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Additional Modification of Thermomagnetic Properties of Objects of Low Relative Permeability in Electromagnetic Field

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This paper presents the characteristics of the foodstuff heating phenomenon using induction heating process by an induction cooker. The simulation setup was prepared according to the proposed magnetic material and configuration of the pot and induction cooker. The material properties of pot were varied among the several alternatives. The helical coil was designed on the base of the limitation of the induction cooker size and given number of coil turns and coil tube diameter with specific supplied electric current density. The data from the simulation analysis have to determine the enhancing of the highest heat transfer from induction cooker into pot. These data led to the modification of the material and geometrical properties of the pot in accordance to a minimum heating time and enhanced safety operation, especially close to unshielded magnetic objects.

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1. Introduction

The induction heating systems use electromagnetic induction, first discovered by Michael Faraday in 1831. Electromagnetic induction refers to the phenomenon by which the electric current is generated in a closed circuit by the fluctuation of current in another circuit close to it. The basic principle of induction heating is that the AC current flowing through a circuit affects the electromagnetic induction in the secondary circuit located near it. Heat loss, which occurs during the induction heating process, has been a major headache, undermining the overall functionality of a system. Heat loss, occurring in the process of electromagnetic induction, can be changed into productive heat energy in an electric heating system. Many industries benefited from this breakthrough by implementing induction heating for furnacing, quenching, and welding. In these applications, the induction heating made it easier to set the heating parameters without the need of an additional external power source. High energy density is achieved by generating sufficient heat energy within a relatively short period of time. This paper describes the possibilities of additional enhancing of induction heating efficiency of materials with low value of relative permeability.

2. Basics principle of induction heating

Induction heating is comprised of three basic factors: electromagnetic induction, the skin effect, and heat transfer. The fundamental theory of induction heating is similar to that of a transformer. Figure 1a shows the simplest form of a transformer, where the secondary current is in direct proportion to the primary current according to the turn ratio. The primary and secondary electric losses are caused by the electrical resistance of windings [1].

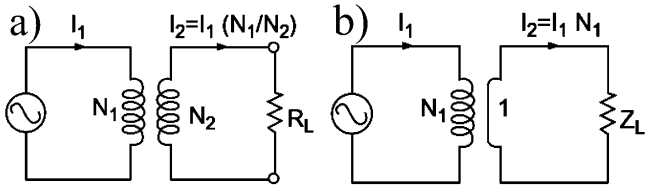

Fig. 1. (a) Equivalent circuit of transformer, (b) scheme of secondary winding short-circuit.

When the coil of the secondary winding is turned only once and short-circuited, there is a substantial heat loss due to the increased secondary winding load current. This is depicted in Fig. 1b. In this figure, the inductive coil of the primary has many turns, while the secondary is turned only once and short-circuited. The inductive heating coil and the load are insulated from each other by a small aperture [1].

Because the primary purpose of induction heating is to maximize the heat energy generated in the secondary winding, the aperture of the inductive heating coil is designed to be as small as possible and the secondary one is made with a substance of low resistance and high permeability. Nonferrous metals decrease the energy efficiency because of their properties of high resistance and low magnetic permeability [2].

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Design of induction heating geometry is shown in Fig. 2.

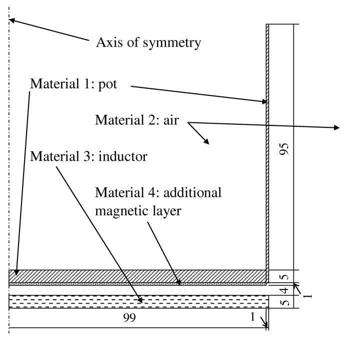

Fig. 2. View (cross-section) on the inductor, pot and the additional magnetic layer.

3. Solution of thermal and electromagnetic field

Numerical solutions were realized according to following assumptions: the arrangement of inductor, pot, and additional magnetic layer was axially symmetrical (the calculation takes place only for one half of the 2D layout areas). Both halves had the center of symmetry identical to the axis of symmetry.

The problem was considered as a linear and weakly coupled. Physical parameters of the considered areas were constant. Losses, due to eddy currents (95%) and hysteresis loss (5%) in the areas of pot and additional magnetic layer produced the non-stationary electromagnetic and temperature field [3].

The heat caused by these losses heated the pot and by the thermal conduction it was transferred to object inserted in the pot. It was considered that the object inserted inside the pot was non-magnetic and of higher electrical resistivity. Also suitable considerations were used of other variables that were not largely influenced by the result of simulation. The input power of inductor was considered $P = 2000$ W (type: ORAVA VP-200I). These assumptions allowed to solve the problem as the weakly coupled, thereby considerably reducing the computation time, and the result was not loaded with significant error (up to 5%) [4].

The solution was realized using the software ANSYS. This program allows user solve all mentioned fields (electromagnetic, thermal), so there was no need to export the data into other third-party programs. This software uses also numerical method of finite element method (FEM).

4. Solution results

The following simulation results are displayed side by side, for pot consisting of magnetic material and pot of non-magnetic material with additional magnetic layer on bottom outer part of the pot.

4.1. Electromagnetic field

These results correspond to the computer model in Fig. 3 and other input data referred in previous chapters.

