Development of Elemental Technology for Superconducting Motor

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ABSTRACT The superconducting phenomenon was discovered in 1911 and the research of making superconducting wire has been advancing since. The superconducting wire was put to practical use and commercial use as the wire to transmit a large current with a low loss. The idea of a superconducting motor using the superconducting wire has been discussed for a long time. And even though a large number of prototypes were produced, there were still a lot of problems for practical use on a commercial level mainly in the technology of cryogenic refrigeration and insulation to maintain the cryogenic state. To solve this problem, we proposed the vacuum insulation structure which was lighter in weight and easier to handle in comparison with the present technology. Further, we produced a prototype of the superconducting motor reflecting the structure and evaluated it. The prototype of the superconducting motor produced this time demonstrated that the superconducting state came into effect easily even though its structure was constructed with a lightweight plastic one.

1. INTRODUCTION

The superconducting phenomenon is the one in which electric resistance becomes zero under the cryogenic temperature and has been researched for a long time since its discovery in 1911 until today. The superconducting wire which was made by making the superconducting material into wire shape is broadly classified into the low temperature superconducting wire composed of metallic materials and the high temperature superconducting wire composed of oxide substances. We, Furukawa Electric Group are the rare company in the world to work on both types of low temperature superconducting materials and high temperature ones.

It is important to improve the efficiency of a motor to realize carbon neutrality for which we have to reduce the emissions of greenhouse gases to total zero by 2050. Approximately more than 50% of domestic power consumption is consumed in motor use. Assuming that the efficiency of all the motors in operation is improved by 1%, 15.5 billion kWh of power consumption will be reduced, and it is equivalent to the reduction of 6,900 thousand tons of CO_2 emission.

The research of the superconducting motor has been carried out for a long time and a large number of prototypes were produced in the research of universities and in the academic-industrial collaboration projects. They aimed at the reduction of the Joule loss which is one of the main factors of motor loss and the improvement of the power density by high magnetic force. The superconducting material is required to be applied to accomplish a high power density that has never been realized by any of the present copper wire motors. However, the cooling technology under −196°C is required even for the high-temperature superconducting wire, which is called a high temperature one in the superconducting industry and also in addition advanced insulation technology is required. Therefore, those problems have demerits such as upsizing, reduced total efficiency, and increased cost by those incidental facilities for cooling and insulation are working against the practical use at a commercial level.

In this paper, we will report on the invented vacuum insulated structure aiming at the practical use of the superconducting motor and the result of the prototype that reflects the structure.

2. THE PRESENT INSULATION TECHNOLOGY

In the field of superconducting technology, the vacuum insulating container was traditionally applied as the insulation technology. Its basic structure is composed of an airtight container containing a refrigerant called a cryostat contained in a vacuum container, even though its shape and accessories are varied for the application. Glass fiber reinforced plastic is applied to the material for the container for its use where the occurrence of an eddy current loss in a high magnetic field becomes a problem. However, it is often made of stainless steel from the viewpoint of easier manufacturing processing and lower cost. Further, the vacuum insulated part includes techniques to

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extremely reduce the heat flow from the outside, such as keeping the high vacuum of 10^{-3} Pa or higher at least to control the convection heat transfer caused by gas molecules and in addition to equip with a reflective material to control the heat transfer caused by radiation. When applying a cryocooler as a substitute for a refrigerant, the structure becomes simpler because no airtight structure is necessary, however, the vacuum container is indispensable for the purpose of insulation. Considering the vacuum container, at least several hours are necessary for the exhaustion depending on the performance of the pump and the size of the container, and further, it results in increasing the weight of the total system because the container is made of metallic material. Although not much influence caused by the weight is harming the fixed equipment such as a generator, it is worried that the merit of the superconducting may be lost in its application in moving bodies such as electric aircrafts and vehicles to which the superconducting motor is expected to perform. Therefore, in this research, we have examined the insulation structure which was easier to handle and more capable of weight reduction in comparison with the present technology.

3. HEAT TRANSFER MECHANISM OF INSULATION MATERIAL

In the market, mainly we have fiber insulation materials represented by glass wool, foam insulation materials such as urethane foam and polyethylene foam, and particulate insulation materials such as silica aerogel.

