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

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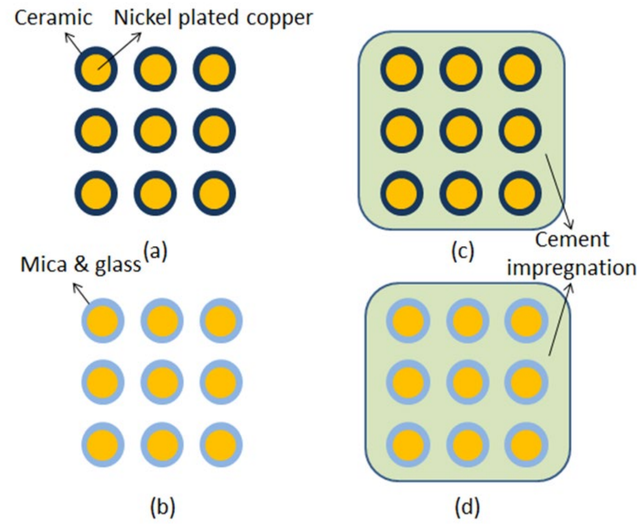
Research Context

- High temperature and high voltage working conditions is an important challenge for thermal insulation of electrical coils applied in electrical machines.
- Ceramic composite is potential candidate for thermal insulation material with high thermal resistance, but low flexibility leads to difficulty of coil fabrication.
- Mica-glass tape is another potential thermal insulation material with high thermal resistance and excellent flexibility, but the disadvantage is large thickness.

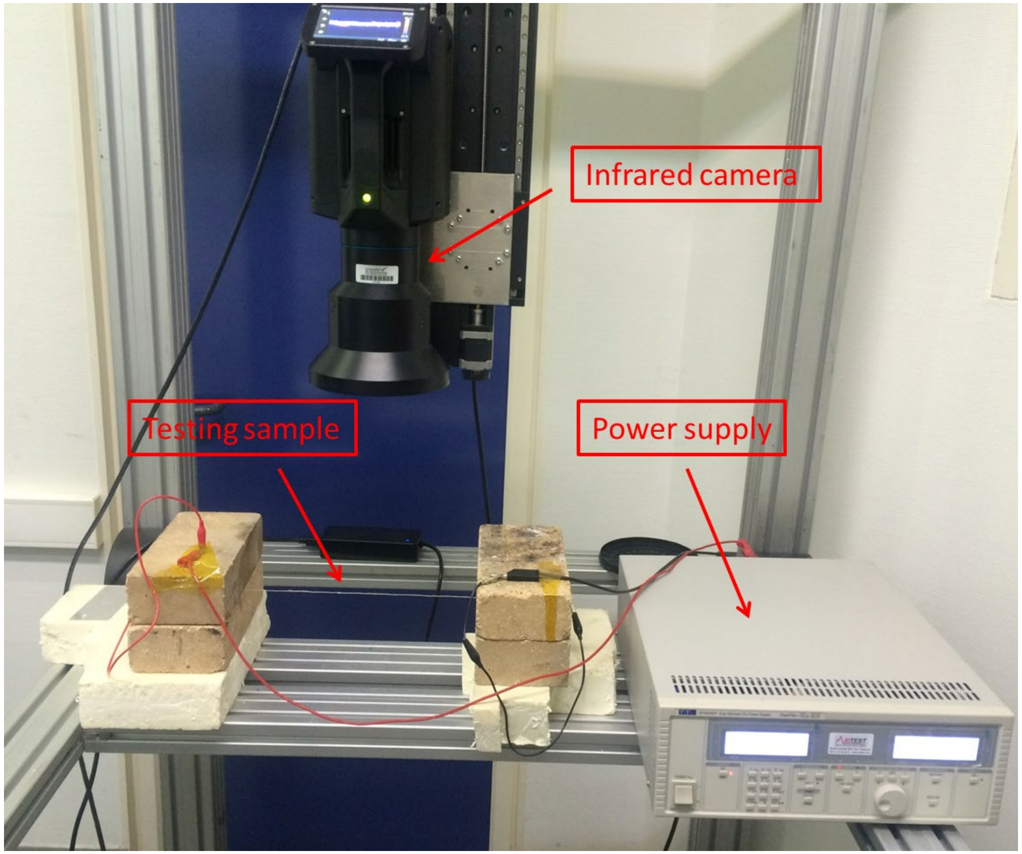
Electrical wires :
- Nickel plated copper without insulation
- Nickel plated copper with ceramic
- Nickel plated copper with mica-glass tape

