Thermal Analysis of a High Frequency Induction Coil for a Casting Furnace

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1. Introduction

Induction heating is used for various applications of the industrial manufacturing process such as heat treating, welding, and melting [1]. It is a complex process of coupling the electromagnetic and thermal phenomena, where eddy currents are generated with the conducting material and work as a source of Joule heating in the subject [2]. We used a commercial analysis program, OPERA 3D, for solving this thermal problem.

The induction furnace was consisted of induction coils, a graphite crucible, an insulator, a melting material, and a chamber. The coils generally have a cooling system to prevent damage in the coils against a high temperature generated by the system.

In this study, we have developed algorithms using conduction, a natural convection, an induction heating and experimental data in order to predict the maximum temperature of the coils, which have no any cooling systems when the graphite crucible achieved at 1500 ^{o}C. Temperature distributions in the induction furnace were calculated through this, during the melting.

2. Numerical Method

Numerical analysis of the induction heating requires the development of a coupling procedure between the electromagnetic and thermal problems. The eddy currents calculated from the electromagnetic solution are used as the heat sources for the thermal analysis.

2.1 Electromagnetic field

In electromagnetic analysis, the displacement currents can be neglected by magneto-quasi-static approximation [2]. Then, Maxwell's equations are

$$\nabla \times \mathrm{H} = \mathrm{J} \quad (1)$$
$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}} \quad (2)$$
$$\nabla \cdot \mathrm{B} = 0 \quad (3)$$

Ohm's law can be written as

$$\mathrm{J} = \sigma \mathrm{E} \quad (4)$$

where H is the magnetic field, J the electric current density, B the magnetic flux density, and σ is the electrical conductivity.

From eqn. (3) the magnetic flux density can be derived from the curl operation of another vector such that

$$\mathrm{B} = \nabla \times \mathrm{A} \quad (5)$$

where A is the vector potential. Using eqns. (1)~(5), the governing equation for current density can be derived as follows, which is called the dispersion equation.

$$\sigma \frac{\partial \mathrm{A}}{\partial \mathrm{t}} - \frac{1}{\mu} \nabla^2 \mathrm{A} = \mathrm{J_s} \quad (6)$$

where μ is the magnetic permeability and J_S is the source current density in the induction coil. In order to calculate the eddy current density in the workpiece, it requires boundary conditions.

2.2 Thermal field

Three dimensional thermal fields can be represented using a single scalar potential *T*. Physically, *T* is the usual temperature field. The thermal gradient intensity DT is given by,

$$\mathrm{DT} = -\nabla T \quad (7)$$

and the heat flux density q by,

$$q = \kappa \mathrm{DT} \quad (8)$$

where κ is the thermal conductivity.

The temperature distribution in the induction system is governed by the heat transfer equation [2],

$$\rho c \frac{\partial T}{\partial \mathrm{t}} - \nabla \cdot (\kappa \nabla T) = \mathrm{Q} \quad (9)$$

where ρ is the mass density, c is the specific heat capacity, κ is the thermal conductivity and Q the energy generated in the material per unit volume and time. The heat transfer equation determines the temperature distribution as a function of space and time. Once the temperature distribution is known, the heat flux within the body or by its surface can be calculated from eqn. (8).

The solution of the equation requires initial and boundary conditions at the interface between the workpiece and the air. Assuming the convection, the boundary condition is then,

$$\mathrm{q \cdot n = h \cdot (T - T_{ext})} \qquad (10)$$

where n is the normal vector, h the convection coefficient, T the temperature of the workpiece, and T_{ext} the ambient temperature.

3. Results

3.1 Model development

The casting furnace is a very complicated piece of equipment. Many different materials are used including graphite in the crucible, stainless steel in the chamber, alumina in the insulator, and copper in the coils.

