Numerical Heat Transfer Analysis for Heat Generating Coil

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Numerical Heat transfer analysis of the heat generating coil is carried out using finite element method for this investigation. This paper describes the numerical results of the heat transfer from heat generating coil at different conditions. The parametric effects on heat transfer were investigated. The varied parameters included ambient conditions, as well as the shape of the cross-section. The numerical results show that the type of the medium where the heat generating coil immerges has strong effects on the heat dissipation rate. As the size of the diameter the heat dissipation to the ambient is decreased. The effects of free convection conditions on the coil surface are also significant. However, the effect of the shape of the cross-section is not very strong. The results presented in this paper provide useful information for the application of heat generating coil.

Introduction

Heat conduction with heat generation is one of the hot topics in the research area. It has wide applications in industry and our daily life, such as electrical furnaces, electrical heating appliances, and ventilation of computer chips. Among those heat conduction problems, the heating elements are the core topic of the heat conduction problems. Different heating elements demonstrate different characteristics in heat conduction. Among many different structures of the heating elements, the coil has been used in many areas because of its compact structure and large thermal expansion. This study has analyzed the heat transfer of the heat generating coil under different conditions by using the finite element method. It provides some useful information on designs and applications of heat generating coil.

Finite element method for heat conduction

In general, heat conduction problems can be studied by experimental, analytical, and numerical methods. In this study, the finite element method is used. Heat conduction problems could be divided into two categories: the steady state and the unsteady state. In a three dimensional heat conduction with internal heat generation problem, the unsteady state temperature distribution T*(x,* y, z, τ) in a Cartesian coordinator system in the **Ω** domain can be solved by the following differential equation:

$$\rho c\frac{\partial T}{\partial \tau}-\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)-\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)-\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-Q=0 \quad (1)$$

The boundary conditions for solving this equation should meet the following conditions in the **Ω** domain:

$$\Gamma_1 + \Gamma_2 + \Gamma_3 = \Gamma$$

Where, $\Gamma 1$, Γ_2, Γ_3 are I[st], **2**[nd], and **3**[rd] types of boundary conditions, respectively. If T and *Q* are unchanged with the time the Equation **(1)** becomes the steady state heat conduction equation with the heat generation.

In the finite element method, Galerkin's approach can be used to convert the heat conduction equation (1) to the finite element equation'". The corresponding finite element matrix of the unsteady state heat conduction is given as follows:

$$\mathbf{CT' + KT = F} \qquad (2)$$

Where, C is the matrix of the heat capacity, K is the matrix of the heat conduction, T is the matrix of temperature, and F is the matrix of the temperature loading. In Equation (2) if the first term becomes zero, the equation becomes the steady state heat conduction finite element equation.

For a 2-Dimentional heat conduction problem, the elements of the matrix could be expressed as

$$K_{ij} = \sum_e K_{ij}^e + \sum_e H_{ij}^e \qquad (3)$$

$$F_i = \sum_e F_{Qi}^e + \sum_e F_{qi}^e + \sum_e F_{Hi}^e \qquad (4)$$

Each term in Equations 3 and 4 can be expressed as followings: The contribution of each cell to the matrix of heat conduction:

$$K_{ij}^e = \int_{\Omega^e} \left(k \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + k \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} \right) d\Omega$$

The correction of heat transfer boundary condition of each cell to the matrix of heat conduction:

$$H_{ij}^e = \int_{\Gamma_3^e} h N_i N_j d\Gamma$$

The temperature loading generated by heat souse in each cell:

$$F_{Qi}^e = \int_{\Omega^e} \rho Q N_i N_j d\Omega$$

The temperature loading from constant surface heat flux:

$$F_{qi}^e = \int_{\Gamma_2^e} q N_i d\Gamma$$

The temperature loading from the convection on the surface:

$$F_{Hi}^e = \int_{\Gamma_3^e} h T_a N_i d\Gamma$$

Where, *Ni****,*** *Nj* are the weighing functions. For a 3-Dimentional heat conduction problem, a similar method can be used for deriving the corresponding finite element equation of heat conduction.

Results and discussions

A coil is a typical structure used for generating heat. Figure 1(a) shows the schematic of a coil. The shape of the cross-section of the coil is circular. The finite element model of the coil is shown in figure 1(b).

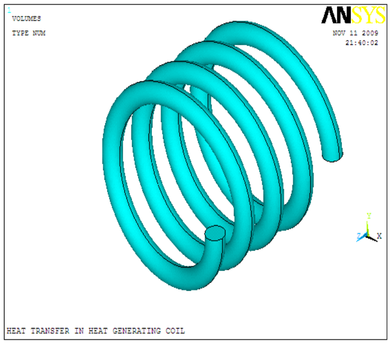


Fig.-1 (a) Model of solid coil

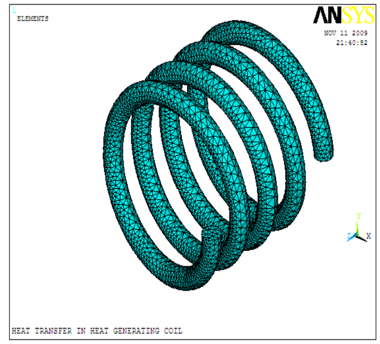


Fig.-1 (b) FEM of coil

List of parameters used for the baseline case in this study are as under.

