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MATHEMATIC MODEL BASED ON ROTATING ELECTROMAGNETIC THEORY USED IN BUILDING A THERMAL CIRCUIT USED IN FOOD HEATER

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ABSTRACT

Rapid development of China's economy, changing population structure and reformed economic structure drives rapid growth of energy consumption. As a result, energy safety gradually becomes a hot spot in energy development. Electricity heating technology has been concerned for a long time as a safe and effective mean; as a result, it has developed into a subject integrating electric engineering, pyrology and materials science. A fundamental research is carried out on food heater in this study. First, static electromagnetic induction heating and dynamic electromagnetic induction heating were introduced. To solve reverse problems of temperature rise, thermal power mathematical theoretical model and thermal circuit model of food heater were established based on electromagnetic field and empirical formula. Finally, under certain rotating speed, thermal power in short-circuited winding as well as eddy current thermal power and magnetic hysteresis thermal power in solid iron core was analyzed.

1.Introduction

In recent years, energy consumption is booming in China. Since 1990s, demand of energy has exceeded supply and the problem becomes even more intensive. Moreover, imbalanced energy distribution and low power generation-transmission efficacy aggravate intense energy supply. When high speed economy in China is facing with dilemma of insufficient power, energy safety problem emerges (Tong, 2006). Electrothermics developed from electric engineering, pyrology and materials science has become an emerging interdisciplinary science. Its basic principle is transforming electric energy into thermal energy. In a broad sense, electrothermics can be researched as a reverse problem of electrical machine and appliance theory (Guoqun et al., 2011). Starting from reverse problem of electrical machine and appliance theory, energy can be completely transformed into thermal energy based on the concept and cause of electrical rotating machine loss using proper material, structure and method. Cheng (Shukang et al., 2008) once explored the above method. Nikrityuk et al. (Nikrityuk et al., 2003) attempted constructing model for thermal transmission in external magnet.

In daily life, food is usually heated by fire, microwave and chemical agent. Heating with fire wastes time and energy and pollutes environment; moreover, the temperature should be controlled by people. Open fire is forbidden in many occasions such as forest or chemical plant. As to heating with microwave oven, microwave produced brings radiation to operator; problems of damaged nutritional ingredients and disturbed power grid also exist (Fukuoka et al., 2005; Halla et al., 2000). Heating food with chemical agents is widely applied in field, mainly for military used food. It will lose efficacy after being affected with damp, though this method causes no fire and smoke. In addition, water is required and improper disposal of chemical agents can pollute environment. To cope with defects of heating with fire, microwave and chemical agents, this study proposed a reusable food heater based on rotating rotating electromagnetic theory and constructed thermal power mathematical theoretical model and thermal circuit model.

1. Materials and methods

2.1. Electromagnetic induction heating

Static electromagnetic induction heating: Alternating electromagnetic field can produce Lorentz force or induced electric field force on free electron inside metal which locates in the electromagnetic field. Two forces produced can induce induced current, *i.e.*, eddy current. As eddy current loop metal has small resistance and current strength of eddy current is relatively large, joule heat produced is large. Induction heating has been applied in medium and high frequency melting technology and microwave cooker (Wang, 2011). As alternating magnetic field produced by coil called inductor is not correlated with movement or relative movement, traditional electromagnetic induction heating is termed as static electromagnetic induction heating (Souley et a.,, 2012). Electro-magnetic induction themogenesis is found in operation process of electromotor at the earliest. But it is considered to be harmful as it reduces efficacy of energy conversion. In industrial field, static electromagnetic induction heating technology is mainly applied in smelting of ferrous and nonferrous metals (Satoshi et al., 1993). Scholars from China and other countries have made a large quantity of theoretical analysis. Yang XG et al. (Xiaoguang, 2004) once comprehensively analyzed the solution of coupled fields, numerical simulation of induction heating and boundary condition of temperature field. Zhang HL (Hongliang et al, 2007) et al. analyzed heat treatment process of steel ball in columnar induction through heating equipment, established a mathematical model for calculating temperature field and made coupling calculation on dynamic eddy current field and temperature field.

