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Electric insulation for energy-saving equipment

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Abstract: Equipment is labelled as energy-saving if it requires less energy during its manufacture and operation. A reduction in energy consumption in the manufacture of large electrical machines and equipment can be obtained by reducing their dimensions with their power preserved. To achieve this, new insulating materials characterized by high thermal conductivity must be used to increase the capacity to carry away the heat generated in the windings.

This paper presents a technique of obtaining insulating composites with increased thermal conductivity, results of tests on composites and the use of these materials in high-power electric machines and for the production of HV insulators with increased resistance to surface discharges.

Key words: energy-saving, dielectrics, thermal conductivity

I. INTRODUCTION

Equipment is labelled as energy-saving if it requires less energy for both its manufacture and operation.

The power of electric equipment is limited mainly by the insulation's permissible maximum working temperature. Thus efforts aimed at designing energy-saving equipment with its overall dimensions and mass unchanged can go in the following two directions:

1. The use of insulating materials with increased thermal resistance. The disadvantage of this approach is the high cost of such materials.
2. Increasing the equipment's heat abstraction through the use dielectrics with increased thermal conductivity.

A theoretical analysis and experimental research have shown the latter course to be the most expedient.

Epoxy composites, produced in the form of cast compounds, laminates and insulating tape consisting of a matrix and filler, are often used in electric machines and HV and LV equipment. The matrix is an amorphous compound, consisting of epoxy resin and a hardening agent.

Coefficient k of a composite can be increased by replacing the conventional hardening agent, i.e. silica flour, with a hardener characterized by a higher thermal conductivity, such as alundum, corundum or periclase.

Insulating materials with increased thermal conductivity are highly suitable for the manufacturing of HV insulators. During an electrical discharge the arc temperature reaches 5000°C. Some of the arc's energy is dissipated to the environment, some is deflected by the insulator's surface and some is accumulated in the insulator's material. The accumulated energy causes a local increase in the insulator's temperature up to several hundred degrees C.

This results in the degradation of the composite's polymeric matrix due to the formation of carbonized tracking paths or the erosion of the material. By increasing the thermal conductivity of the composite the temperature of its surface can be lowered and consequently, the composite's resistance to arcing can be increased.

II. THERMAL CONDUCTIVITY OF COMPOSITES

The relationship between the composite's thermal conductivity, the thermal conductivity of its components, the volume fractions of the latter and the shape of the filler's grain is expressed by the Hamilton-Crosser formula [1]:

$$k_c = k_M \frac{k_F + (n-1)k_M - (n-1)f(k_M - k_F)}{k_F + (n-1)k_M + f(k_M - k_F)} \quad (1)$$

where:

k_c – thermal conductivity of the composite
k_F - thermal conductivity of the filler
k_M - thermal conductivity of the matrix
f – volume concentration of the filler
n–a shape factor of the filler's grains

$n = 3/S$, S - sphericality, which is a ratio of the surface area of a sphere corresponding to the filler grain's volume to the surface area of the filler, e.g. $S = 1$, $n = 3$ for a sphere and $n \cong 50$ for a long needle.

Relation (1) is valid for $k_F >> k_M$, $f < 0.3$.

For filler volume fraction $f > 0.3$ measurement k_c is higher than the result yielded by relation (1), which is due to the separation of filler grains.

It follows from expression (1) that a composite's thermal conductivity can be increased by using fillers with high thermal conductivity (k_F), high grain shape factor (n) and as large as possible filler fraction in composite (f).

Anywhere from ten to twenty dielectrics characterized by very high thermal conductivity – over 100 W/m.·K – are known, e.g. diamond, nitrides of aluminium, boron, silicon and gallium, beryllium oxide and beryllium sulphide. These

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are expensive (diamond and nitrides) or toxic (beryllium oxide) materials.

There are, however, other cheap fillers (used mainly in ceramics) having quite good thermal conductivity (15÷40 W/m.·K), such as aluminium oxides (corundum, alundum), magnesium oxide (periclase), magnesium carbonate (magnesite) and calcium silicate (wollanstonite). These fillers were used in the tested cast epoxy composites with epoxy resin as the matrix and diaminediphenylmethane as the hardener. For comparison, a composite with the most common filler, i.e. silica flour, was tested.

III. RESULTS OF TESTS ON COMPOSITES

Measurements of the thermal conductivity of cast composites with the chosen fillers are presented in table 1.