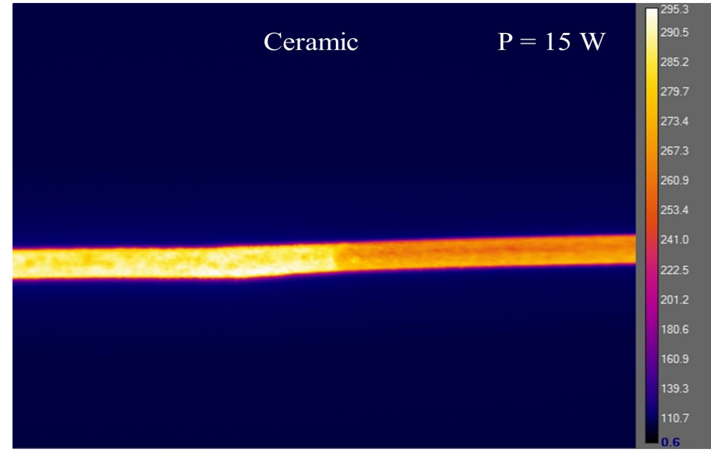
Electrical coils:
- Ceramic
- Mica-glass
- Ceramic with cement impregnation
- Mica-glass with cement impregnation



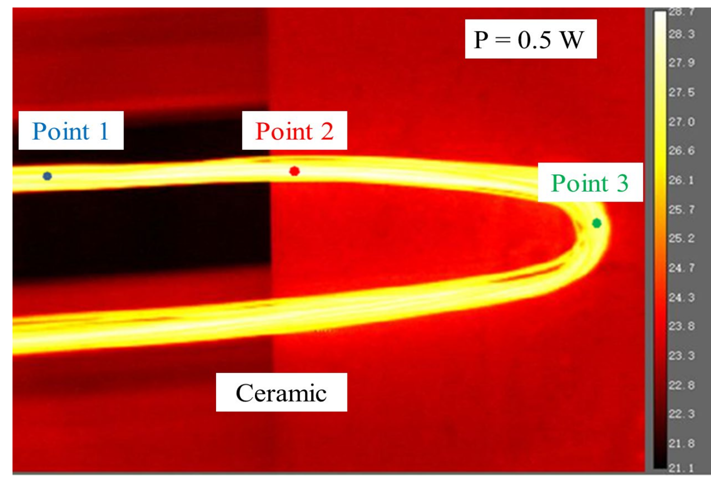
Cross-sections of coils made from nickel plated copper wire covered with (a) ceramic and (b) mica-glass, and same wires with (c, d) cement impregnation.

Experimental Setup





Electrical wire



Electrical coil

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Experimental Setup

1. Heating power: $Q = UI$

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

2. Thermal conduction from core to external surface of wire:

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

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.

3. Thermal convection and radiation on wire surface:

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

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:

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

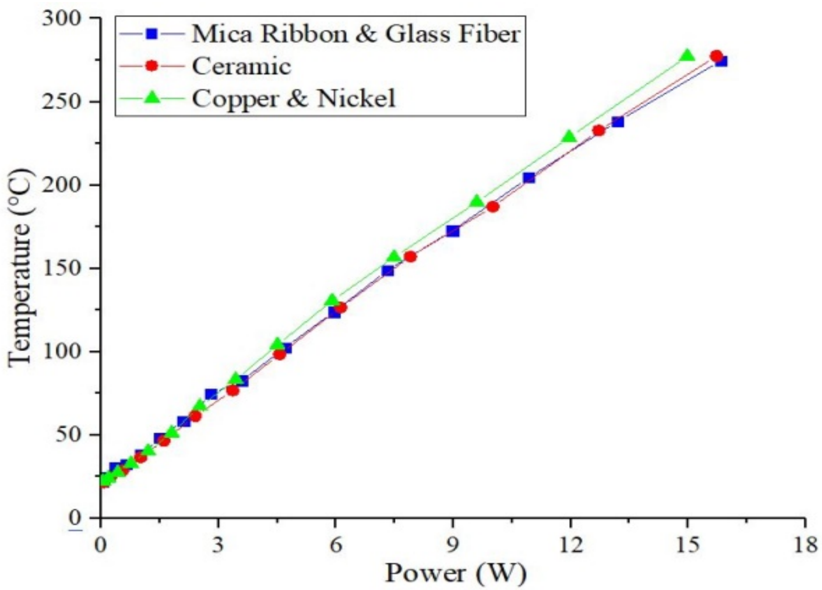
$$Nu = \{0.6 + \frac{0.387 Ra^{1/6}}{[1+(\frac{0.559}{Pr})^{9/16}]^{8/27}}\}^2 \; ; \; Pr = \frac{\mu \cdot Cp}{k} \quad ; \quad Gr = \frac{D^3 \rho^2 g \Delta T \beta}{\mu^2}$$

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

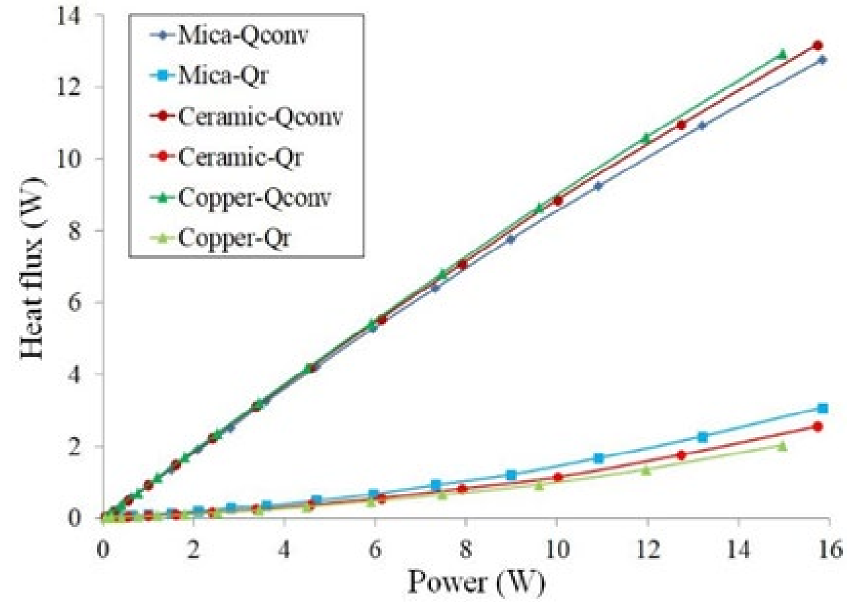
where k is thermal conductivity of air, D is wire external diameter, Nu is Nusselt number, Ra is Rayleigh number, Pr is Prandtl number, Gr is Grashof number, μ is dynamic viscosity of air, Cp is heat capacity of air, ρ is density of air, g is acceleration due to gravity, ΔT is temperature difference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

