Thermal Characterization of Insulated Wires and Coils for High-temperature Application

Pin CHEN[1,2*], Souad HARMAND[1], Ali RIAHI[1,2], Safouene OUENZERFI[1], Gabriel VELU[2], Raphaël ROMARY[2]

[1]Laboratoire d'Automatique, de Mécanique et d'Informatique Industrielles et Humaines (LAMIH-UMR CNRS 8201)
Université Polytechnique Hauts-de-France – 59313 Valenciennes
[2]Laboratoire Systèmes Electrotechniques et Environnement
Faculté des Sciences Appliquées, Technoparc Futura, Université d'Artois – 62400 Béthune
*(auteur correspondant : Pin.Chen@uphf.fr)

Abstract- With potential application for high-temperature electrical machine, resistive heating of ceramic insulated and mica-glass fiber tape wrapped nickel plated copper wires as well as four coils winded by these two insulated wires (two with extra cement impregnation) was investigated under infrared camera in present study. Compared with uninsulated nickel plated copper wire, two insulation methods can effectively reduce surface temperature. However, the assemblage of wires is unfavorable for heat dissipation and surface temperature increases significantly by comparing to single wire. Cement impregnation can considerably reduce surface temperature and responses slowly to heating power change.

Keywords: infrared technique; thermal insulation; high temperature; inorganic material; cement impregnation.

Nomenclature

A	heat exchange surface
Cp	specific heat capacity
D	diameter
g	gravity acceleration
Gr	Grashof number
h	natural convection coefficient
I	electric current
k	thermal conductivity
Nu	Nusselt number
P	heating power
Pr	Prandtl number
Q	heat flux
Ra	Rayleigh number
R_{th}	thermal resistance
T	temperature
U	electric tension
Greek symbols	
β	volume expansion coefficient
ε	emissivity
ρ	density
ΔT	temperature difference
μ	dynamic viscosity
σ	Stefan-Boltzmann constant

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1. Introduction

Electrical machines have been more and more frequently applied at high temperature and high voltage working conditions, for example applications in aerospace aircrafts [1], nuclear reactors [2] and geothermal systems [3]. In these fields, temperature rating up to 500 °C is an important challenge for thermal insulation of electrical windings. Common organic insulation materials cannot withstand temperature level more than 300 °C for long time with consequence of accelerated aging and metal oxidation. With high thermal resistance, inorganic composite materials are potential replacements for winding insulations of electrical machines at high temperature.

In this study, two types of inorganic materials are used for manufactures of high-temperature insulated wires: ceramic composite or more exactly a glass ceramic with several types of metal oxides constituting it and inorganic fiber tape. Ceramic insulated wire shows high temperature resistance but low bend radius which increases difficulty in conventional coil winding. The other inorganic insulated wire is mica-glass tape wound wire, which can be fabricated for coils by conventional winding method due to higher flexibility than ceramic insulated wire. However, the disadvantage of mica-glass tape wound wire is the large thickness of tape (about 200μm) which will create challenges for the miniature of electrical equipment. The conductor materials for two inorganic insulated wires are nickel plated copper. Copper is a good thermal and electric conductor and nickel layer was applied to prevent metal oxidation and ion diffusion between copper and insulation material. According to the research of D. Cozonc *et al.* [4], ceramic insulated wire shows lower partial discharge inception voltage than organic material, but it still satisfies the manufacturing of high-temperature electrical winding. The reason is that building defects (cracks and pores) of ceramic layer will become tiny channels for short circuit under high voltage. V. Iosif *et al.* tested ceramic insulated wire wound coils with very short term voltage spikes as high as 3.8 kV, but any partial discharge can be detected [5]. L. Fang *et al.* measured partial discharge inception voltage and breakdown voltage of ceramic insulated wire and mica-glass tape wound wire at low pressure for the sake of space environment simulation [6]. Ceramic insulated wire reveals low breakdown voltage but high thermal stability after high-temperature heating of 14 days. For mica-glass tape wound wire, breakdown voltage measurement is considerably deviated from standard value due to irregularly tape surface. Moreover, its dielectric performance is deteriorated with appearance of partial discharge after short term high-temperature heating.