Table 1. Effect of kind of filler on thermal conductivity of epoxy composites.

No	Filler	Filler volume fraction [%]	Coefficient λ [W/m·K]
1.		0	0.25
2.	silica flour	40	0.80
3.	magnesite	40	0.80
4.	periclase	40	1.15
5.	corundum	40	1.10
6.	corundum	50	1.60
7.	alundum	50	1.45
8.	wollanstonite	50	1.15

The relationship between the thermal conductivity of the cast epoxy compounds and the filler volume fraction is shown in fig. 1. The test results were compared with curves obtained from theoretical relation (1).

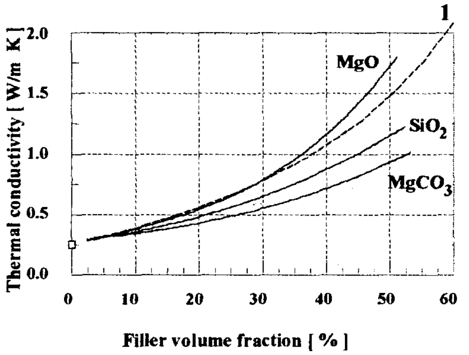

Fig.1. Compound's thermal conductivity versus kind and volume fraction of filler (broken line represents theoretical trace for n=5, k_M=0,25, k_F=25)

The experimental curves shown in fig. 1 are in agreement with theoretical curve (1).

The thermal conductivity of traditional laminar materials, tapes and laminates is 0,35÷0,45 W/m·K. It can be increased significantly by introducing powder fillers which are good thermal conductors into the composition. For the tests powder periclase (MgO) was chosen as the filler. The thermal conductivity of the laminar composites with increased thermal conductivity is compared with that of traditional materials in table 2.

Table 2. Thermal conductivity of selected composite materials.

Materials	Filler vol. fraction [%]	k [W/m·K]
1	2	3
Epoxy-fibreglass laminate (fibreglass fabric)	35	0.43
Epoxy-fibreglass laminate (fibreglass fabric + periclase)	37 + 11	0.58
Epoxy-fibreglass laminate (fibreglass mat + periclase)	26 + 25	0.67
Epoxy-fibreglass tape (fibreglass tape + mica)	95	0.39
Epoxy-fibreglass tape (fibreglass tape + mica + periclase)	80 + 16	0.70
Porous epoxy-fibreglass micatape (fibreglass tape + mica + periclase)	70 + 10	0.51

The filler used is given (in brackets) in column 1 and its volume fraction – in column 2.

IV. APPLICATION OF MATERIALS WITH INCREASED THERMAL CONDUCTIVITY

High-power induction motor's insulating system

The result of the application of micanite tape, with its thermal conductivity increased by 30%, in a 21 kW, 10.6 kV hydrogenerator is described in [2]. The result was a drop in the stator bars' temperature from 110°C to 100°C and a 5 kW reduction in loss [2].

Similar investigations were carried out by the authors of the present paper.

Fig. 2. shows a 630 kW induction motor stator slot model made by the authors.

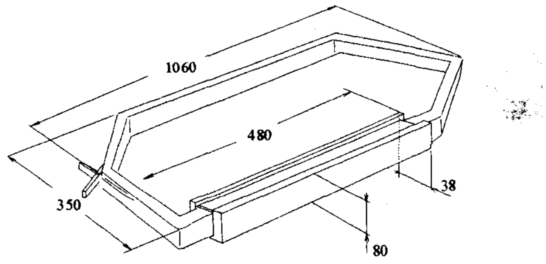

Fig.2. 630 kW induction motor stator slot model.

The model was made in two versions:

With a conventional insulating system and with an insulating system with increased thermal conductivity. In the former case the master micatape with thermal conductivity k=0.39 W/m·K was used for the insulation and the epoxy-fibreglass laminate with thermal conductivity k=0.43 W/m·K was used for the slot wedge. In the latter system the mica tape with thermal conductivity k=0.51 W/m·K and the epoxy-fibreglass laminate with thermal conductivity with k=0.70 W/m·K were used and additionally, the gap between the slot material and the winding was filled with insulating varnish. A Cu-CuNi thermocouple was placed inside the winding. In both cases the winding was loaded with the power of 900 VA. The trace of temperature until it stabilized is shown in fig. 3. For the former version (1) the stable temperature was 165°C and for the version with increased thermal conductivity (2) it was 145°C. Later in the experiment the load was increased for version 2 until the temperature of 165°C was reached. This temperature was reached for the power of 1080 VA, i.e. 20% higher than for version 1 with the conventional insulating system [3].