The heat transfer phenomena in insulation materials are classified into three mechanisms, those are the solid heat transfer in which heat is transferred through the solid heat conduction, the convection heat transfer in which heat is transferred accompanying the convection movement of gas molecules, and the radiation heat transfer in which heat is transferred through the movement of radiation heat. And the heat moves along with the apparent thermal conductivity which is the total of each mechanism of the heat transfer. The solid heat transfer depends on the density of the material and the lower the density of the material becomes, the less the heat is transferred in general. The convection heat transfer is almost free from the influence of the material density and contributes less to the heat transfer along with the longer mean free path. Therefore, its influence on the apparent thermal conductivity is almost zero in the area where the degree of vacuum is higher than a certain level (Figure 1).

The apparent thermal conductivity of insulation materials in a vacuum strongly depends on the properties and conditions. The convection heat transfer largely contributes to that of the fiber insulation materials. The apparent thermal conductivity is low in a high vacuum, but it increases rapidly when the degree of vacuum becomes lower. The foam insulation materials are less influenced by the convection heat transfer and have a stable thermal conductivity free from the degree of vacuum, but their fundamental solid thermal conductivity tends to be higher than that of the fiber insulation materials. Silica aerogel which is applied to a core material of vacuum insulation panels because the particulate insulation materials are porous materials with more than 90% of porosity per its volume to have a small material density. Further, because either particle size or porous size is nano level, both the solid thermal conduction among particles and the convection heat transfer in a porous are restrained and the surface area of radiation and scattering is increased to have a high insulation effect. In addition, it is known that the increase of its thermal conductivity caused by the lowering degree of vacuum is slower than that of fiber insulation materials and foam insulation materials (Figure 2).

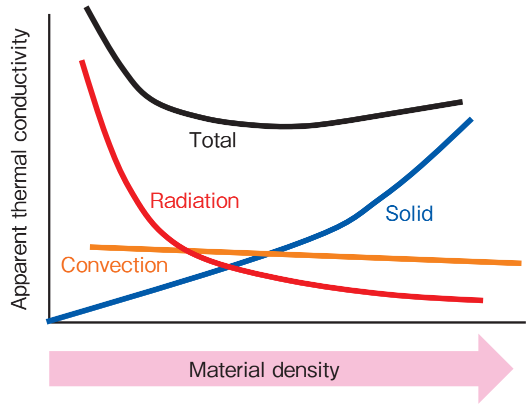

Figure 1 Apparent thermal conductivity of insulating materials.

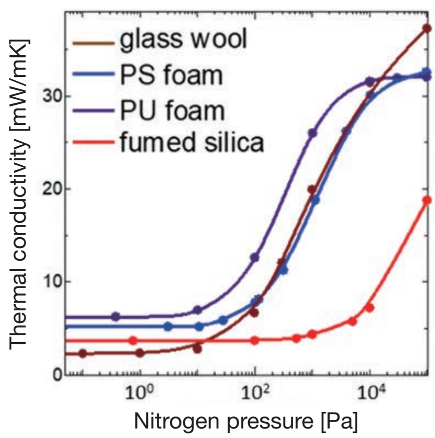

Figure 2 Effects of atmospheric pressure on thermal conductivity of insulation materials[1].

4. NEW CONCEPT OF INSULATION STRUCTURE

We have focused on the fact that the thermal conductivity of the particulate insulation materials was not so dependent on the degree of vacuum even in the area of the low degree of vacuum around 10^2 Pa. And applying the particulate insulation materials in the low degree of vacuum, we have examined an easy gain in the insulation performance which is equivalent to that of the present insulation structure in the high degree of vacuum (Figure 3). The following advantages are expected as the required degree of vacuum for the insulation is reduced to the level of a low degree of vacuum.

(1) The process of vacuum is simplified. (The exhaust time is remarkably reduced because only low to medium vacuum pumps are required for the vacuum exhaust equipment.)
(2) Organic materials such as plastic can be positively applied because the insulation performance is not sensitive to outgases.
(3) Restrictions on the materials and the processing accuracy can be relaxed.