Experimental results and discussions

Electrical wires



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

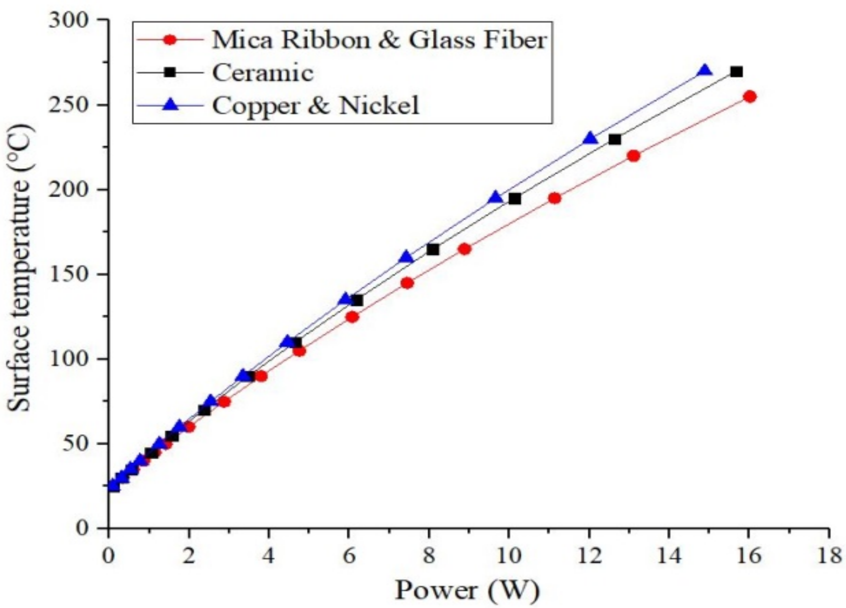
Formulas of fitting line :

- Mica-glass T = 16.239 P + 24.573
- Ceramic T = 16.557 P + 21.491
- Nickel plated copper without insulation T = 17.369 P + 22.209

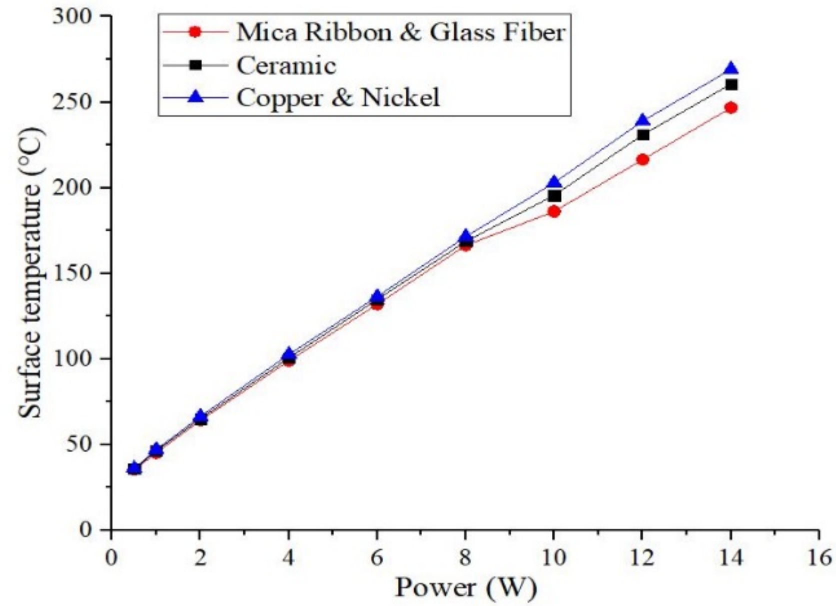
- The main heat dissipation method is natural convection.
- Radiative heat flux increases exponentially with heating power

Experimental results and discussions

Electrical wires



(1) Calculation



(2) Simulation

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

- Theoretical calculation according to aforementioned equations
- COMSOL Multiphysics® with heat transfer module was used to simulate heat dissipation process