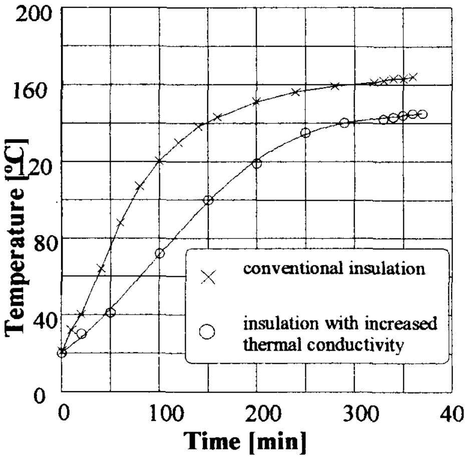

Fig.3. Temperature inside coil versus time for which it was supplied with power of 900 VA.

2. Lifting magnet

A cast epoxy compound with a sustained working temperature of 155°C, increased thermal conductivity (k=1.2 W/m·K) and increased resistance to mechanical impact was developed in IEL/OW in 1997.

This compound was used as a constructional-insulating material in a lifting magnet for the transport of scrap in a steel plant.

The 20.5 kW lifting magnet 2 m in diameter, with the lifting power of 15 tons was repaired in a specialized repair shop in Lubliniec. The thermal conductivity of the cast epoxy compound was increased which resulted in better heat abstraction from the windings to the lifting magnet's surface whereby the working temperature was lowered by about 30°C. Since the repair the lifting magnet has been operating failure-free round the clock in extreme conditions for three years now.

3. HV insulators

Resistance to arcing is a material's ability to withstand the impact of arcing, expressed by the time which passes since the first discharge to the failure of the material in the interelectrode space [5].

The failure of the material consists in the formation a current-conducting carbonized tracking path or in the erosion of the material, leading to mechanical damage to the insulator. These mechanisms are set in motion by an up-to-a few-hundred-°C increase in the temperature of the insulator's surface at the place of the discharge.

To determine the effect of the insulator material's thermal conductivity on its resistance to arcing and indirectly, on its surface temperature, two experiments were carried out [4]. In the first experiment the dependence of the arcing resistance of specimens made of cast epoxy compounds on their thermal conductivity was investigated (in accordance with IEC 61621).

Measurements for specimens with different volume fractions of chosen fillers are shown in fig. 4.

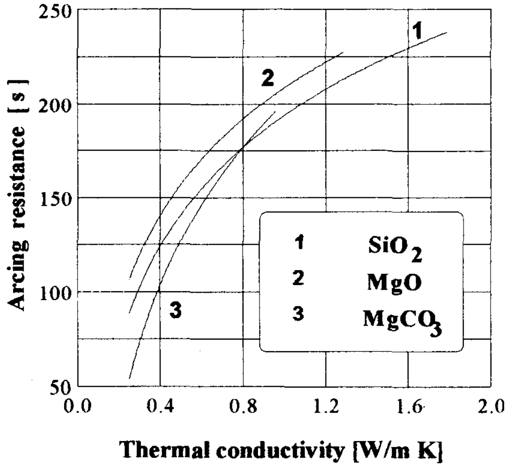

Fig.4. Arcing resistance versus thermal conductivity.

In the second experiment the dependence of the surface temperature of a specimen, made of an epoxy compound with the thermal conductivity of 0.25 W/m·K subjected to arcing at the current strength of 10 mA and the voltage of 12.5 kV, on arcing time was investigated. The surface temperature was measured by a Cu-CuNi thermocouple with 0.05 mm-diameter wires, whose weld had been machined flat and glued to the specimen's surface using a heat-resistant adhesive with increased thermal conductivity. The measurements are shown in fig. 5.