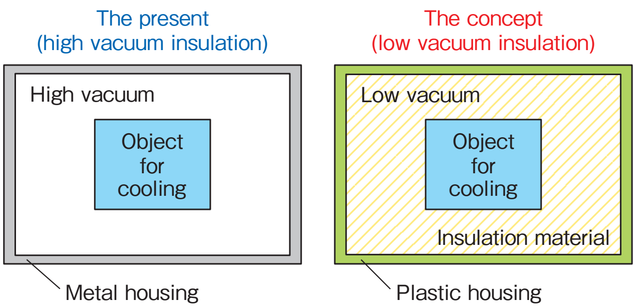

Figure 3 Conceptual diagram of insulation structure.

We have analyzed the heat transfer with simulation to verify our tentative theory. As an analysis model, we have designed such a structure which had a cooler of liquid nitrogen and a motor with a vacuum container containing the cooler, and we have calculated the dependence of the vacuum container on the degree of vacuum against the heat flow from the outside to the low temperature part under the condition of normal outside temperature and normal outside pressure. The result is shown in Figure 4.

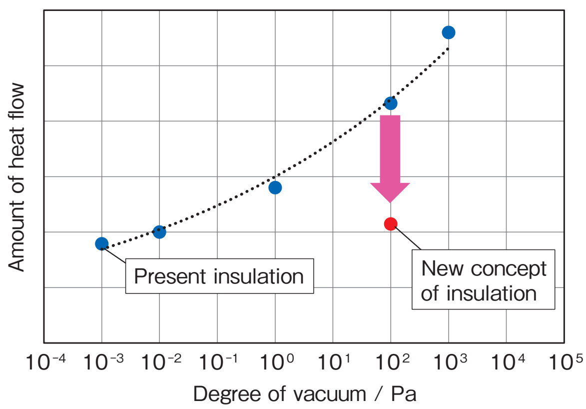

Figure 4 Heat flow into insulated structures.

In the present technology, the heat flow is increasing along with the lowering of the degree of vacuum. On the other hand, it was verified that in the conceptual model in which an insulation material was adopted, the heat flow was reduced even in the low vacuum area, and almost the same level of heat flow as the high vacuum area of the present technology was gained. This result is not applicable to all cases because it depends on the influence of the volume and shape of the container, and physical properties and condition of the insulation materials. However, it suggests that good insulation can be realized even in the low degree of vacuum when applying the design with a proper structure and proper materials based on our heat transfer analysis.

5. PROTOTYPE OF THE SUPERCONDUCTING MOTOR

We have designed and made a prototype of the superconducting motor based on the result of our analysis of the conceptual structure to examine the insulation structure of low vacuum conditions. It was the basic idea behind the design of prototype models of the superconducting motor produced in the past to apply a stronger magnet force excited by the superconducting coil replacing that of a permanent magnet in order to improve the power density. And in its cooling structure, a coolant was circulated in the shaft of a rotor to cool the superconducting coil of the field magnet. We estimated that the cooling structure mentioned above was adopted because its structure could be simpler in comparison with the structure in which the armature coil of a stator was cooled with a coolant.

We have designed a superconducting motor with a small power which emphasized small size and lightweight, because the purpose of our research was to examine our insulation concept in the low vacuum. Our 3-D design model is shown in Figure 5 and the specifications are shown in Table 1.

To make the motor smaller in size and lighter in weight, we adopted a rotor with a magnetic field exited by a permanent magnet and applied the superconducting coil to the armature coil of a stator. The superconducting coil was manufactured with the REBCO high temperature superconducting wire made by SuperPower Inc., a mem-

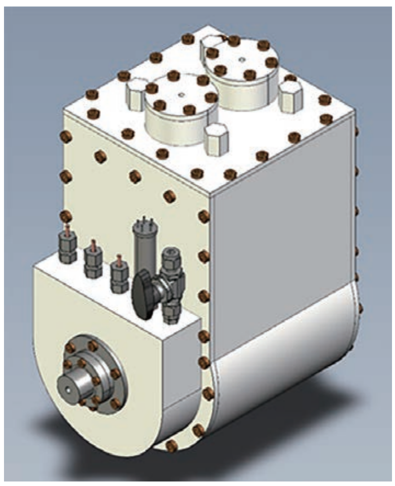

Figure 5 3-D design model of our superconducting motor.

Table 1 Superconducting motor specifications.