2.2. Dynamic electromagnetic induction heating

Dynamic electromagnetic induction heating means transforming electric energy fully into thermal energy with proper materials, structure and method, i.e., transforming loss in conventional sense into effective thermal energy (Linhuang et al., 2014). Dynamic electromagnetic induction heating is also based on electromagnetic induction principle, but it has two points of difference with static electromagnetic induction heating. The first point is that alternating magnetic field is produced from multiphase rotating magnetic field or rotating permanent magnet rather than non-motor magnet exciting coil. The second point is that, dynamic electromagnetic induction heating based on eddy-current and magnetic hysteresis effect of iron core should also sense electric current effect of rotational voltage in closed coil using cutting magnetic line and meanwhile make use of eddy-current effect and magnetic hysteresis effect of block iron core in rotating magnetic field.

Multiphase rotating magnetic field or rotating permanent magnet which can produce thermal power when dragged by electromotor, water turbine and draught fan can be used to construct a novel environmental friendly dynamic electromagnetic induction heating equipment (Carrillo, 2008; Kaneda et al., 2000). As thermal energy produced by loss of rotating electromagnet is high efficient, safe and environmental friendly, it is applied in power drying in some countries. Figure 1 demonstrates the drying equipment operating based on a low speed rotating cylinder driven by rotating magnetic field (Takashi et al., 2005).

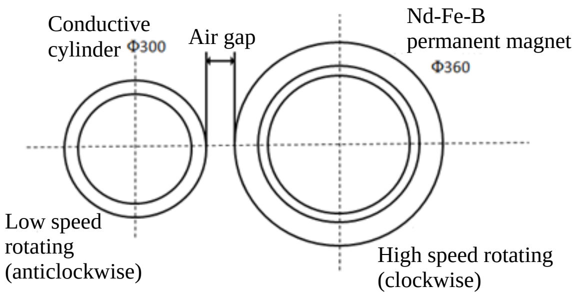

Figure 1. Principle of drying equipment

2.3. Mathematical model for heat generation of food heater

2.3.1. Magnetic hysteretic thermal power in iron core

Magnetic hysteretic thermal power on teeth and yokes should be calculated separately due to different distribution of magnetic density. They can be used to express function of maximum of magnetic density. On teeth, magnetic hysteretic thermal power in unit volume is:

$$P_{ht} = K_h f B_{tm}^{\beta} \ \ (\mathrm{W/m^3}) \qquad (1)$$

$$P_{hy} = K_h f B_{ym}^{\beta} \ \ (\mathrm{W/m^3}) \qquad (2)$$

where: k h is constant of material performance; β is a value between 1.6 and 2.2; *f* is frequency of magnetic field change; B tm is maximum of magnetic density on teeth; B ym is maximum of magnetic density on yoke.

Magnetic hysteretic thermal power of iron core in heater can be obtained from formula (1) and (2).

$$P_h = P_{ht}V_t + P_{hy}V_y = K_h f(B_{tm}^{\beta}V_t + B_{ym}^{\beta}V_y) \ \ (\mathrm{W}) \qquad (3)$$

2.3.2. Eddy-current thermal power in iron core

Insulating treatment between laminations leads to decrease of conductivity as well as low eddy-current parameter (Park et al., 2012). Based on that, it is assumed that, solid iron core is made of superposed laminations in same height; eddy current is radial and axial eddy current is ignored; moreover, lamination is not insulative, which means conductivity between laminations is conductivity of solid iron core. Eddy-current thermal power on teeth and yokes should be calculated separately as well. On teeth, eddy-current thermal power in unit volume is:

$$P_{et} = K_e\,(fB_{tm})^2 \ \ \ (\mathrm{W/m^3}) \qquad (4)$$

On yokes, eddy-current thermal power in unit volume is:

$$P_{ey} = K_e\,(fB_{ym})^2 \ \ \ (\mathrm{W/m^3}) \qquad (5)$$

In the formula, k_e is constant of material performance.