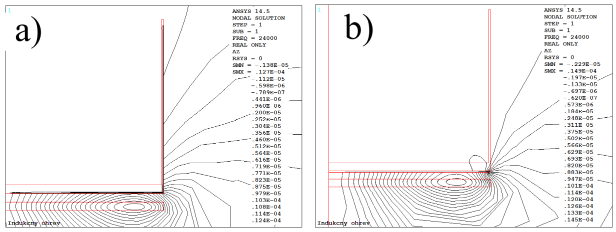

Fig. 3. Magnetic field lines of the electromagnetic field of (a) magnetic pot and (b) non-magnetic pot with thin magnetic layer.

The pot was placed symmetrically above the inductor coil. The outer coat of the pot caused distraction of the electromagnetic field into itself, whereby it took ("removed") the part of electromagnetic field from the bottom part.

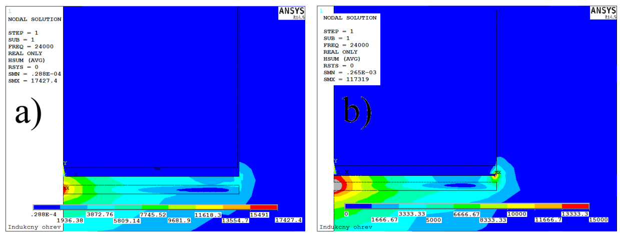

Fig. 4. Magnetic field intensity vector sum around the (a) magnetic and (b) non-magnetic pot with thin magnetic layer.

TABLE I

I Material parameters for simulation.

Material	μ_r	ρ_{el} [Ωm]	λ [$\frac{\text{W}}{\text{m K}}$]	c [$\frac{\text{J}}{\text{kg K}}$]	ρ_{mass} [$\frac{\text{kg}}{\text{m}^3}$]
1. pot	20	8.8×10^{-7}	40	460	7850
2. air	1.0005	1.3×10^{16}	0.0257	1005	1.2
3. coil	0.99994	1.7×10^{-8}	401	385	8960
4. layer	950	8×10^{-7}	41	430	7800

μ_r is relative magnetic permeability, ρ_{el} is electrical resistivity, λ is thermal conductivity, c is specific heat capacity, ρ_{mass} is volumetric mass density

Distribution of magnetic intensity in Fig. 4 corresponded to theoretical assumptions [3] and field lines from the previous figure. As shown in the Fig. 3, the magnetic pot attenuated the magnetic intensity to a much thinner layer than that in non-magnetic pot, so there should be used thin magnetic layer on the bottom part of a pot of Fe_2O_3 or ferritic stainless steel (used data of 29Cr–4Mo–2Ni), see Table I [4, 5]. This was due to parameters of magnetic materials, relative permeability, which had the effect of the reduction of magnetic intensity in a much thinner layer from the surface than in non-magnetic materials according to a skin effect formula

$$a = \sqrt{\frac{2\rho}{\omega\mu}}, \tag{1}$$

where a is a skin depth [m], ρ is a electrical resistivity of material [Ωm], ω is a circular frequency $\omega = 2\pi f$, and the μ is magnetic permeability of material $\mu = \mu_0 \mu_r$ [H/m].

4.2. Thermal field

As it was mentioned above, the temperature field was solved on the basis of the generation of thermal energy in the pot, which was transmitted from the electromagnetic field in the temperature field. Calculation of temperature field was carried out again according to physical data and assumptions referred earlier.

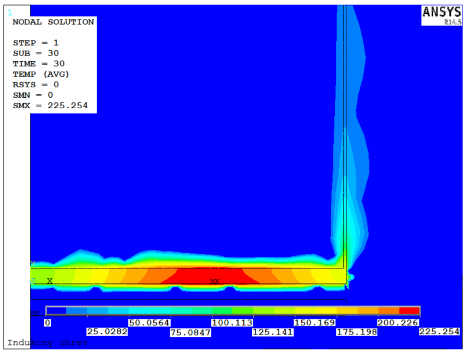

Fig. 5. Dependence of temperature of the magnetic pot after 30 s period.

Figure 5 shows the temperature distribution during the heating process of the magnetic pot after 30 s. The main criterion for the solid was to heat up the inserted material to safety temperature point that was approximately 250 °C. It followed that the heating process could be stopped for the magnetic pot behind the range of 30 s. The temperature was unevenly distributed. The similar temperature distribution was achieved when the additional thin magnetic layer was applied on bottom part of non-magnetic pot (according to Fig. 4b).

5. Conclusions

The main focus of this paper was to describe the induction heating process of magnetic pot and non-magnetic pot with additional thin magnetic layer. Understanding of basic concepts of induction heating and power system of inductor controlled by electronics with resonant inverter should develop the appropriate tools for various applications. The results showed that the additional thin magnetic layer of Fe_2O_3 or ferritic stainless steel (there were used data of 29Cr–4Mo–2Ni) applied on outer bottom part of the pot could heat by induction heating system also glass and ceramic materials. In these application the thin magnetic layer of appropriate relative permeability due to skin effect increase the temperature and by electrical conduction they heat the attached non-magnetic pot. It is possible to place a magnetic material into the inner part of a pot, but there must be used stainless steel material or material with the proper non-toxic coating of a high thermal conductivity and correspondent relative permeability (according to skin depth, $f = 24\,000$ Hz). It is necessary to note here that it is forbidden to use highly electrically conductive materials as a pot and also close to inductor, because they create one-turn secondary winding, so they could be heated very quickly. Normally, the commercially used inductors are equipped with the measuring test of secondary impedance, so the inductor will be in that case switched off.

Acknowledgments

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