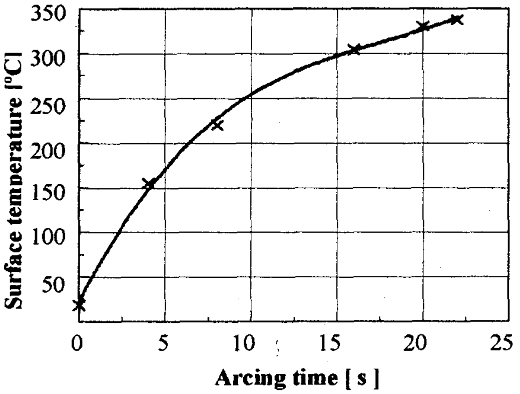

Fig.5. Temperature on surface of specimen made of epoxy compound with thermal conductivity of 1.2 W/m

Taking into account arc instability during the measurement of the specimen's temperature and the fact that the thermal flux impact area on the specimen's surface is small, a resistance heater 14 mm in diameter heated up to a constant temperature of 1100°C was used as the heat source in the further part of the experiment. The tested specimen was pushed under the heater, keeping a distance of 4 mm. Measurements were made for specimens with thermal conductivity of 0.25 W/m·K and 1.2 W/m·K. The surface temperature was measured by a Cu-CuNi thermocouple 0.05 mm in diameter. The measurements are shown in fig. 6.

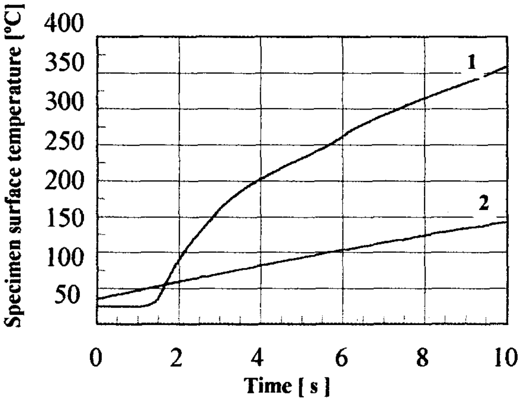

Fig.6. Temperature on surface of specimen made of epoxy compound with thermal conductivity 0.25 W/m·K (1) and 1.2 W/m·K (2).

A comparison of the temperature traces shows that the specimen with thermal conductivity k=0.25 W/m·K heats up to 350°C in 10 s whereas the specimen with k=1.2 W/m·K heats up to 150°C.

The research conducted currently in IEL/OW is aimed at formulating a mathematical relation which will describe the thermal field in an insulator with arcing taking place on its surface. Once the relationship between the insulator surface temperature during arcing and the insulator's thermokinetic properties, i.e. thermal conductivity and thermal diffusivity, is established it will become possible to develop a new composite with increased resistance to arcing.

V. CONCLUSIONS

On the basis of the research it can be concluded that:

- the thermal conductivity of insulating polymeric composites can be increased through the use of an inorganic compound with high thermal conductivity;
- the use of insulating materials (epoxy-fibreglass-mica tape, laminate, etc.) with thermal conductivity increased by 30% results in a 20°C drop in the temperature of the winding;
- if new materials with increased thermal conductivity are used as the slot insulation and a technology which eliminates the air-gaps between the winding and the slot material is applied, the slot's power can be increased by 10÷20% without changing its dimensions;
- the use of insulating materials with increased thermal conductivity in high-power electric machines will result in a reduction of the quantity of energy needed for their manufacture (smaller dimensions) or in reduced material costs (cheaper insulation) at unchanged dimensions and mass;
- the use of polymer composites with increased thermal conductivity will result in higher resistance of the insulation to surface discharges.

VII. REFERENCES

[1] M. Jäckel, "Thermal properties of polymer/particle composites at low temperatures", Cryogenics, 35, p. 713-716, 1995.

[2] R. Brommer, T. Karlson, D. Rudolfson, "Insulating micatapes with increased thermal conductivity", 28 August-3 September, Session CIGRE.

[3] L. Moroń, B. Zych, M. Adamowska, "Investigation of heat transport mechanism in electric insulation to be used for construction of energy-saving electrical equipment" (in Polish), Target Project No. 8, T10A 036 96C/3139, Wrocław, 1998.

[4] B. Zych, L. Moroń, M. Adamowska, "Investigation of effect of physical properties of composite material on degradation of surface under arcing and crawling currents" (in Polish), Technical Documentation, IEL/OW, 1997.

[5] Dry, solid insulating materials - resistance test to high-voltage, low current arc discharges, IRC 61621, 09, 1997.