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

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INTRODUCTION

Electrical machines have been more and more frequently applied at high temperature and high voltage working conditions, for example applications in aerospace aircrafts, nuclear reactors and geothermal systems. 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.

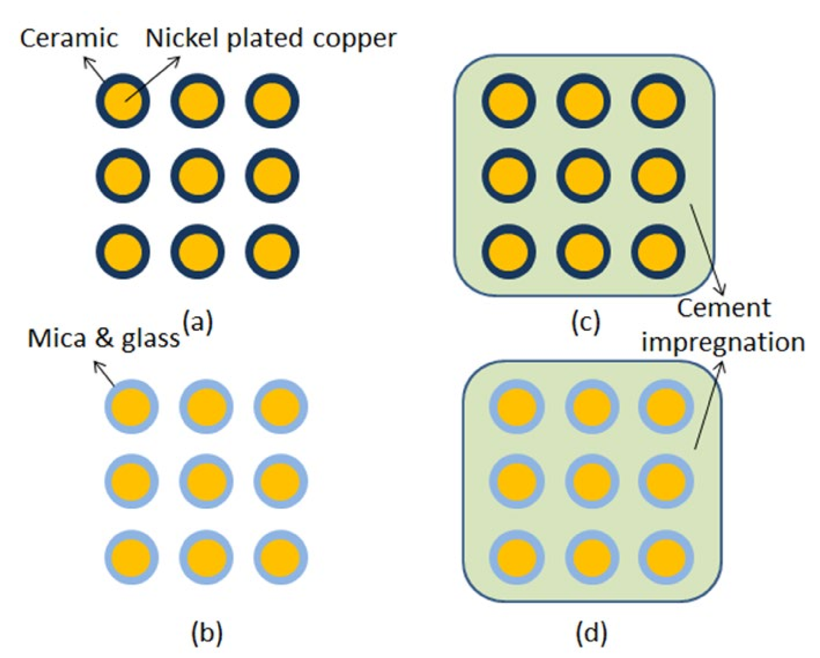
In this study, two types of inorganic materials are used for manufactures of high-temperature insulated wires: ceramic composite or more exactly a glass ceramic with several types of metal oxides constituting it and inorganic fiber tape. Ceramic insulated wire shows high temperature resistance but low 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.

EXPERIMENTAL PROCESS

Testing Materials

The candidate wires with inorganic insulation are nickel plated copper wires with <u>ceramic insulation</u> and <u>mica-glass tape</u>, whose experimental results are compared with wire without any thermal insulation. Then 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.

Material	Density (kg/m3)	Thermal conductivity (W/K·m)	Specific heat capacity (J/kg·K)	Emissivity
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



Investigation Methods

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.

In addition to experiments, theoretical calculation and numerical simulation (COMSOL Multiphysics® with heat transfer module) were also used to analyze thermal characteristics of three candidate wires.

- Heating power:

$$Q = UI$$

- Thermal conduction from core to external surface of wire:

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

- Thermal convection and radiation on wire surface:

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

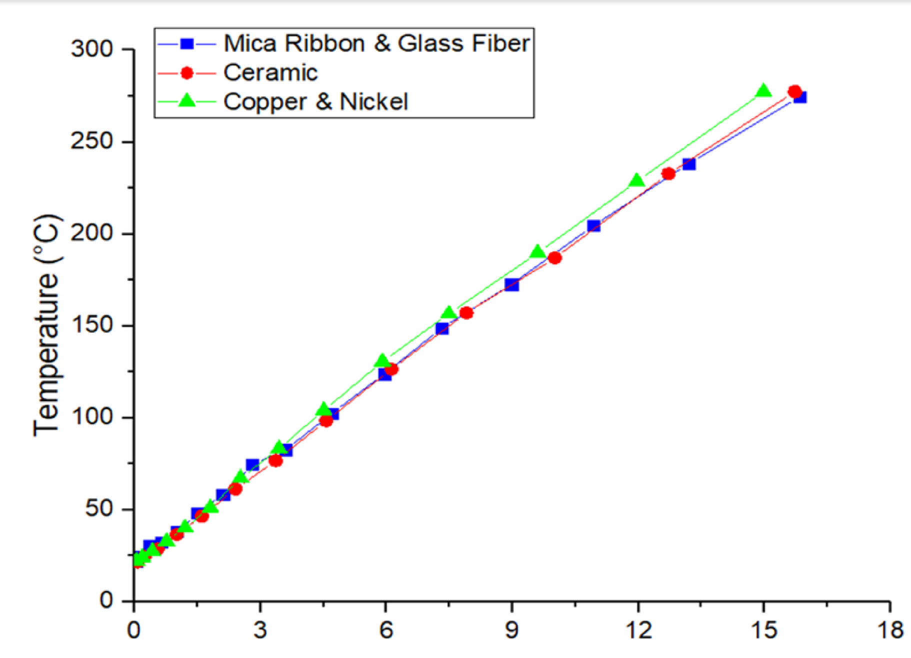
$$h = \frac{Nu \cdot k}{D}$$

$$Nu = \{0.6 + \frac{0.387Ra^{1/6}}{[1+(\frac{0.559}{Pr})^{9/16}]^{8/27}}\}^2 ; \quad Pr = \frac{\mu \cdot Cp}{k} ; \; Gr = \frac{D^3\rho^2 g\Delta T\beta}{\mu^2}$$

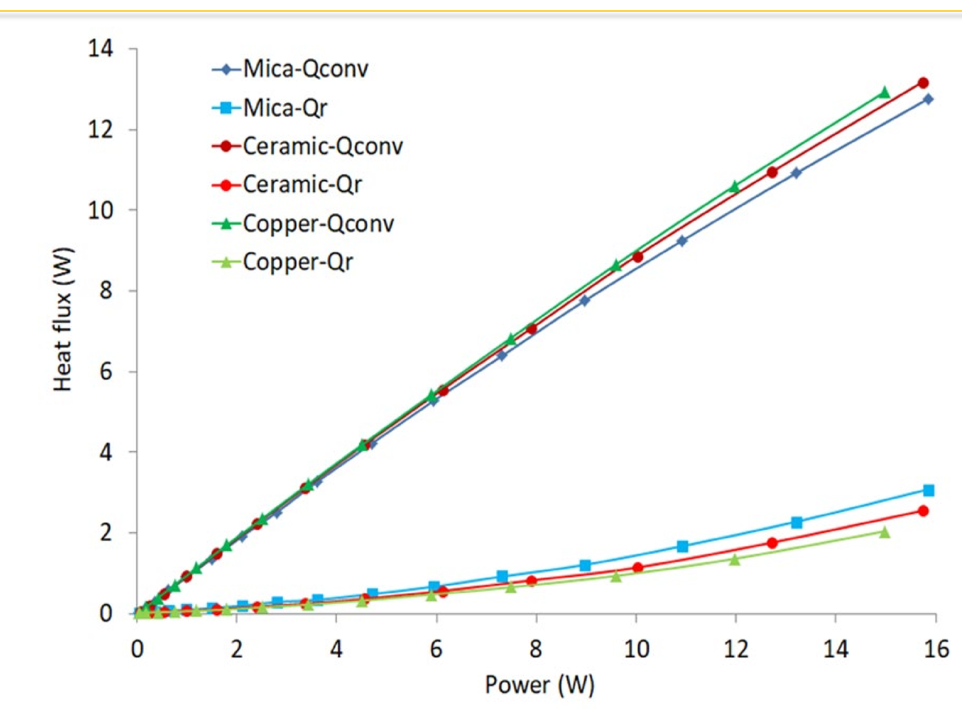
for $Ra < 10^{12}$, $Ra = Pr \cdot Gr$

RESULTS AND 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.