Thus eddy-current thermal power of iron core of heater can be obtained:

$$P_e = P_{et}V_t + P_{ey}V_y = K_e f^2 (B_{tm}^2 V_t + B_{ym}^2 V_y) \ \ \ (\mathrm{W}) \qquad (6)$$

2.3.3. Thermal power of short circuit winding

Current in short circuit winding in static state is I (A). Based on Joule-Lenz's law, thermal power in winding is:

$$P_{Cu} = I^2 R \ \ \ (W) \qquad (7)$$

R is resistance of copper wire. Total length of winding I (m), wire cross section S (m^2) and electrical resistivity of wire ρ(Ω ·m) are substituted into formula (7), and then thermal power of short circuit winding of heater can be obtained.

$$P_{Cu} = I^2 \rho \frac{l}{S} \ \ \ (\mathrm{W}) \qquad (8)$$

2.3.4. Mathematical model for heat generation of food heater

Mathematical model for heat generation of food heater can be obtained based on formulas (3), (6) and (8).

$$P = P_h + P_c + P_{Cu} = K_h f\left(B_{tm}^{\beta} V_t + B_{ym}^{\beta} V_y\right) + k_e f^2\left(B_{tm}^2 V_t + B_{ym}^2 V_y\right) + I^2 \rho \frac{l}{s} \text{ (W)} \quad (9)$$

2.3.5. Thermal circuit model of food heater

Specific heat capacity refers to thermal absorbed or released by unit mass of substance when temperature rises or falls one degree (Wollti et al., 2001). Usually, expression for correlation between thermal variation and temperature variation is:

$$Q = C \cdot m \cdot \Delta T \quad (10)$$

where Q stands for heat, m stands for quality, ΔT stands for temperature variation and C stands for specific heat capacity.

Copper heat loss thermal power in short circuit winding and magnetic hysteretic and eddy-current thermal power in solid iron core are taken as effective heat source for heater in modeling of temperature rise of heater. It is assumed that, heat is isolated between heater and external environment; thermal source distributes evenly in stator core and thermal conductivity of stator is good; influence of heat-transfer patterns such as convection and radiation is ignored; thermal performance parameter of materials is not affected by temperature in transient heat transfer process.

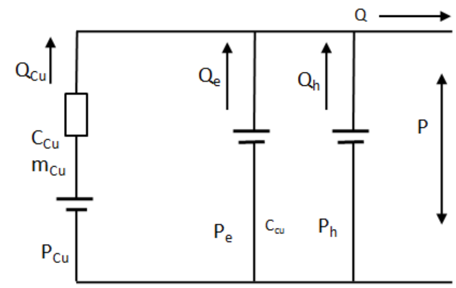

Figure 2. Equivalent thermal source

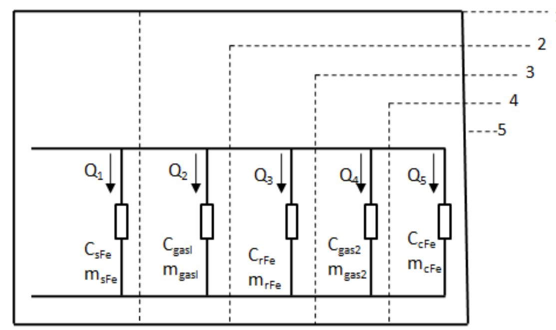

Figure 3. Equivalent thermal load of heater (1-level 1 load, 2-level 2 load, 3-level 3 load, 4-level 4 load, 5-level 5 load)

Mathematical model for temperature rise of heater

$$\begin{cases} Q = Cm\Delta T \\ Q = Pt \end{cases} \quad (11)$$

Where P stands for effective thermal power of heater and t stands for heating time. Establishing multiple-grade thermal circuit model is to heat different thermal load with the same thermal source. P_{Cu} is thermal power of short circuit winding of heater, Pe is eddy-current thermal power, Ph is magnetic hysteretic thermal power, Q_{Cu} is heat produced by short circuit winding in a period, Qe is heat produced by eddy current in a period, Q_h is heat produced by magnetic hysteresis in a period, C_{Cu}, C_{sFe}, C_{gas1}, C_{rFe}, C_{gas2} and C_{cFe} is specific heat capacity corresponding to different materials of heater (unit: J/ (Kg·°C)).