Items	Composition
Type of motor	DC brushless inner rotor type
Field magnet source	Permanent magnet
Armature	Superconducting coil
Superconducting wire	REBCO
Number of poles	4 poles
Slots	3 slots
Full external dimensions	L 287 x W 180 x H 324 mm
Weight	13 kg
Method of cooling	Superconducting coils immersed in liquid nitrogen
Maximum torque	3.0 N·m
Maximum rotation speed	1770 rpm
Power supply voltage	24 V
Maximum current	30 A
Control method	PWM control with inverter

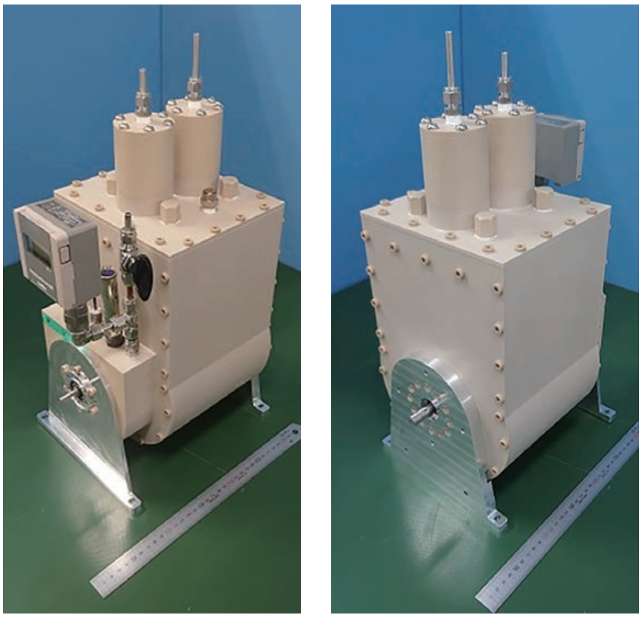

Figure 6 Prototype superconducting motor.

ber of our group. Further, we have applied a stator core made of laminated electromagnetic steel sheets because the motor did not require a high magnetic force for its rather small power. With a mind based on our analysis of electromagnetic field not to create magnetic saturation in the stator core and to reduce the magnetic field to which the superconducting coil is exposed as much as possible, we have designed dimensions, shape, magnet, coil, and structure of the motor to achieve the required torque and rotational speed. Further, applying the advantage of the insulation structure against the low vacuum, we have adopted a plastic material for the vacuum container. An external appearance of our prototype of the superconducting motor is shown in Figure 6.

We cooled the prototype motor with liquid nitrogen to find that the liquid nitrogen could be stored in the internal low temperature container without frost sticking on the surface of the vacuum container and confirmed that our superconducting coil could rotate as a motor in the superconducting state.

6. EVALUATION OF THE SUPERCONDUCTING MOTOR

In order to calculate the efficiency of our superconducting motor, we put a counterforce by regeneration of a dynamometer against a rotational force of the superconducting motor and calculated the efficiency from the torque and the rotation speed in the state based on the equation (1). Further, we measured the efficiency of a copper wire motor which had an equivalent power. Although we could not compare them precisely because the magnet and the coil structure of the copper wire motor were different from those of the superconducting motor, the comparison could be instructive as a reference when the size of electromagnetic steel sheets from which the power could be estimated was similar. The conceptual diagram of the evaluation of motor efficiency is shown in Figure 7 and the evaluation results of the motor efficiency are shown in Figure 8.