All aforementioned studies were focused on dielectric characteristics of inorganic insulated wires. However, thermal characteristics of these wires have not been investigated, which is beneficial for cooling system optimization of electrical machines. In present study, thermal performances of ceramic insulated wire and mica-glass tape wound wire by resistive heating were investigated under infrared camera. Additionally, surface temperature evolutions of four types of coils, among which two have cement impregnation, were presented.

2. Experimental setup

The candidate wires with inorganic insulation are nickel plated copper wires with ceramic insulation and mica-glass tape, whose experimental results are compared with wire without any thermal insulation. Dimensions and properties of three wires are listed in Table 1 and 2 respectively. These two insulated wires are used to wind four type electrical coils. Among them, two coils are fabricated only by insulated wires and two coils have cement impregnation between wires. As good thermal conductor and flexible material, cement impregnation can dissipate heat from wires quickly and tolerate thermal expansion. For testing thermal characteristics of inorganic insulated wires and coils, an infrared camera (FLIR X6580SC, 640 × 512 pixels, 200Hz, 15 µm detector pitch) is utilized to measure surface temperature. The incertitude of temperature measurement is ±1 °C and the maximum is 300 °C. Candidate wires and coils are connected to a power supply which can provide heating power as much as 600 W. The measuring areas on surfaces of wires or coils are painted to become black, which are approximately considered as black bodies and then enable the calibrated infrared camera to guess the true surface temperature. Also a voltmeter is used to measure voltage applied on wires or coils and then applied heating power can be calculated. The environmental temperature is controlled at 23 °C by air conditioner. Each test is repeated for at least three times in order to guarantee repeatability.

	Diameter D	Heat exchange surface A
Wire	m	m^2
Nickel plated copper	4.65×10^{-4}	5.551×10^{-4}
Ceramic	5.13×10^{-4}	6.122×10^{-4}
Mica-glass	6.86×10^{-4}	8.189×10^{-4}

Table 1: *Sizes of testing wires*

	Density ρ	Thermal conductivity k	Specific heat capacity Cp	Emissivity ε
Material	$kg.m^{-3}$	$W.K^{-1}.m^{-1}$	$J.kg^{-1}.K^{-1}$	
Copper	8930	400	385	-
Nickel	9800	90.7	445	0.68
Ceramic	2510	1.5	900	0.77
Mica-glass	2882	3.5	866	0.71

Table 2: *Physical and thermal properties of materials*

3. Experimental results and discussions

3.1 Inorganic insulated wires

In this section, three candidate wires have the same length of 0.38 m and they were heated up gradually until maximum power of about 15 W. Surface temperature of each wire is the average value of measure area and an interval of 2 minutes under infrared camera when electric wire is at steady state. Figure 1 displays the relationship between heating power and surface temperature for three candidate wires. For all the wires, surface temperature increases linearly with augmentation of applied power. The formulas of fitting lines between surface temperature (T) and heating power (P) for mica-glass tape wound wire, ceramic insulated wire and nickel plated copper wire are T = 16.239 P + 24.573, T = 16.557 P + 21.491 and T = 17.369 P + 22.209 respectively. With same power supply, surface temperature of nickel plated copper wire will arrive at the highest level while that of wire insulated by mica-glass tape will be the lowest. However, during this heating power range, the difference of surface temperature is not significant between wires with thermal insulation. According to Table 2, nickel and copper have higher thermal conductivity and lower specific heat capacity than inorganic insulation materials. Therefore, heat can be conducted through these metals swiftly and self-temperature can be heated up more easily than inorganic insulation materials.