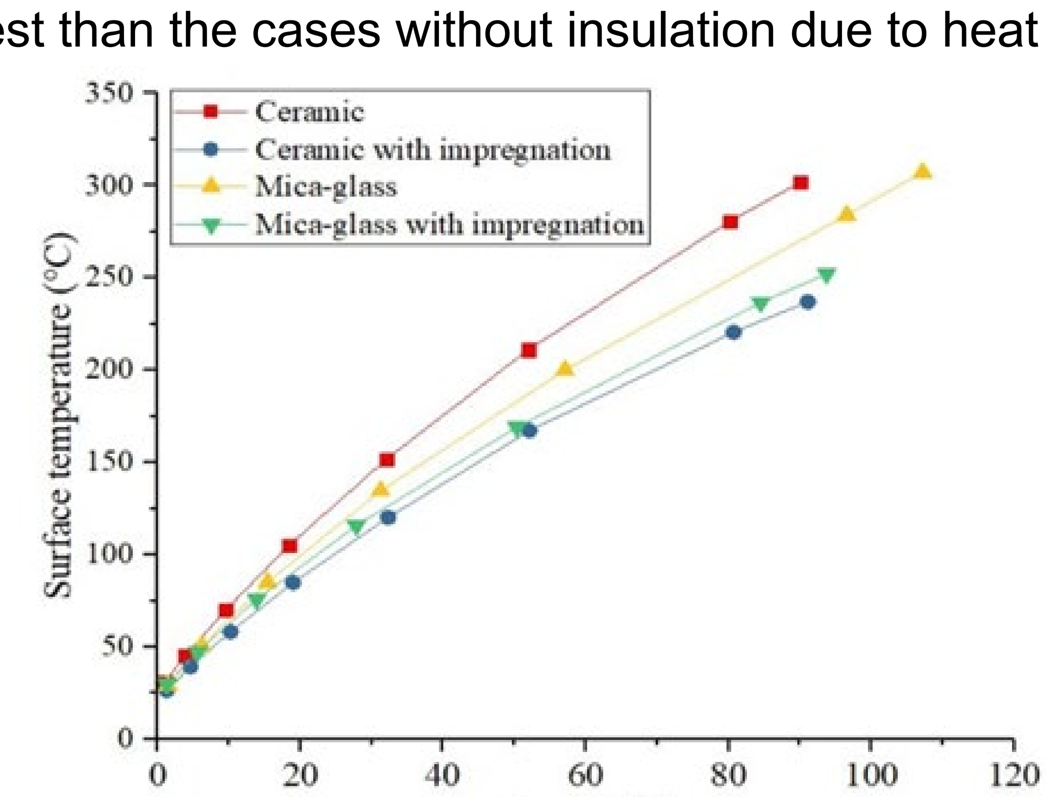


Evolutions of surface temperature of three testing wires as a function of heating power