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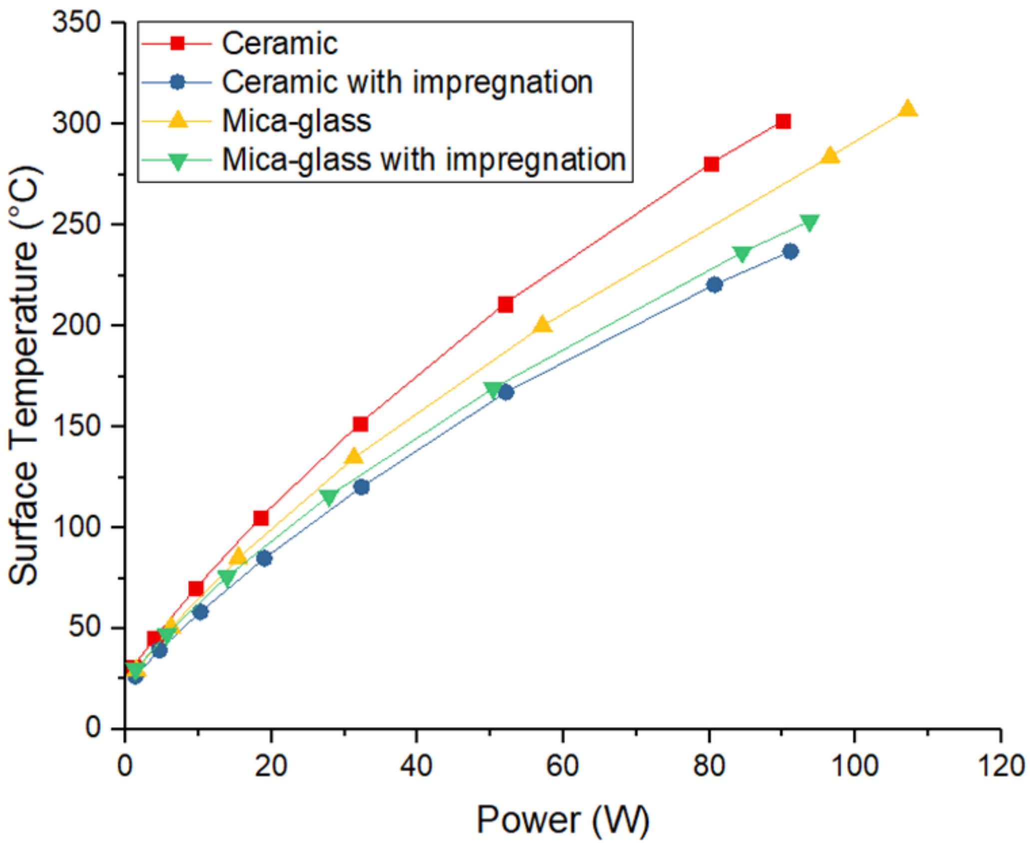
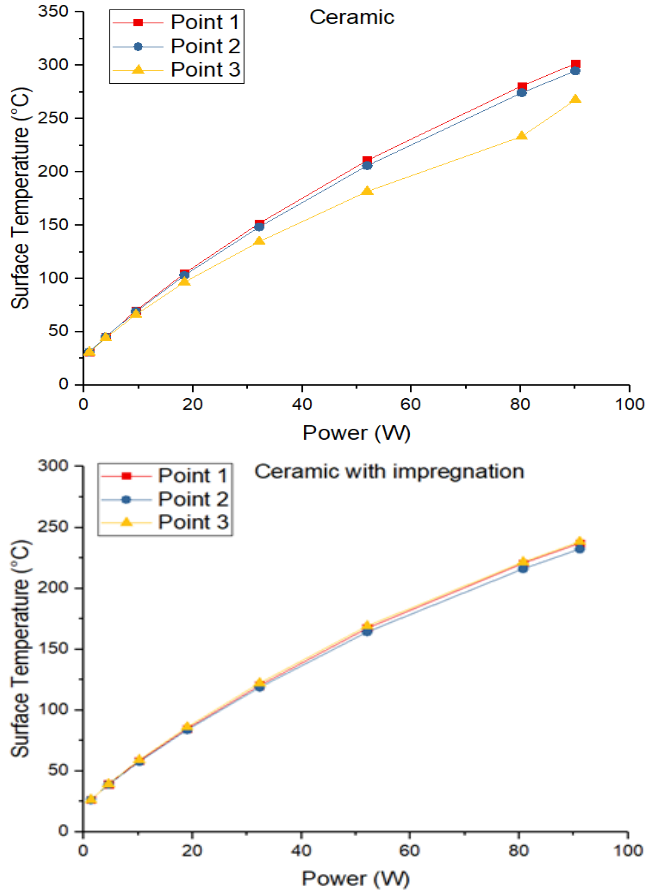
Experimental results and discussions