Figure 2 shows convective part and radiative part of total heat dissipation on wire surface as a function of heating power. Evidently, the most part of heat is removed by natural convection and convective heat flux increases linearly with heating power. Radiative heat flux takes small portion of total heat dissipation, but it increases exponentially with heating power. Consequently, radiation will be very important at high temperature, which is an inevitable challenge for the design of high-temperature electrical machine. For dissipating same quantity of heat, the proportion of natural convection is the highest for nickel plated wire while the lowest for mica-glass tape wound wire. Accordingly, radiative proportion is in completely inverse situation.

In addition to experiments, theoretical calculation and numerical simulation were also used to analyze thermal characteristics of three candidate wires. When the heat transfer of an electrical wire is at steady state, heat flux goes through different materials from core to external surface of wire by thermal conduction. Then heat is dissipated by thermal convection and radiation on wire surface.

a) Heating power:

$$Q = UI \tag{1}$$

Q is heat flux, U is electric tension, I is electric current.

b) Thermal conduction from core to external surface of wire:

$$Q = Q_{cond} = \frac{T_0 - T_1}{R_{th}} \tag{2}$$

T_0 is temperature at center of wire, T_1 is surface temperature of wire, R_{th} is global thermal resistance from center to external surface of wire.

c) Thermal convection and radiation on wire surface:

$$Q = Q_{conv} + Q_r = hA(T_1 - T_{air}) + \sigma\varepsilon A(T_1^4 - T_{air}^4) \tag{3}$$

A is heat exchange surface, T_{air} is air temperature, σ is Stefan-Boltzmann constant, ε is emissivity, h is natural convection coefficient which is calculated by following equations:

$$h = \frac{Nu \cdot k}{D} \tag{4}$$

$$Nu = \{0.6 + \frac{0.387Ra^{1/6}}{[1+(\frac{0.559}{Pr})^{9/16}]^{8/27}}\}^2 \text{ [7]} \tag{5}$$

$$Pr = \frac{\mu \cdot Cp}{k} \tag{6}$$

$$Gr = \frac{D^3\rho^2 g\Delta T\beta}{\mu^2} \tag{7}$$

for $Ra < 10^{12}$,

$$Ra = Pr \cdot Gr \tag{8}$$

where k is thermal conductivity of air, D is wire external diameter, Nu is Nusselt number, Ra is Rayleigh number, Pr is Prandtl number, Gr is Grashof number, μ is dynamic viscosity of air, Cp is heat capacity of air, ρ is density of air, g is acceleration due to gravity, ΔT is temperature difference between wire surface and air, β is volume expansion coefficient of air.

According to equation 1~8, surface temperature and convective heat transfer coefficient of each wire were calculated. At the same time, COMSOL Multiphysics® with heat transfer module was used to simulate heat dissipation process of each candidate. Figure 3 represents calculation and simulation results. Same as experiments, nickel plated copper wire shows the highest surface temperature, while the mica-glass insulated one has the lowest surface temperature for both theoretical calculation and numerical simulation. And the values of surface temperature estimated by theoretical analysis and simulation agree well with experimental results. Thus the theoretical equations can give some clues for the reason why the surface temperature of nickel plated copper wire is always the highest. Refer to equation 3, the coefficients hA and $\sigma\varepsilon A$, which influence on heat flux convective and radiative respectively, are the highest for wire with mica-glass tape and lowest for nickel plated copper wire on basis of theoretical calculation. Mica-glass tape wound wire has larger surface area and higher emissivity than nickel plated copper wire. Thus with assumption of same surface temperature or same temperature difference between surface and air, heat flux dissipated on surface of nickel plated copper wire is lower than that on mica-glass insulated wire surface. If it needs to remove same quantity of heat flux, nickel plated copper wire must have higher surface temperature or higher temperature difference between surface and air, which is in correspondence with research observations.