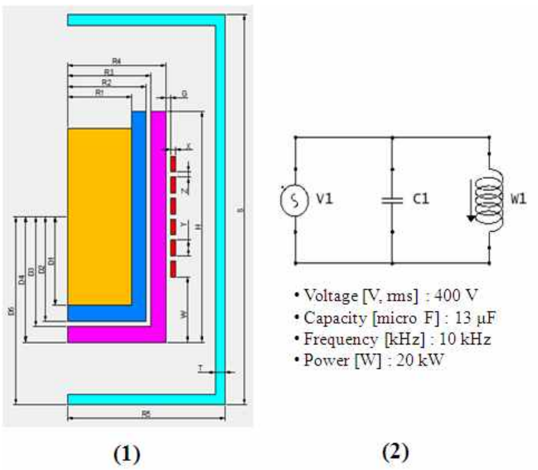

Fig. 1. (1) The schematic geometry of the induction furnace and (2) the circuit diagram of the input currents.

The model was considered on the 3D axis-symmetry and an alternating current which is 10 kHz and 20 kW was fed to the induction coils.

Material properties depending on the temperature follow the graph in Fig. 2.

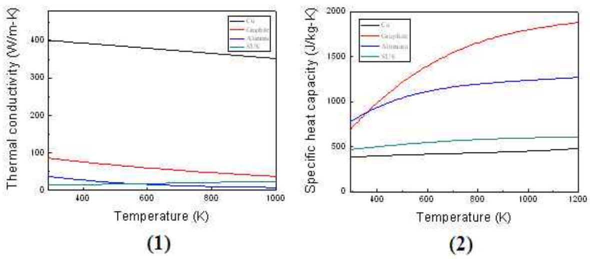

Fig. 2. (1) Thermal conductivity k, in W/m·K, and (2) Specific heat capacity c in J/kg·K of copper, graphite, stainless steel, and alumina [3].

3.2 Numerical results

Fig. 3. shows the temperature distribution in the induction furnace and coils when the maximum graphite crucible temperature is at 1500 °C.

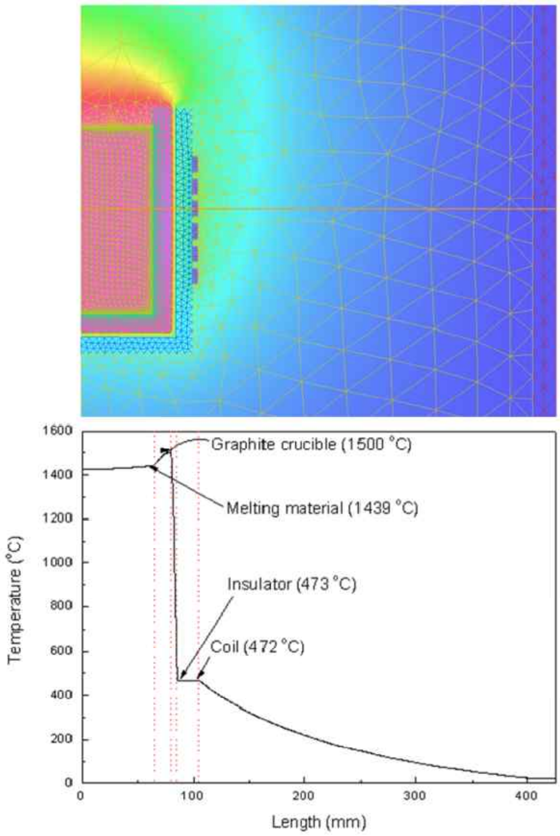

Fig. 3. Temperature distribution of the induction furnace and coils when the maximum graphite crucible temperature achieved at 1500 °C.

The maximum melting material (copper) temperature is at 1439 °C, the casting insulator is at 473 °C, and the coils at 472 °C.

4. Conclusions

Using the cylindrical model geometries, a thermal analysis algorithm was developed to predict the maximum temperature of the induction coils.

The algorithm was successful in predicting the maximum coils temperature when the maximum graphite crucible temperature achieved at 1500 °C. The result showed that the coils could maintain their function without any deformations during the melting operation in the induction furnace.

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[3] http://www.matweb.com/