Diameter of coil	0.5m
Length of coil	5m
Heat generation rate	30 kW/m^3
Heat transfer coefficient	60 W/m^{2}K
Conductivity of Pure Copper	401 W/m K
Ambient Temperature	30^{o}C

Based on the above heat conduction analysis using the finite element method, the problem of heat generating coil is solved by ANSYS 9 analysis software for above set of parameters. The temperature distribution within the heat generating coil is shown in figure.

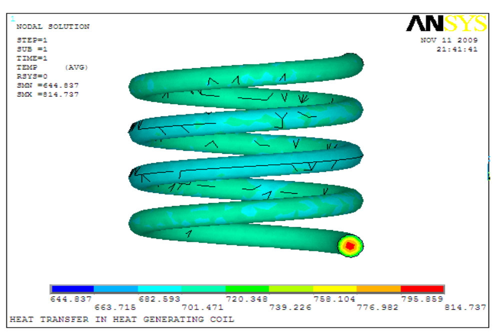


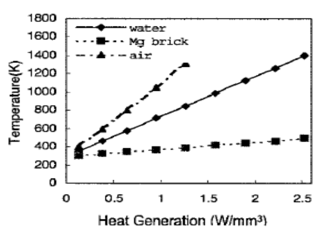
Figure 2- : Temperature distribution in Heat Generating Coil

Effects of medium type

Figure 3 shows the surface temperature versus the heat generation at different types of mediums. At the same heat generation rate, the surface temperature is different at different medium. The air and water has small heat conductivity, the corresponding surface temperature is therefore higher. However, the Mg brick's heat conductivity is high, causing high heat transfer rate between the coil and the Mg brick and thus low surface temperature of the coil.

Effects of free convection

When the free convection in the air is considered, the surface temperature decreases significantly as shown in Figure 4. This indicates significant impacts of the free convection to the heat transfer between the coil and the air. When heat generation increases, the surface temperature also increases, but with smaller increment because the free convection causes lower heat resistance.



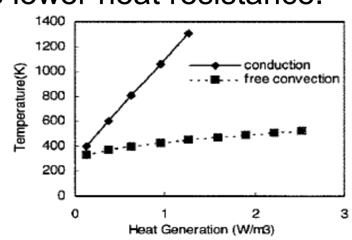


Figure 5: Effect of Materials

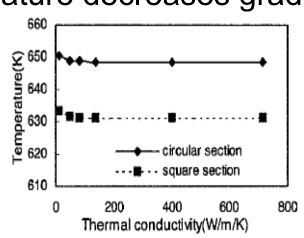
Figure 6 : The Effects of Diameter

Effects of Materials

Different material has different heat conductivity. Figure 5 shows the effects of material of coils. It plots the relationship between the surface temperature and the thermal conductivity for 6 different materials. The surface temperature decrease slightly with the increases of heat conductivity when the heat conductivity is less than 50 W/m.K and then show little effects afterwards.

Effects of Diameter

Figure 6 shows the effect of the diameter of the coil on the surface temperature. For a given heat generation rate, when the diameter increases, initially the surface temperature decreases very rapidly and then the surface temperature decreases gradually.



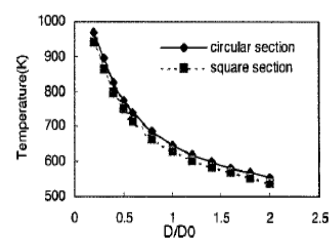


Figure 5: Effect of Materials

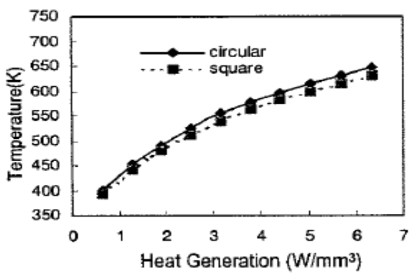
Figure 6 : The Effects of Diameter

Effects of Heat Generation Rate

Figure 7 shows the effect of heat generation rate. As expected, the higher the heat generation rate, the higher the surface temperature.

Effects of Ambient Temperature

This paper has also studied the effects ambient temperature on heat transfer. As shown in Figure 8 at low ambient temperature, there is little change of the surface temperature with the ambient temperature. At higher ambient temperature, the surface temperature increases with the increase of ambient temperature.



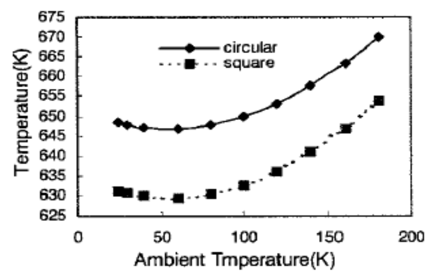


Figure7: Effects of Heat Generation   Figure 8: Effects of Ambient Temperature

Conclusion

This paper has established the heat conduction model of the finite element method based on the basic theory of heat conduction. Numerical analysis was conducted for various heat generating coil. A number of computations were performed to investigate parametric effects on heat transfer. It is found that the type of medium and the free convection have significant impacts on heat transfer between the coil and the medium. The effects of the area and the diameter of the coil are relatively large. There is almost no effect of type of materials. In general, the increase of heat generation rate and ambient temperature causes higher surface temperature.

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