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Magneto-Thermal-Fluid Analysis Taking Account of Natural Convection Using Semi-Lagrange Coordinate System

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Abstract - The method for magneto-thermal-fluid analysis taking account of natural convection using semi-Lagrange coordinate system is developed. The developed method is applied to a simple induction heating model in which the steel plate is heated due to eddy current. It is shown that the result considering the convection in air is different from the result neglecting it.

Index terms - Magneto-thermal-fluid analysis, semi-Lagrange coordinate system, natural convection

I. INTRODUCTION

In order to evaluate the temperature rise of an electrical machine due to joule loss or iron loss, the magneto-thermal field analysis, in which the heat transfer coefficient is given on the surface of machine and only the temperature in the machine is calculated, has been carried out[1]. However, the heat transfer coefficient is affected by the convection around the machine. Therefore, the convection should also be taken into account in order to calculate the temperature rise accurately.

In this paper, the magneto-thermal-fluid analysis method taking account of natural convection is developed. Firstly, the method for thermal-fluid analysis using the semi-Lagrange (moving) coordinate system, in which the velocity of fluid is defined by the Euler (fixed) coordinate system and the time derivative term is calculated using the Lagrange coordinate system, is developed. The Lagrange coordinate system has some advantages compared with the Euler coordinate system in the eddy current analysis in the moving conductor[2]. Secondly, the method of combining the magnetic field analysis with the thermal-fluid analysis is described. Finally, the calculated temperature rise is compared with measurement in a simple induction heating model.

II. METHOD OF ANALYSIS

A. Magnetic Field Analysis

In the magnetic field analysis, A - ϕ method (A : magnetic vector potential, ϕ : electric scalar potential) is used. The fundamental equations are as follows:

$$\text{rot}(\text{vrot}A) = J_o - \sigma \left(\frac{\partial A}{\partial t} + \text{grad}\phi \right) \quad (1)$$

$$\text{div} \left\{ -\sigma \left(\frac{\partial A}{\partial t} + \text{grad}\phi \right) \right\} = 0 \quad (2)$$

where J_o is the magnetizing current density, v and σ are the reluctivity and electric conductivity, respectively.

B. Thermal Analysis

In the thermal analysis, the following heat-conduction equation is used[3]:

$$\rho_0 c \frac{DT}{Dt} = \text{div}(\kappa \text{grad}T) + Q \quad (3)$$

where T is the temperature and ρ_0 is the mass density at the reference temperature T_0 . c and κ are the heat capacity and the thermal conductivity coefficient, respectively. Q is the heat source density. D/Dt denotes the time derivative using the Lagrange coordinate system.

C. Fluid Analysis of Natural Convection

In the fluid analysis of natural convection, the following Navier-Stokes equation[3] with penalty function[4] is used:

$$\rho_0 \frac{Dv}{Dt} = \bar{\lambda} g \text{grad} \text{div} v + \eta \nabla^2 v + \rho_0 g \beta (T - T_0) \quad (4)$$

where v is the velocity vector and g is the gravity acceleration vector ($=9.8\text{m/s}^2$). η and β are the viscosity and the coefficient of volume expansion, respectively. $\bar{\lambda}$ is penalty number. In the first term on right-hand side (penalty term), the reduced integration technique[4] is applied.

D. Time Differential Term

The Lagrange coordinate system is applied to the time differential terms in (3) and (4). For example, the time derivative $DT_p^{t+\Delta t}/Dt$ at the point p at the instant $(t+\Delta t)$ can be discretized using the backward difference method as follows:

$$\frac{DT_p^{t+\Delta t}}{Dt} = \frac{T_p^{t+\Delta t} - T_q^t}{\Delta t} \quad (5)$$

where Δt is the time interval. q means the position where the point p at the instant $(t+\Delta t)$ existed at

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the instant t . The position of point q_1 in the fluid shown in Fig.1 (CASE 1) is obtained by deducting $v\Delta t$ from the position of point p_1 . If the position of point q_2 is in the solid (CASE 2) or the position of point q_3 is out of the analyzed region (CASE 3) as shown in Fig.1, the points q_2 and q_3 are moved to the positions of intersections q_2^* and q_3^* .

E. Coupled Method

The flow chart for magneto-thermal-fluid coupled analysis is shown in Fig.2, and it is explained as follows:

- ① The distribution of heat source due to eddy current loss in a conducting body (solid) is obtained from the magnetic field analysis. The ac steady state magnetic field analysis is carried out because the time constant is very small compared with that of thermal analysis.
- ② The time interval Δt is calculated by the velocity of fluid considering the maximum movement during Δt .