3. Results and discussions

3.1. Analysis of thermal power of food heater

Thermal power of short circuit winding: Induced electromotive force produced in copper on stator side by rotating magnetic field is bound to produce induced current; the condition is similar to operation of permanent magnet synchronous generator in short circuit condition (Ran et al., 2011). Analysis of heater model with finite element method suggests that, there are 9 complete short circuit current waveforms within one cycle, which conform to operation principle of 9-antipode permanent magnet synchronous generator.

Based on formula $f_c = \frac{F_c}{F_c} = 1 = h_c$, thermal power of short circuit current, P_{Cu} can be calculated as follows.

$$P_{Cu} = n \cdot R \cdot I^2 = n \frac{1}{\sigma} \frac{1}{S} \frac{1}{T} \int I^2(t)dt \quad (12)$$

In the formula, n stands for number of short circuit winding, σ stands for conductivity of copper (S/m); S stands for cross section area of copper bar (m^2) and $\frac{1}{T}\int I^2(t)dt$ stands for quadratic mean of current in one cycle.

3.2. Eddy-current thermal power of solid iron heater

To enhance eddy-current loss, iron core of food heater is made to be solid (Chy et al., 2010). We assume that, solid iron core is made of laminations in same height; there is no insulating treatment between laminations; conductivity of laminations is the same as solid iron core; eddy current in iron core is radial and axial eddy current is ignored; eddy current in iron core is two dimensional (Zhizhen et al., 2003).

It can be known from formula $P_e = K_e(Bf)^2$ (Pe stands for eddy-current loss and k_e stands for eddy-current loss coefficient), when rotating speed is constant, then frequency of alternating magnetization in stator core is also constant. Thus eddy-current thermal power is correlated to magnetic density amplitude. Figure 4 demonstrates magnetic density distributing along radial cross section at one time point. It can be seen from the figure that, the part of iron core embedded with copper, i.e., slotted section, has relatively large magnetic density. As distribution and amplitude of magnetic density on teeth and yokes are different, eddy-current thermal power on teeth and yokes should be considered separately. Cross section of magnetic density on teeth and yokes is shown in Figures 5 and 6 respectively. Magnetic density shown in figure 5 and 6 is at the same time point. An oscillograph involving maximum of magnetic density on teeth and yokes can be obtained by connecting maximum of magnetic density on teeth and yokes at every time point in one cycle according to the time order. Maximum of magnetic density on teeth and yokes changes intensively, and meanwhile maximum of magnetic density on teeth is higher than yokes, which conforms to distribution rule of motor field (Lahiri et al., 2014; Katoh et al., 2004).

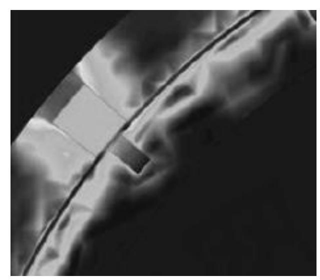

Figure 4. Distribution of magnetic density along radial cross section under a magnetic pole at a time point when rotating speed is 1, 400 r/min

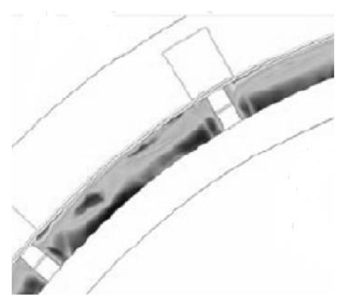

Figure 5. Distribution of magnetic density on teeth along radial cross section at a time point when rotating speed is 1, 400 r/min

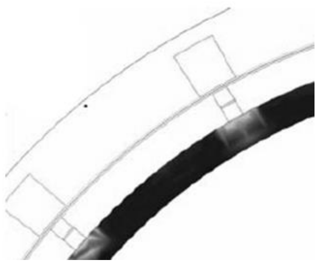

Figure 6. Distribution of magnetic density on yokes along radial cross section at a time point when rotating speed is 1, 400 r/min

