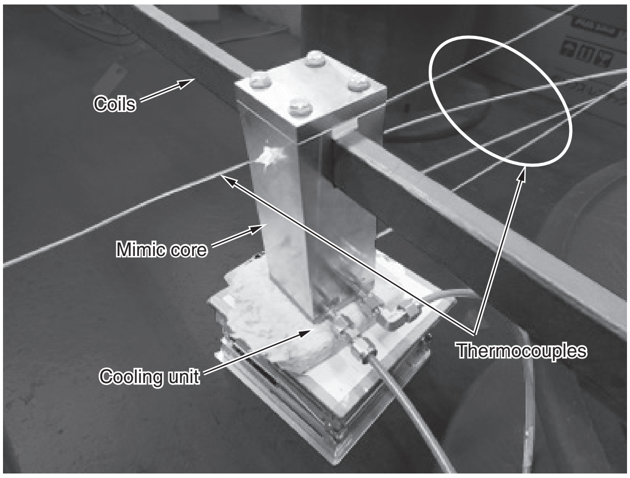


Fig. 11 **Mimic Core (Temperature Measuring Section)**

A mimic core is shown. The lower part of the mimic core is connected with a cooler unit and thermocouples are embedded in multiple positions.

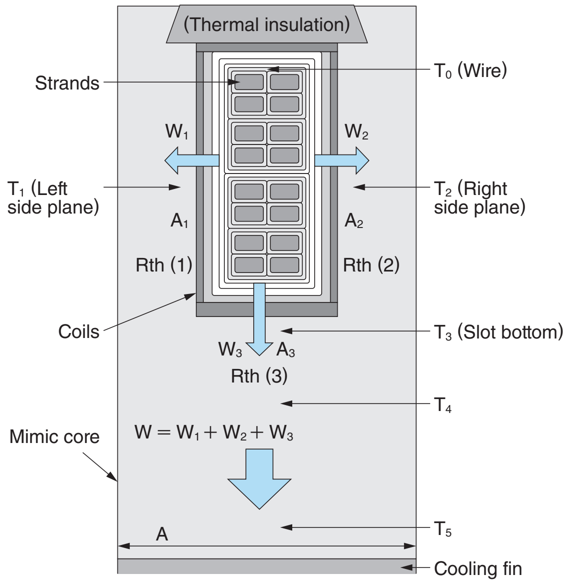


Fig. 12 **Schematic Diagram of the Inside of Mimic Core Interior**

A schematic diagram of the mimic core cross-section is shown. Thermocouples embedded in multiple positions of the coil interior and mimic core are used to measure temperatures in order to determine thermal resistance.

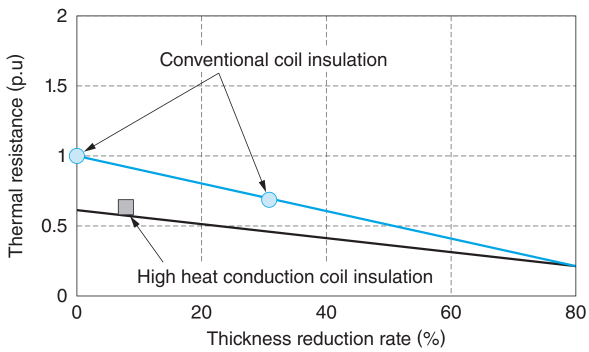


Fig. 13 **Comparison of Thermal Resistance between Actual Measurement and Analysis Calculation**

Compared with conventional coil insulation, high heat conduction coil insulation lowered its thermal resistance by 40%. This value was almost identical with the result of the calculation.

heat is generated and dissipated in three directions: left side plane, right side plane, and slot bottom plane. Since the strands are covered with an adiabatic material, dissipated heat is finally joined and discharged to the cooling fins. The total thermal resistance is a sum of thermal resistances on the left-side, right-side, and slot-bottom planes. By measuring these values, quantitative evaluation of cooling performance can be achieved.

Fig. 13 shows a comparison of thermal resistance between the actual measurement and analysis calculation. Compared with conventional coils, thermal resistance of high heat conduction coils was reduced by approximately 40%. When thickness of conventional coil insulation was reduced by 30%, thermal resistance was reduced by 30% as a result. These measured results are almost identical to the thermal resistance values from the calculation based on the equivalent thermal conductivity method.

2.6 Voltage Endurance Test

In order to examine the dielectric strength of high heat conduction coil insulation, a long-term voltage endurance test was carried out. For the voltage endurance test, there are test methods recommended by IEC60034-18-32 and IEEE1553. Table 2 shows the standards for the long-term voltage

Table 2 Standards for Long-Term Voltage Endurance Test

Standards for long-term voltage endurance test of stator coils are shown.

Standard	Testing specifications
IEC 60034-18-32	Lifetime is estimated based on the result of testing under the 3 conditions below. (1) Insulation breakdown time: About 100 hours (2) Insulation breakdown time: About 1000 hours (3) Insulation breakdown time: About 5000 hours
IEEE 1553	Schedule A: 2.17Un – 400 hours or longer Schedule B: 2.53Un – 250 hours or longer Un: Rated voltage

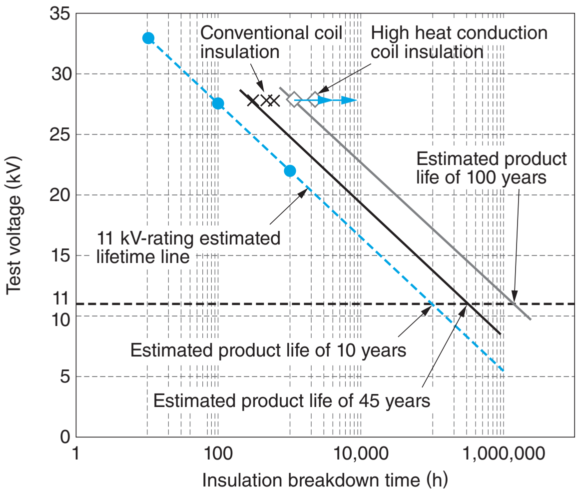


Fig. 14 Result of Long-Term Voltage Endurance Test

Based on the presumed product life of 10 years for the insulation of rated voltage 11 kV, the presumed product life of high heat conduction coil insulation is estimated to be 100 years against the fact that the presumed product life of conventional coil insulation is about 45 years.

endurance test. Testing for this time conforms to an international Standard IEEE1553-Schedule B.

Fig. 14 shows a result of a long-term voltage endurance test. The insulation of the conventional coils was destroyed within 600 hours. The minimum value is 300 hours, while in the case of high heat conduction coil insulation, no insulation was destroyed even after the lapse of more than 1000 hours. Some items withstood for more than 2000 hours. Compared with conventional coil insulation, the high heat conduction coil insulation has a potential of having a voltage endurance life for more than two times of that of conventional coil insulation.

3 Postscript

When high heat conduction mica tapes were used for main insulation layers and stator coils were manufactured by the press heating method, we verified that the thermal conductivity was raised almost twice that of the conventional stator coils and thermal resistance could be reduced by about 40%.

In the future, similar testing will be carried out on coils where insulation thickness is reduced by 30% in order to realize a higher performance. We will conduct reliability tests and will promote further development in order to commercialize new products with new coils.

《Reference》

(1) Naoki Kunimine Edition: "A Guidebook to Thermal Fluid Analysis for Electronic Equipment," Nikkan Kogyo Shimbun, 2009, p.170