Estimation Method for Heating Efficiency of Induction Heating Cooker by Finite Element Analysis

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***Abstract*—This report proposes an estimation method for the heating efficiency of an induction heating cooker. In the cooker, two processes transfer energy from the coil to the water in the pan. In the first process, magnetic energy is transferred from the coil to the pan. In the second process, heat energy is transferred from the pan to the water. Copper loss occurs in the first process, and heat loss to the air and other materials occurs in the second process. We estimated the heat value in the pan and the losses in the coil and the aluminum ring by using the 3D finite element method for eddy current problems. Next, we estimated the heat energy transferred to the water and the heating efficiency by using the 3D finite element method for heat transfer problems. The estimation results for the heat value of the pan, the losses and the heating efficiency were validated by the experimental results.**

***Index Terms*—Induction heating cooker, heating efficiency, copper loss, 3D finite element analysis.**

I. Introduction

Induction heating cookers have been used for a long time. Although they can operate at high heating efficiency [1], this is not always the case. The efficiency depends on the size and the shape of the pan, and the current frequency of the coil [2]. It is desirable to predict the heating efficiency for each frequency and pan size.

Thus, we propose an estimation method for the heating efficiency of induction heating cookers that is based on finite element analysis. The two processes that transfer energy from the coil to the water were simulated. The first process, which transfers magnetic energy from the coil to the pan, was simulated by a 3D finite element analysis for eddy current problems, and the heat value in the pan and the losses in the coil and the aluminum ring were estimated. The second process, which transfers heat energy from the pan to the water, was simulated by a 3D finite element analysis for heat transfer problems, and the heat energy transferred into the water was estimated.

In this report, the estimation results for the heat value of the pan, the losses and the heating efficiency are validated by the experimental results. In the first experiment, we examined whether the estimated sum of the heat value in the pan and the losses in the coil and the aluminum ring was equal to the measured supplied power to the coil. Next, we examined whether the heat energy transferred to the water divided by the integral power consumption (the product of the above estimated summation and the heating time) was equal to the measured heating efficiency.

II. Calculation Method for Heating Efficiency

A. *Analytical model for induction heating cooker*

Fig. 1 shows the analytical model for the induction heating cooker. The dimensions and arrangements of the materials were set to those of the experimental system. The experimental system has rotational symmetries through 22.5 degrees. Therefore, the analytical model was set as a 1/16 model and all boundaries were set as a fixed boundary [3]. The pan was made of SUS430. The thickness of the pan was set at 1.5 mm or 3.0 mm, and z_w was set so that the volume of the water was 1 liter. In the case that the thickness was 1.5 mm, x_p, z_p, and z_w were set at 98.5 mm, 135.5 mm, and 168.3 mm, respectively. In the case that the thickness was 3.0 mm, x_p, z_p, and z_w were set at 97.0 mm, 137.0 mm, and 170.8 mm, respectively. A coil whose diameter and turns were 2.0 mm and 20, respectively, was arranged in the coil area. The relative permeability of the ferrite core and the pan was set at 1800 and 250 respectively, that of all other materials was set at 1.0. Table I shows the material properties, including electric conductivity, heat conductivity, specific heat, and density.

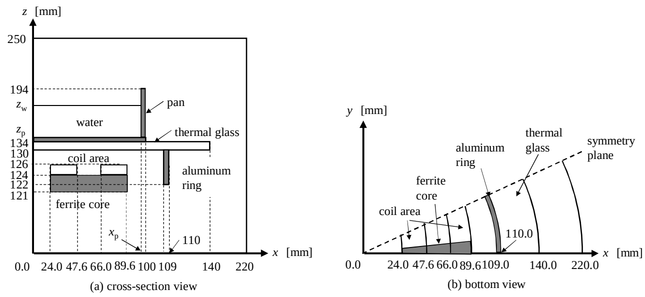

Fig. 1. Analytical model

TABLE I
MATERIAL PROPERTIES

	Pan	Water	Thermal glass	Aluminum ring
Electric conductivity σ (S/m)	1.67×10^6	0.00	0.00	3.69×10^7
Heat conductivity λ (W/m・K)	2.56×10	7.00×10^{-1}	9.40×10^{-1}	2.05×10^2
Specific heat c (J/kg・K)	4.60×10^2	4.20×10^3	6.76×10^2	9.00×10^2
Density ρ (kg/m^3)	7.75×10^3	1.00×10^3	2.30×10^3	2.70×10^3

B. Calculation method for heat value and losses

The 3D finite element analysis for eddy current problems was performed to calculate the heat value in the pan and the losses in the coil and the aluminum ring. After performing the analysis without setting the conductivity of the coil, the heat value in the pan P_{pan} was calculated as follows [4]:

$$P_{\text{pan}} = \sum_{e=1}^{n_{\text{pan}}} \frac{1}{\sigma_{\text{pan}}} \left| J_e^e \right|^2 V^e. \quad (1)$$

Here, σ_{pan} is the conductivity of the pan, n_{pan} is the number of pan elements, V^e is the volume of element e, and J_e^e is the eddy current density in element e. The heat value (loss) in the aluminum ring P_{Al} was calculated in like fashion.