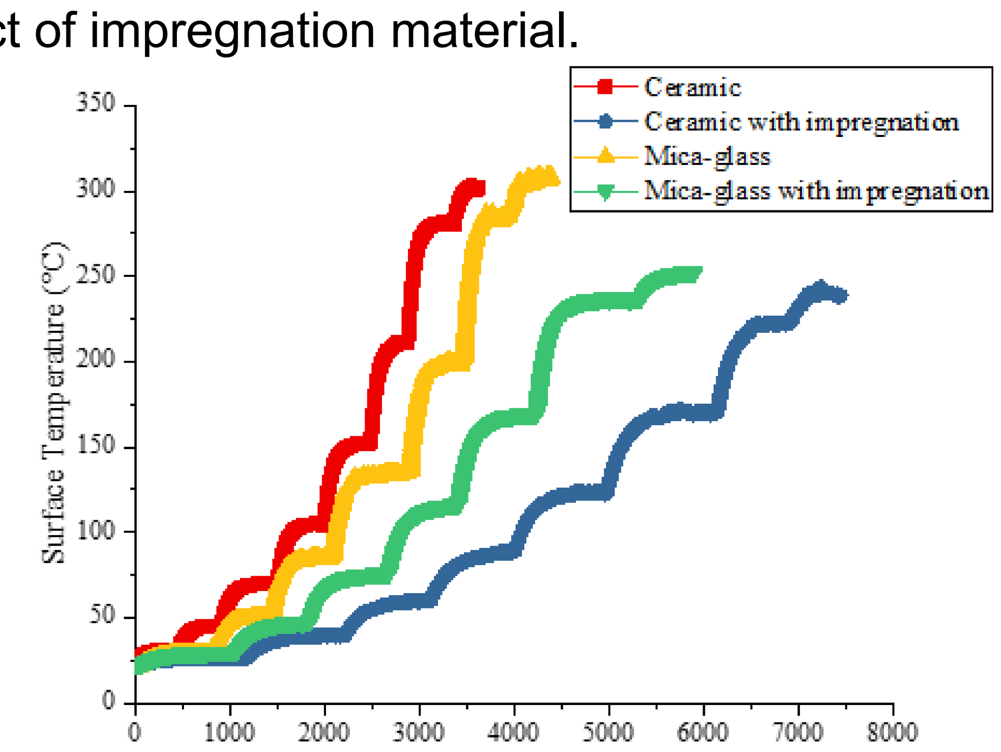


Evolutions of heat transfer by convection and by radiation for three testing wires as a function of heating power

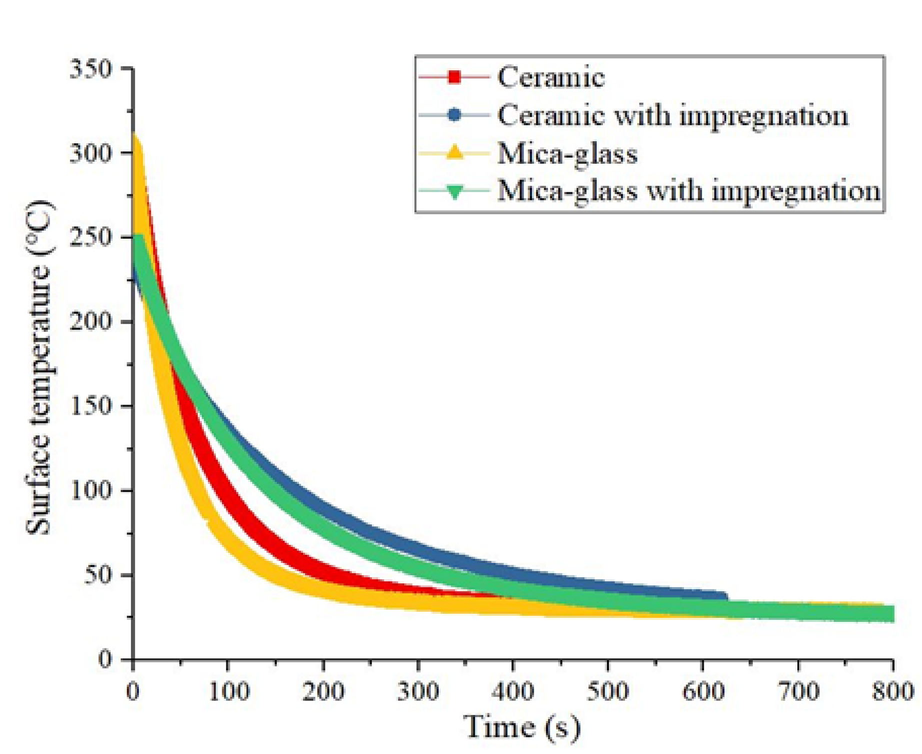
- For electric coil tests, surface temperatures of coils fabricated by two inorganic insulated wires are significantly higher than the cases of single wire. In fact, less space between wires of coil leads to heat dissipation deterioration. The other two coils with cement impregnation show better heat 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 the cases without insulation due to heat storage effect of impregnation material.



Evolutions of surface temperature of four inorganic insulated coils as a function of heating power



(a) Heating



(b) Cooling

Surface temperature evolutions when (a) heating and (b) cooling by natural convection

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