Electrical coils



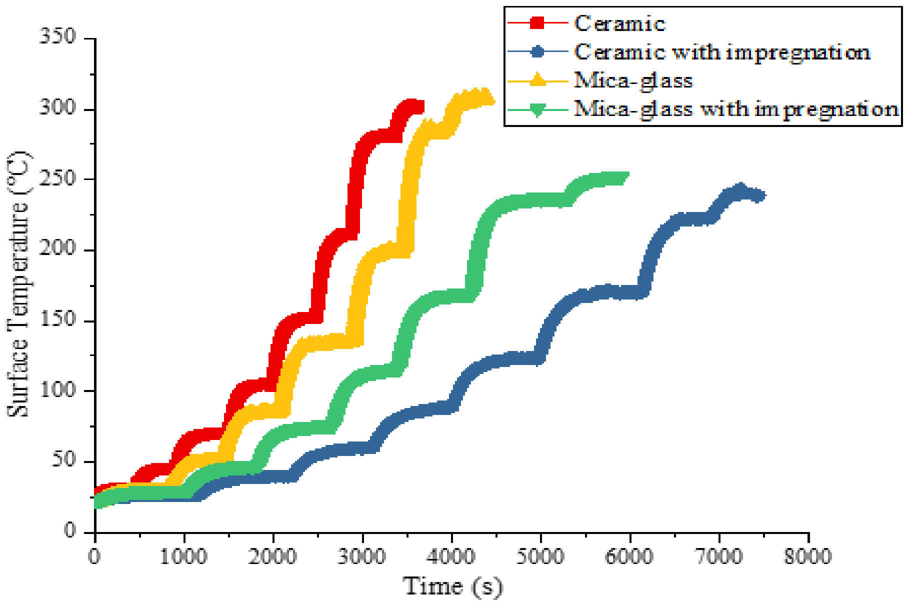
Evolutions of surface temperature of four inorganic insulated coils as a function of heating power at measure point 1



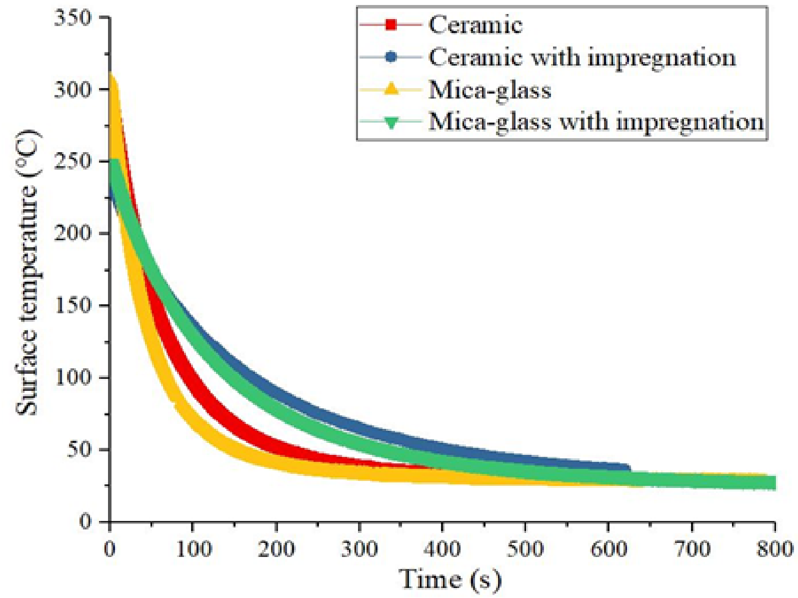
Comparisons of surface temperature among three measuring points as a function of heating power