3.2 Inorganic insulated coils

In the second part of study, four types of inorganic insulated coils (two made from ceramic insulated wire, two wound by mica-glass tape, among which two coils have extra cement impregnation) were investigated under infrared camera. Figure 4 shows the temperature distribution of coil made from ceramic insulated wire. The surface temperature is measured at three different points of wire in order to verify temperature distribution homogeneity and the value is the average measurement for 2 minutes.

Surface temperatures of coils were measured at different heating power and temperature evolutions at measuring point 1 are represented in Figure 5. With same power supply, the temperatures of coils made from inorganic insulated wires are higher than the ones with cement impregnation. The coil of ceramic insulated wire possesses the highest surface temperature while the one of mica-glass tape wound wire is less hot, which agrees with investigations in first section of study. The two coils with cement impregnation show lower surface temperature and not large temperature difference between them due to more efficient heat dissipation by impregnation material. By comparing surface temperature measurements at three measuring points, surface temperatures of two coils with cement impregnation are very close. However, the temperature of point 3 is much lower than that of two other points for two cases without impregnation. The reason is that at point 3, the bunch of wires is looser with more space between wires, which is beneficial for heat dissipation.

When gradually heating these inorganic insulated coils, temperature of ceramic insulated one without impregnation increases faster than other coils (Figure 6.a). Surface temperatures of coils with impregnation increase more moderately and take more time to arrive at stable level. When suddenly stopping the heating, surface temperature of mica-glass tape wound coil without impregnation goes down the fastest among testing coils (Figure 6.b). This is because the wires wound by mica-glass tape have a larger diameter as well as exchange surface, so that heat can be removed more quickly. Temperatures of coils with impregnation rise and fall more slowly than cases without impregnation. Although impregnation material has relative high thermal conductivity, the volume of cement impregnation is exceedingly larger than ceramic insulation or mica-glass tape. With same quantity of heat flux, it takes more time to heat up cement impregnation by comparing with warm-up of very thin inorganic insulation layer. Similarly, for natural cooling of coils, the amount of heat stored in cement impregnation is considerably more than that in inorganic insulation materiel. Therefore, it needs more time to be dissipated in the air and surface temperature reduces to environmental level.

Figure 7 shows comparisons of surface temperatures between inorganic insulated wires and their winding coils as a function of current. Surface temperature of coil is found to be greatly higher than that of single wire with same current for both types of wire. This is can be explained by that the assemblage of wires reduces the space between wires, which deteriorates natural convection and increases surface temperature.

4. Conclusions

For electric wire tests, by comparing to nickel plated copper wire without thermal insulation we can conclude that inorganic insulation materials (ceramic and mica-glass tape) can effectively reduce surface temperature. Also, results of theoretical calculation and numerical simulation are similar to experimental observations. At experimental temperature range from ambient temperature to 300 °C, the main way of heat transfer on wire surface is natural convection. But the proportion of heat dissipated by radiation increases exponentially with heating power, which will be an important problem for application at very high temperature.

For electric coil tests, surface temperatures of coils fabricated by two inorganic insulated wires are significantly higher than the cases of single wire. In fact, less space between wires of coil leads to heat dissipation deterioration. The other two coils with cement impregnation show better heat transfer performance as well as lower surface temperature. Moreover, when suddenly starting or stopping the heating, surface temperature changes of coils with impregnation are more modest than cases without insulation due to heat storage effect of impregnation material.

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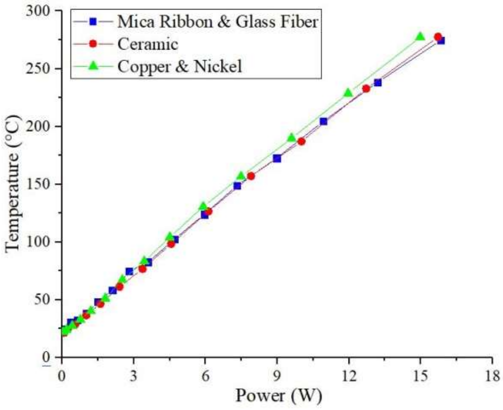