Based on formula $P_e = K_e(Bf)^2$, eddy-current thermal power can be calculated as follows:

$$p_{et} = K_e \cdot \left(\frac{1}{T}\int B_{tm}(t)dt \cdot \frac{Pn}{60}\right)^{\beta} \cdot (\pi r_1^2 - \pi r_2^2 - ah_t b) \cdot l \cdot \rho \quad (13)$$

where k_e stands for eddy-current thermal power coefficient, 0.00022W/kg·Hz2·T2; P stands for number of pole-pairs of rotor; n stands for rotating speed of rotor (r/min), $\frac{Pn}{60}$ stands for frequency of alternating magnetization in iron core, $\frac{1}{T}\int B_{tm}(t)dt$ stands for average value of maximum of magnetic density on teeth in one cycle; β is 2; r_1 stands for external diameter of stator core, r_2 stands for distance from stator slot base to center, ht stands for height of iron core of teeth, α stands for number of short-circuit copper embedded with stator on one side, b is slot width of stator core, I stands for length of stator core, $(\pi r_1^2 - \pi r_2^2 - ah_t b) \cdot l$ stands for volume of iron core on teeth, ρ stands for density of iron core material, *i.e.*, type 10 steel. Eddy-current thermal power on yokes can be obtained using the following formula:

$$p_{ey} = K_e \cdot \left(\frac{1}{T}\int B_{ym}(t)dt \cdot \frac{Pn}{60}\right)^{\beta} \cdot (\pi r_2^2 - \pi r_3^2) \cdot l \cdot \rho \quad (14)$$

where $\frac{1}{T}\int B_{tm}(t)dt$ stands for average value of magnetic density amplitude on yokes in one cycle and r_3 stands for inner diameter of stator core.

3.3. Magnetic hysteretic thermal power of solid iron core

In alternating magnetic field, magnetic domain orientation of ferromagnetic material tends to change under periodic repeated magnetization, leading to magnetic hysteretic loss (Tang et al., 2012). Thus magnetic hysteretic loss is considered to be closely correlated to frequency of alternating magnetization and magnetic density amplitude (Sakai *et al*, 2001). As to food heater, magnetic hysteretic thermal power in stator core can be ignored during analysis as frequency of alternating magnetization in stator core is low. In analysis of magnetic hysteretic thermal power of stator core, teeth and yokes should still be considered separately.

Based on formula (1), magnetic hysteretic thermal power on teeth can be calculated with the following formula:

$$p_{ht} = K_h \cdot \frac{Pn}{60} \cdot \left[\frac{1}{T}\int B_{tm}(t)dt\right]^{\beta} \cdot (\pi r_1^2 - \pi r_2^2 - ah_t b) \cdot l \cdot \rho \quad (15)$$

where k_h stands for coefficient of magnetic hysteretic thermal power, 0.045 W/kg·Hz·T2; P is number of pole-pairs of permanent magnet in rotor, n stands for rotating speed of rotor (r/min), $\frac{Pn}{60}$ stands for frequency of alternating magnetization in iron core, $\frac{1}{T}\int B_{tm}(t)dt$ stands for average value of maximum of magnetic density on teeth in one cycle, β is 2, r_1 stands for external diameter of stator core, r_2 stands for distance from slot base of stator to center, ht stands for height of iron core on teeth, α stands for number of short circuit winding embedded with stator on one side, b stands for slot width of iron core of stator, I stands for length of iron core of stator, $(\pi r_1^2 - \pi r_2^2 - ah_t b)$ stands for volume of iron core on teeth and ρ stands for density of iron core material, *i.e.*, type 10 steel.

4. Conclusions

Food heater is based on electromagnet. Thermal power in food heater can be divided into three categories, *i.e.*, magnetic hysteretic thermal power and eddy-current thermal power in solid iron core and short-circuit current thermal current; and thermal power of short-circuit current is the main source of thermal power of heater. Taking food heater as research objects, this study constructed thermal power mathematical theoretical model and thermal circuit model and made a numerical analysis of various thermal powers of heater. Simulation results suggest that, thermal power of short-circuit winding accounts for 90% among total thermal power and eddy-current and magnetic hysteretic thermal power both account for more than half.

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