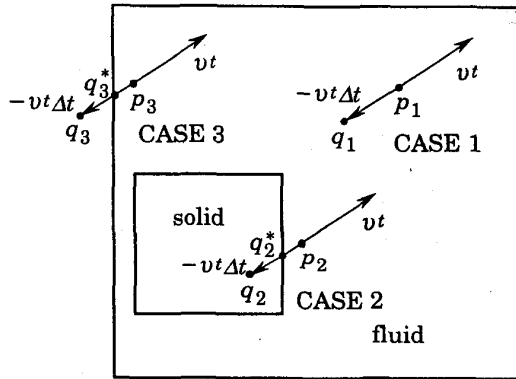


Fig. 1. Solid and fluid.

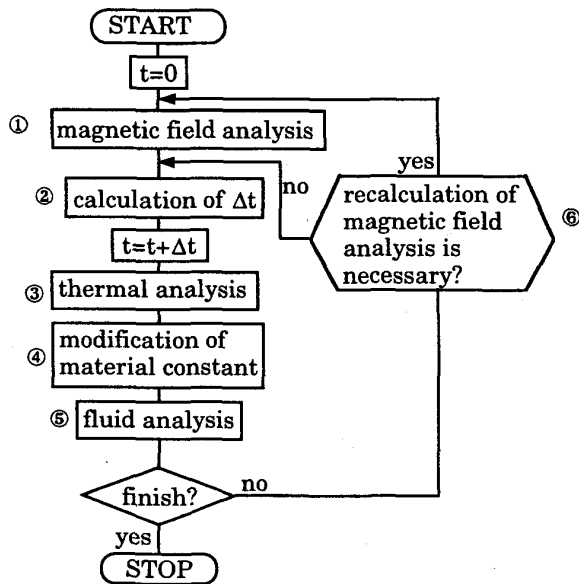


Fig. 2. Flow chart.

- ③ The temperature distribution in and around the conducting body is calculated by thermal analysis.
- ④ The material constant for thermal and fluid analyses, such as η , is modified by the temperature rise obtained from thermal analysis.
- ⑤ The velocity of fluid due to natural convection around the conducting body is calculated by fluid analysis.
- ⑥ The thermal and fluid analyses are iterated until the material constant for magnetic field analysis, such as σ , is modified due to the temperature rise.

III. VERIFICATION MODEL

The developed code is verified by comparing the calculated result with measured one. A simple induction heating model composed of a coil and a steel plate (SS400) set in a box made of the heat insulating material (foam polystyrene) shown in Fig.3, is chosen as a verification model. The temperature in the steel plate rises due to the eddy current loss in the steel plate and joule loss in the coil when the coil is excited by ac current (max155AT, 1kHz). The material constants at 20 °C are shown in TABLE I. The relative permeability of the steel plate is set to 2000. This value is obtained from the measured average flux density (0.144T) of the steel at $z=0$. The transient analysis is carried out until $t=600s$ from the initial temperature 20 °C.

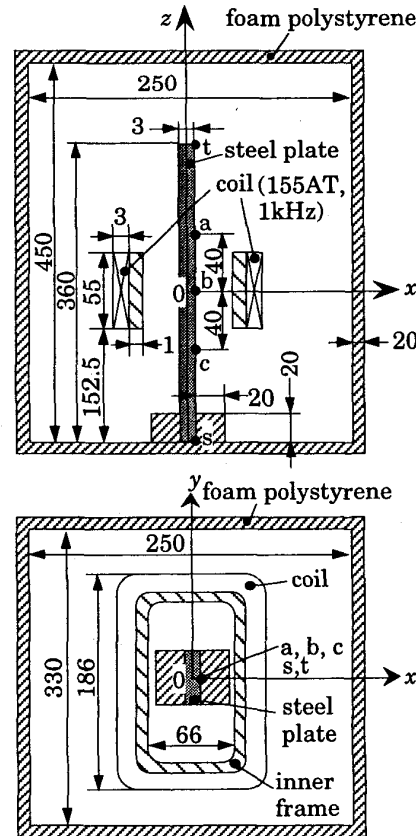


Fig. 3. Verification model.

TABLE I
MATERIAL CONSTANTS (20°C)

material	steel plate (SS400)	coil (copper)	inner frame of coil (paper)	air
relative reluctivity ν_r	1/2000	non-magnetic materials		
electric conductivity σ (S/m)	7.5×10^6	no eddy current		
mass density ρ_0 (kg/m ³)	7850	8880	900	1.18
heat capacity c (J/kg·K)	465	386	1300	1007
thermal conductivity κ (W/m·K)	43	398	0.06	0.0261
viscosity η (Pa·s)	solid			18.62×10^{-6}
coefficient of volume expansion β				3.32×10^{-3}

IV. ANALYSIS

A. Magnetic Field Analysis

3-D linear ac steady state magnetic field analysis using the finite element method is carried out. 1/8 of whole region is subdivided into 15,912 1st-order nodal brick elements. The flux and eddy current distributions and the contour lines of eddy current loss are shown in Figs. 4-6. These figures denote that the skin effect in the steel plate is very large.