Figure 1: *Evolutions of surface temperature of three testing wires as a function of heating power*

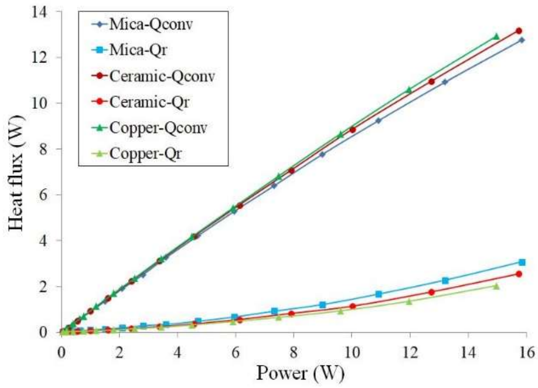
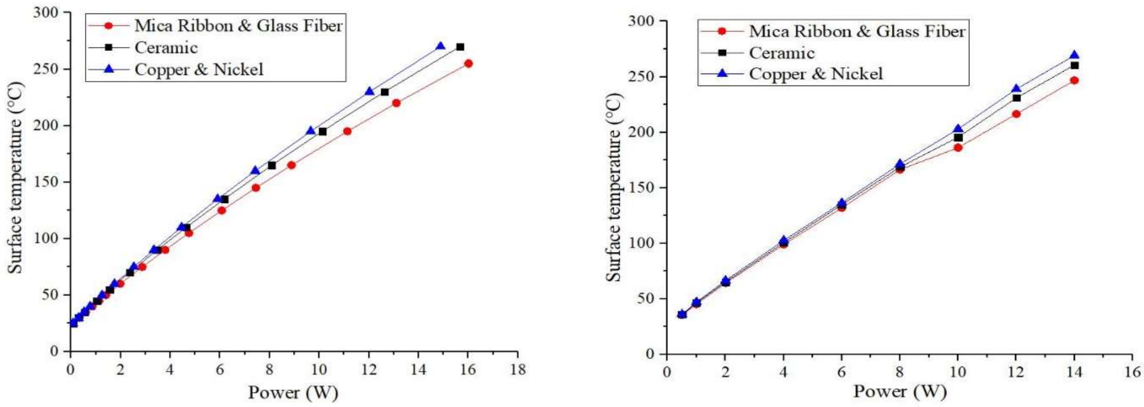


Figure 2: *Evolutions of heat transfer by convection and by radiation for three testing wires as a function of heating power*



(1) Calculation *(2) Simulation*

Figure 3: *Surface temperature of three testing wires obtained by (1) theoretical calculation and (2) numerical simulation as a function of heating power*