Experimental results and discussions

Electrical coils



(a) Heating

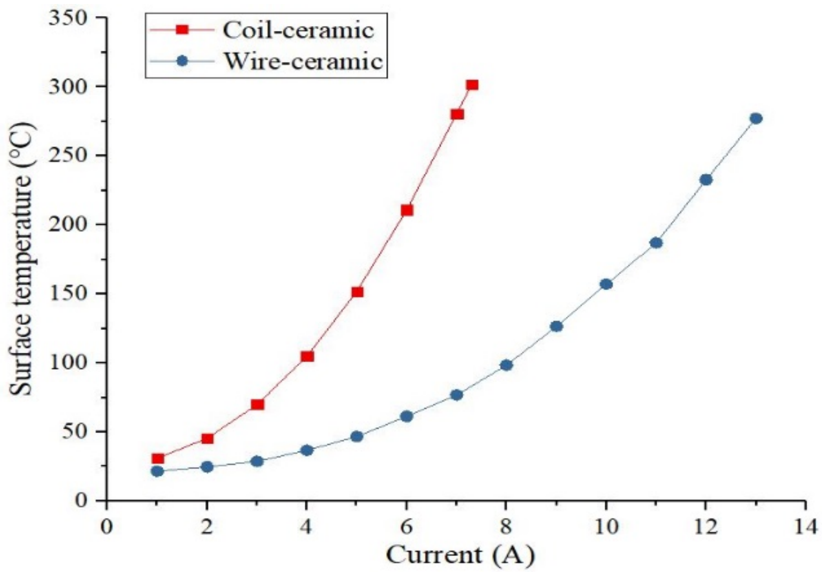


(b) Cooling

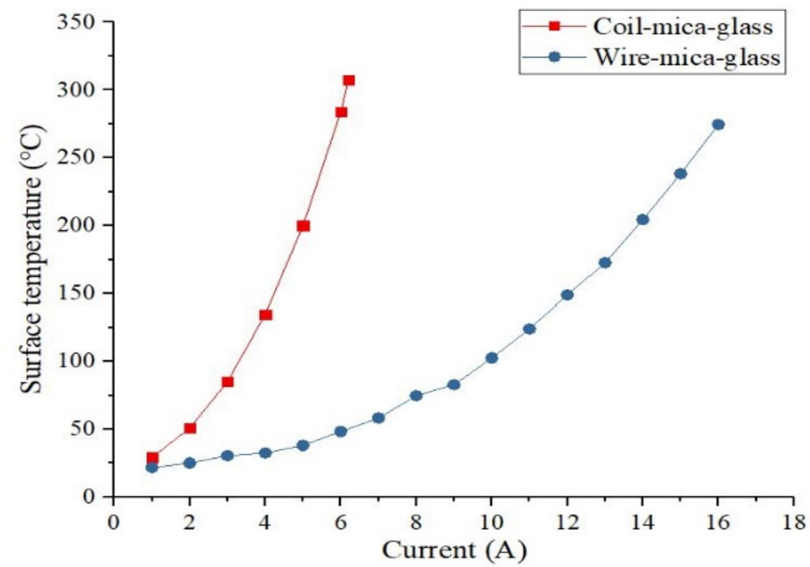
Surface temperature evolutions when (a) heating and (b) cooling by natural convection at point 1

Experimental results and discussions

Electrical coils



(a) Ceramic



(b) Mica-glass

Surface temperature comparisons between electrical wire and coil as a function of current

Conclusions

Electrical wires:

- Inorganic insulation materials (ceramic and mica-glass tape) can effectively reduce surface temperature.
- The main heat dissipation method on wire surface is natural convection at temperature range from ambient temperature to 300 °C.
- Radiative heat transfer increases exponentially with heating power, which will be an important problem for application at very high temperature.

Electrical coils:

- Surface temperatures of coils fabricated by two inorganic insulated wires are significantly higher than single wire and also the cases with cement impregnation.
- Cement impregnation can considerably reduce surface temperature and responses slowly to heating power change.

Thank You !