Next, the analysis with setting the conductivity of the coil was performed and the coil resistance r_{coil} was calculated as follows [5]:

$$r_{\text{coil}} = \frac{8}{m\sigma_{\text{coil}} d_s^2} \sum_{j=1}^{n_t} a_j + m \frac{\pi^2 d_s^4 \omega^2 \sigma_{\text{coil}}}{32} \sum_{j=1}^{n_t} \left[a_j \left\langle B_{\text{rms}}^2 \right\rangle_j \Big/ I_j^2 \right]. \quad (2)$$

Here, m is the number of strands per turn (=50), σ_{coil} is the conductivity of the coil (=5.76 × 10^7 S/m), d_s is the strand diameter (=0.3 mm), n_t is the number of coil turns (=20), a_j is the average radius of the jth turn winding, ω is the angular frequency, $\langle B_{\text{rms}}^2 \rangle_j$ is the square of the average magnetic flux density in the jth winding element, and I_j is the average current through the jth winding cross-sections. The copper loss in coil P_{coil} was defined as the product of the coil resistance r_{coil} and the square of the actual measured current in the experiment.

C. Calculation method for heating efficiency

The 3D finite element analysis for heat transfer problems was performed to calculate the heat energy transferred to the water. The analytical model shown in Fig. 1 was used. However, the air, the coil, and the ferrite elements were ignored. The heat transfer boundaries with the coefficient of heat transfer (=4 $W/m^2 \cdot K$) were set around the water, the pan, the thermal glass, and the aluminum ring. Water convection was not considered, and so the average temperature rise of the water was calculated as the heat transfer energy to the water divided by the heat capacity of the water for each iteration. The time step Δt was 5 s. The heating efficiency η was defined as follows:

$$\eta = \frac{(T_{\text{end}} - T_{\text{ini}}) \times c_{\text{water}} \rho_{\text{water}} \sum_{e=1}^{n_{\text{water}}} V^e}{(P_{\text{pan}} + P_{\text{coil}} + P_{\text{Al}}) \times t_{\text{heating}}}. \quad (3)$$

Here, T_{end} and T_{ini} are the end and the initial temperatures, respectively, of the water, c_{water} is the specific heat of the water, ρ_{water} is the density of the water, n_{water} is the number of the water elements, and t_{heating} is the heating time.

III. CALCULATION RESULTS FOR HEATING EFFICIENCY

A. Calculation result of heat value and losses

First, we examined whether the estimated sum of the heat value in the pan and the losses was equal to the measured supplied power to the coil. The measured values for the induction heating cooker are shown in Table II. The coil current and the frequency employed in the finite element analysis were little changed for either pan thickness. The average power supplied to the coil was calculated as the integral power consumption divided by the heating time.

The estimated values obtained by using the proposed method are shown in Table III. For either pan thickness, the summation of the heat value in the pan P_{pan}, the losses in the coil P_{coil} and the aluminum ring P_{Al} was in agreement with the measured average power supplied to the coil. From this, the estimated heat value in the pan, the losses in the coil and the aluminum ring were deemed reasonable. The loss rates in the first process to transfer magnetic energy from the coil to the pan were less than 3.6% for either pan thickness.

TABLE II
MEASURED VALUES

Thickness of pan (mm)	1.5	3.0
Coil current (A)	24.0	23.5
Frequency (kHz)	23.4	23.5
Initial temperature (℃)	21.4	23.1
End temperature (℃)	80.4	79.9
Heating time (s)	240	255
Average power supplied to coil (W)	1257	1254

TABLE III
ESTIMATED VALUES

Thickness of pan (mm)	1.5	3.0
Heat value P_{pan} (W)	1206	1165
Copper loss P_{coil} (W)	38.49	37.47
Heat value (loss) P_{Al} (W)	6.581	6.367
Sum of P_{pan} and P_{coil}, P_{Al} (W)	1251	1206

B. Calculation result of heating efficiency

Next, we examined whether the estimated heating efficiency was equal to the measured heating efficiency. The estimated and the measured heating efficiencies are shown in Table IV. As shown, the estimated values agree well with the measured values. From this, the estimation method described in this report is shown to be very helpful for designing pans and induction heating cookers.

TABLE IV
HEATING EFFICIENCY RESULTS

Thickness of pan (mm)	1.5	3.0
Estimated value (%)	81.4	74.0
Measured value (%)	81.9	74.4

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