B. Thermal and Fluid Analyses

In the thermal and fluid analyses, 2-D analyses in x-z plane using the finite element method are carried out, because many time iterations are

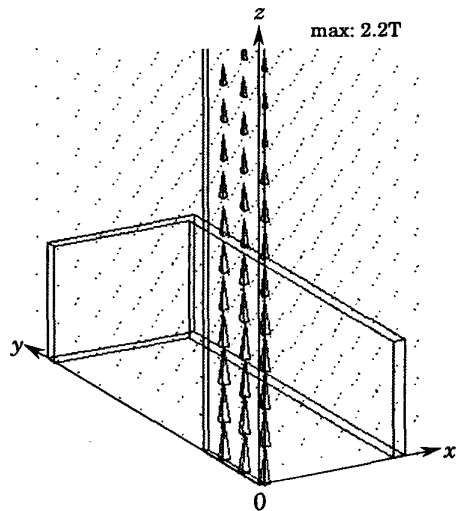


Fig. 4. Flux distribution (t=0, current is maximum).

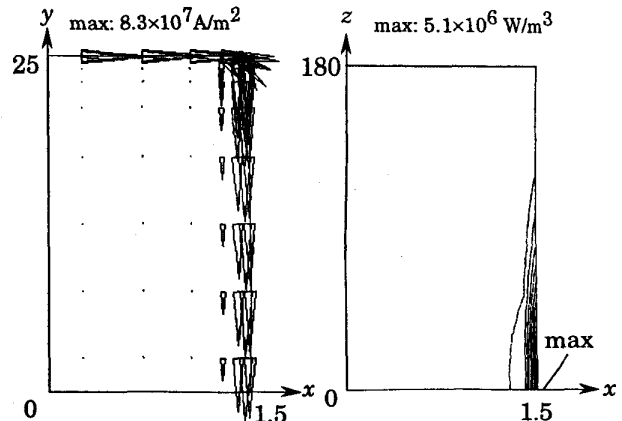


Fig. 5. Eddy current distribution (z=0, current is zero). Fig. 6. Distribution of eddy current loss (y=0).

required. 1/2 of whole region is subdivided into 690 1st-order nodal rectangular elements. The time interval Δt is decided so that $v_{max} \Delta t$ becomes 20mm (v_{max} : maximum velocity) and the maximum Δt is 1s. The penalty number λ is chosen as 10^7 .

Figs.7 and 8 show the temperature distribution and the natural convection at the instants $t=50$,

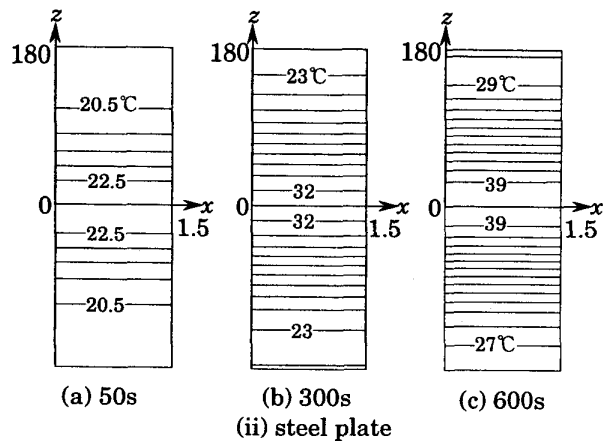
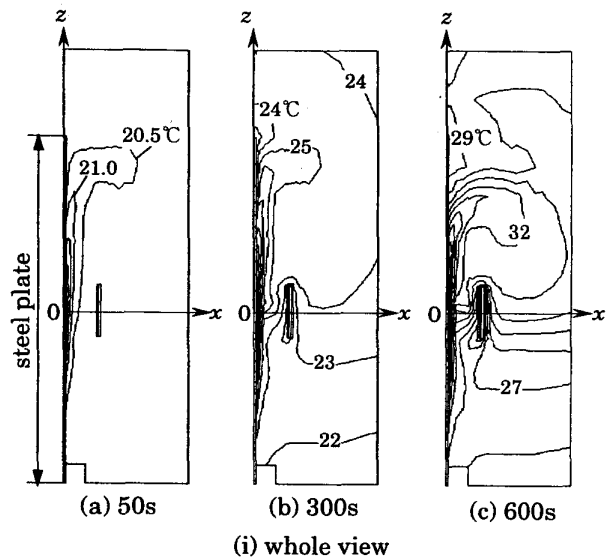


Fig. 7. Contour of temperature.