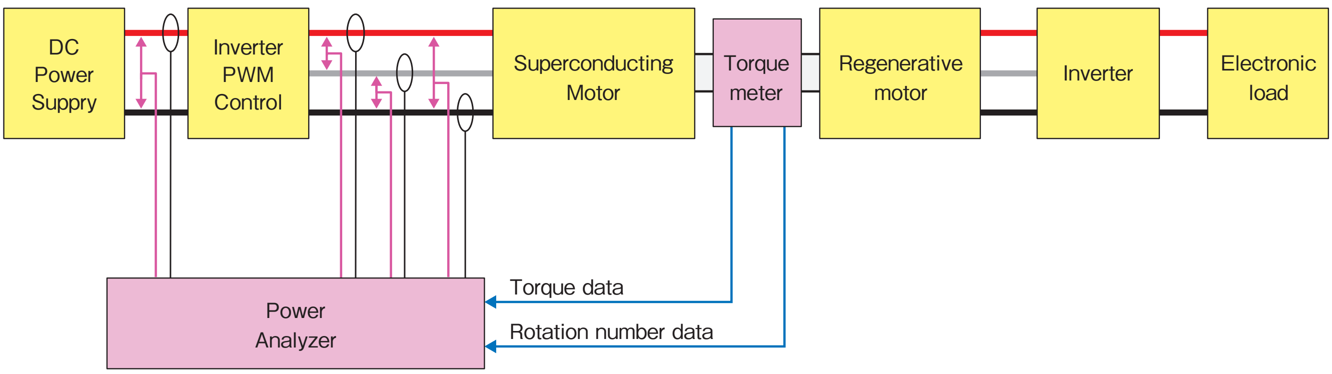

Figure 7 Conceptual diagram of motor efficiency evaluation.

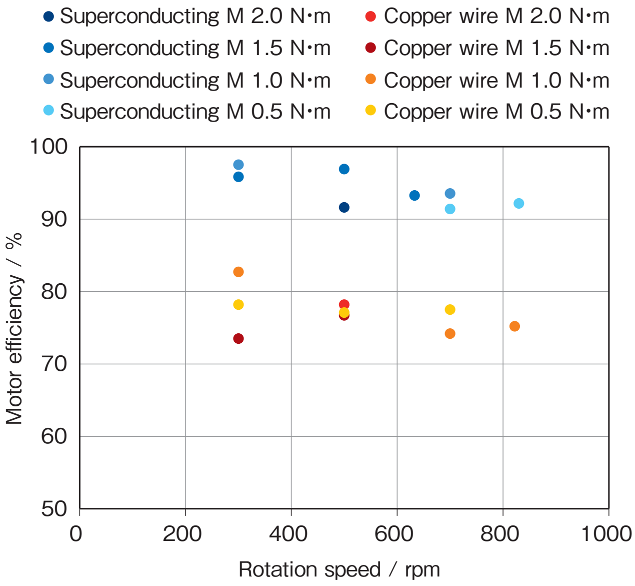

Figure 8 Motor efficiency evaluation results.

In general, as the efficiency of a motor fluctuates depending on its operation speed, it is optimized to have a high efficiency at its rated operation speed. In such a motor as for an automobile, which is required to have a wide operation area, the ratio of Joule loss increases either in a low speed area and in a high speed area to cause a lowering of the efficiency. Joule loss in an armature coil is zero in the superconducting motor and we have confirmed that the efficiency of the superconducting motor was higher at each measured operation speed.

In the operation of our superconducting motor, the degree of vacuum reached to the required level in 15 minutes or less of the vacuum exhaust time. We have steeply reduced the process time until the start of cooling in comparison with that of the present technology. Further, it is an advantage of the operation in the low vacuum that maintenance and leakage repair are easier with the use of general-purpose sealing material or a glue. Furthermore, the weight of our prototype motor is approximately 13 kg and that with a vacuum container made of present stainless steel is 35 kg or more according to our tentative calculation. As a result, we have realized a great weight reduction.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{2\pi}{60} \times \frac{T \times N}{P_{in}} \quad (1)$$

η : Motor efficiency
P_{in} : Supply power to the motor
P_{out} : Power from the motor
T : Power torque (N·m)
N : Power rotation speed (rpm)

7. CONCLUSION

112 years have passed since the discovery of the superconducting phenomenon. We, Furukawa Electric have continued to research it for many years, however, applied products that have been put to practical use were limited to MRI magnets and the instruments used such as in accelerator fields and fusion fields where none of the present normal conducting materials could be applied, and the worldwide scale of the business has been still small. The main factors of the limited practical use mentioned above are expensive superconducting materials, a high hurdle against cooling and insulating to utilize the superconducting phenomenon and that the superconducting technology itself is still in the research phase and many parts of it are still unresolved. A lot of research on the superconducting material itself has been carried out, however, elemental technologies to make use of the superconducting technology have not matured yet.

In this research, we have worked on developing the insulation technology, one of the elemental technologies for the superconducting motor. The fruits of this research were that we have successfully developed a superconducting motor that was lightweight with a short start-up time based on a vacuum container making use of the advantages of low-vacuum insulation structure and found that it operated at a higher efficiency at each of various rotation speed in comparison with that of a normal temperature conducting motor. Applying the fruits of this research to the experiment and the evaluation related to the superconducting field, we are contributing to the research and development to make the superconducting technology familiar and easier to use.

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