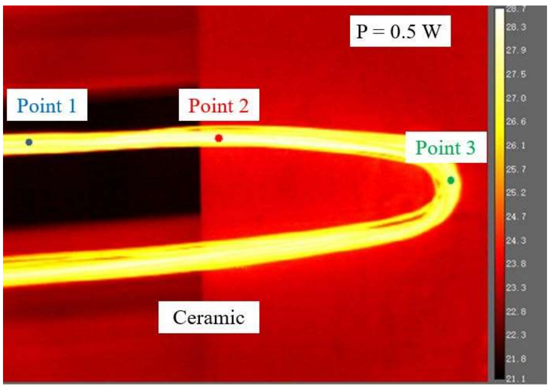


Figure 4: *Thermal mapping of electric coil made from ceramic insulated wire*

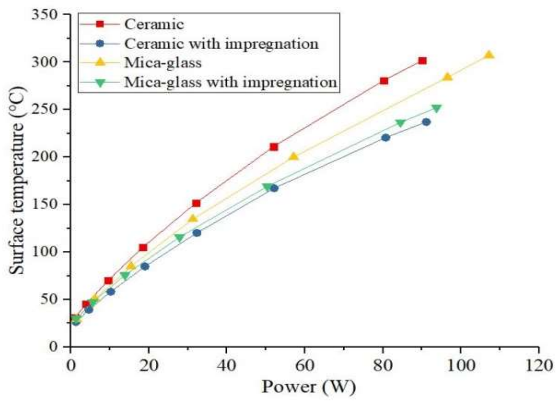
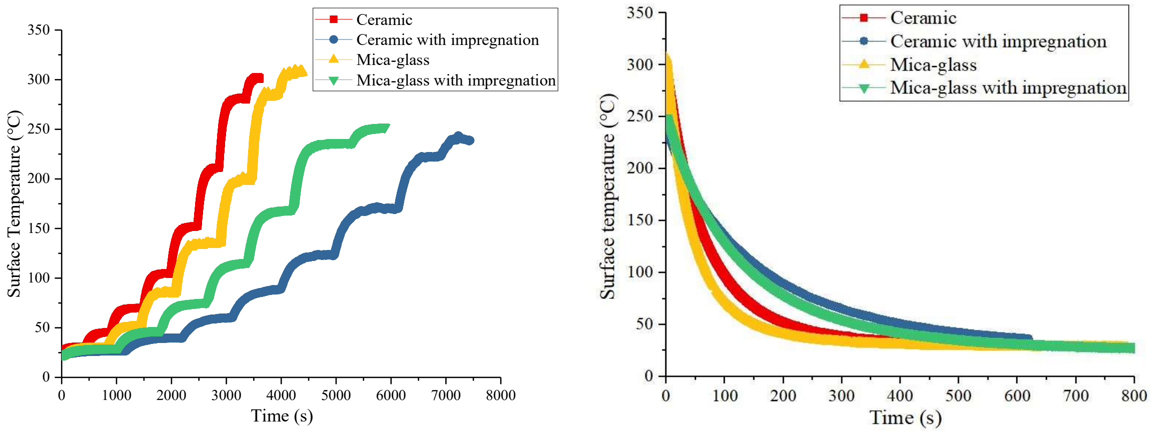
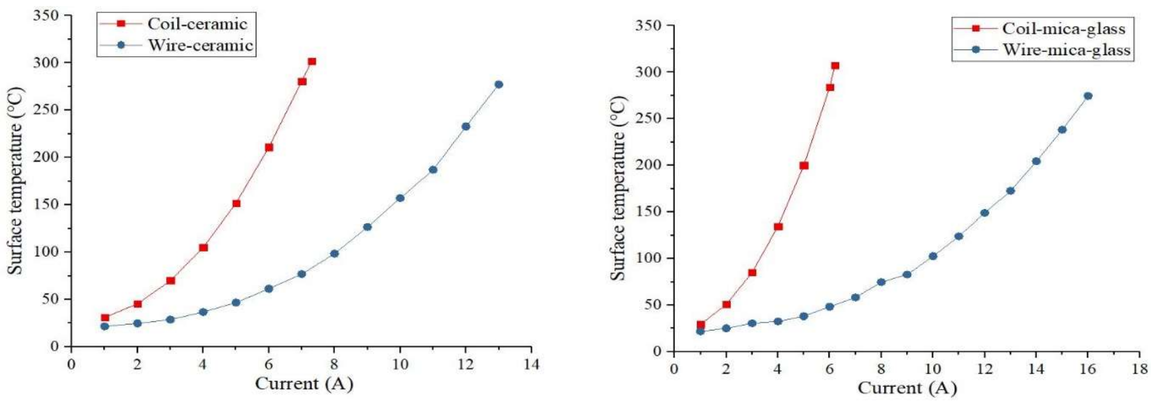


Figure 5: *Evolutions of surface temperature of four inorganic insulated coils as a function of heating power at measure point 1*



(a) Heating *(b) Cooling*

Figure 6: *Surface temperature evolutions when (a) heating and (b) cooling by natural convection at point 1*



(a) Ceramic *(b) Mica & Glass*

Figure 7: Surface temperature comparisons between electric wire and coil as a function of current

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