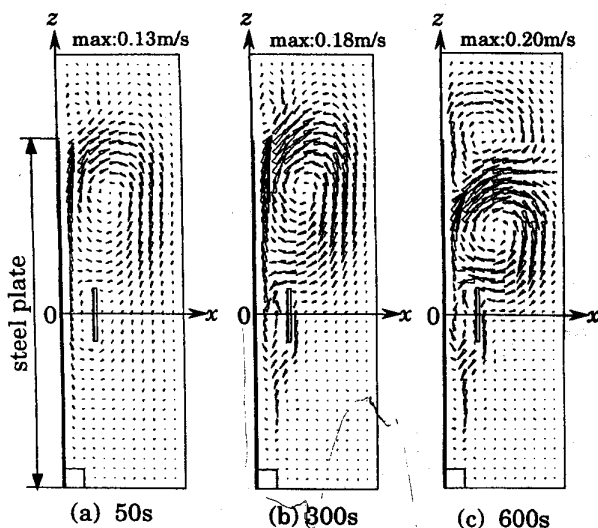


Fig.8. Natural convection.

300, 600s. It is shown that the temperature in the upper part is higher than that in the lower part, due to the natural convection. Fig.9 shows the effect of the natural convection on the temperature distribution along the surface $s-t$ of steel plate. The figure denotes that the natural convection should be considered.

V. MEASUREMENT

The experimental model is shown in Fig.10. The temperature at the points a, b and c shown in Fig. 3 is measured using the thermocouple (copper-constantan). Fig.11 shows the comparison of temperature rise obtained by measurement and calculation taking account of natural convection. Although there is a difference between calculation and measurement, the tendency is almost the same. The reason for the discrepancy seems to be due to the linear analysis of magnetic field and 2-D thermal and fluid analyses.

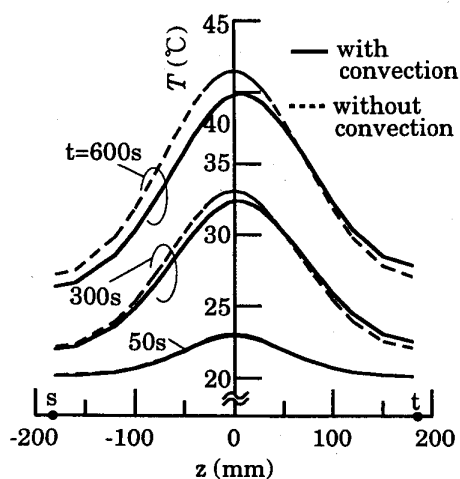


Fig. 9. Effect of convection.

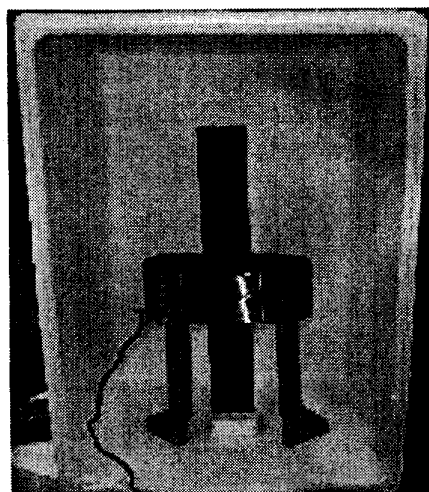


Fig.10. Experimental model.

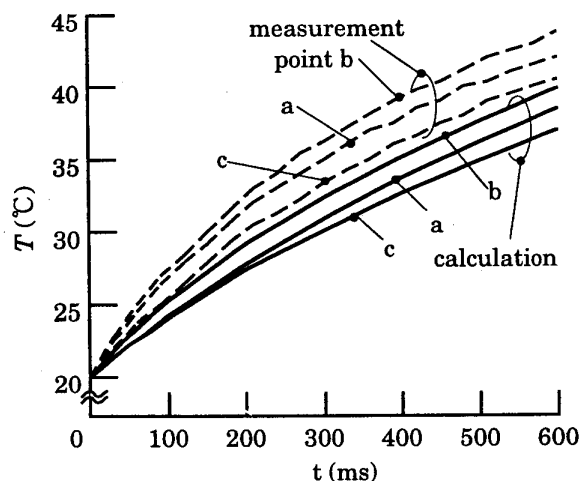


Fig.11. Comparison of temperature rise obtained from measurement and calculation.

VI. CONCLUSIONS

The magneto-thermal-fluid coupled method using semi-Lagrange coordinate system is developed and the new code is verified using the simple induction heating model. More accurate analysis taking account of nonlinearity of the permeability of steel and 3-D thermal and fluid phenomena should be carried out in future.

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