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Household Induction Cookers: Calculation and Design of Structural Elements

Pantelyat M. G., Hryshchuk Yu. S., Chepeliuk O. O., Yeloiev A. K.

National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

E-mail: *m150462@yahoo.com, grischuk-kpi@ukr.net, chep1@i.ua, mauser98kar@gmail.com*

A technique for calculation and design of main structural elements of household induction cookers – inductors and magnetic cores is proposed. The technique consists of two stages. The first stage has been developed on the basis of engineering methods for calculating copper inductors of industrial induction heaters, taking into account the design features and operating modes of induction cookers, done in steps such as selection of geometrical dimensions of the inductor, calculation of main electrical and energy indicators of the inductor, calculation of the system "inductor-dishes", determination of the number of turns of the inductor and calculation of the width of the turn. The second stage represents an engineering approach for the calculation and design of magnetic cores made of MnZn ferrites, done in steps such as choice of material for the manufacture of magnetic core rods, choice of geometric dimensions of ferrite rods, calculation of the mass of the magnetic core and calculation of power losses in the magnetic circuit. The calculation results and designs of the inductors and magnetic cores with respect to a number of modes of heating of dishes of various geometric sizes are presented and analyzed. The developed techniques and the results obtained on its base are supplemented and supported by preliminary numerical analysis of the electromagnetic field distribution in induction cookers and heated dishes as well as by experimental research on the workbench developed. Conceptual designs of induction cookers developed by using the proposed approaches illustrate the techniques presented. The developed techniques can be used in the process of research and design of structural elements of household induction cookers, as well as in the educational process for the preparation of Bachelors and Masters in relevant educational programs.

Keywords: household induction cooker; inductor; magnetic core; ferrite; calculation; design

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Introduction

Household induction cookers represent a class of modern electrical household appliances that is relatively new but already very popular among consumers – electrical kitchen stoves which heat metal dishes with meal by eddy currents generated by electromagnetic field with frequency of 20-100 kHz. The main structural parts the induction cookers are: inductor – a one-turn or multi-turn coil, the alternating current flow in which generates an electromagnetic field which in its turn induces eddy currents in heated dishes with meal; magnetic core made of ferromagnetic material and designed to shield the electromagnetic field created by the inductor, in order to reduce the scattering of the field and, thus, increase the efficiency of the cooker.

Of considerable interest is the investigation of electromagnetic and thermal processes that occur in induction cookers during their operation, as well as the development of techniques for calculation and design of their main structural elements – inductors and magnetic cores. The developed technique and the results obtained should be intended for use in the practice of design of household induction cookers, as well as even in the educational process for the training of students in the relevant field of study [1].

There are publications for example [2–5] devoted to induction cookers' electromagnetic and thermal fields computations using various formulations and approaches. However, the analysis of literary sources in the field showed that there are no publications on development and utilization of relatively simple and reliable engineering techniques for calculation and design of above-mentioned household induction cookers' structural parts to use them in the process of promising research and design work on the development of such appliances.

Therefore, the *goal of this paper* is to develop and validate relatively simple, clear and reliable engineering approaches for calculation and design of inductors and magnetic cores of modern household induction cookers and also to supplement and support them by preliminary numerical analysis of the electromagnetic field distributions in induction cookers and heated dishes as well as by experimental research on the workbench developed by authors. On this base, conceptual designs of induction cookers are proposed.

Scientific novelty of the study is that for the first time engineering techniques for calculating and designing the main structural elements (inductors and magnetic cores) of household induction cookers are developed and applied in practice, which are also based on numerical analysis of electromagnetic field distribution and confirmed experimentally. The performed analysis of literature sources shows that this work is the first domestic comprehensive study on household induction cookers. In addition, the paper focuses for the first time on the development, validation and use of mainly engineering approaches for the calculation and design of inductors and magnetic cores of household induction cookers, while the known works by other authors [2–5] are devoted to numerical methods of calculation and optimization of these objects.

1 Calculation and design of inductors of household induction cookers

1.1 A technique proposed

Due to the significant similarity of the physical processes occurring in household induction cookers and industrial equipment for induction heating of metals, the proposed technique has been developed on the basis of engineering methods for calculating inductors of industrial induction heaters [6] taking into account the design features and operating modes of induction cookers.

Initial data for engineering calculations and design are:

- geometry (diameter of the bottom, wall thickness) of the heated dishes (pans, pots);
- temperature-dependent electrophysical properties of the material of the dishes;
- electromagnetic field frequency and inductor voltage;
- power released in heated dishes and heating temperature.

Following [6] the main steps of the calculation and design of induction cookers' inductors are:

- selection of the main structural parameters of the inductor (outer and inner diameters of the inductor, the gap between the inductor and the dishes, the thickness of the inductor);
- calculation of electrical and energy indicators (specific surface power in the dishes, magnetic field strength on the surface of the inductor and dishes, coupling coefficient, active and reactive power in the inductor and in the gap, total power of the inductor-dishes system, electrical efficiency, power factor, current in the inductor, fill factor, etc.);
- determination of the number of turns of the inductor and calculation of the width of the turn.

Consider briefly the main stages of the calculation. The sketch of the "inductor-dishes" system is shown in Fig. 1.

1) *The geometrical dimensions of the inductor are selected (see Fig. 1).* The outer diameter of the inductor d_{12} is taken equal to the diameter of the heated surface, i.e. the diameter of the bottom of the dishes d_2:

$$d_{12} \approx d_2. \tag{1}$$

The inner diameter of the inductor d_{11} is selected by the relationship:

$$d_{11} \approx 4\delta, \tag{2}$$

where δ denotes the gap between the inductor and the heated dishes, which, as in the design of inductors of industrial induction heating devices, is assumed to be minimal, based on the presence of thermal and electrical insulation and taking into account technological requirements. For household induction cookers, it is fashionable to take, for example, $\delta = 0.01\,\mathrm{m}$.

The inductor thickness δ_1 is selected from the condition for minimizing losses:

$$\delta_1 \geq 1.3\Delta_1, \tag{3}$$

where Δ_1 denotes the penetration depth of the electromagnetic field (skin layer thickness) into the inductor material (nonmagnetic copper), calculated by the well-known formula.

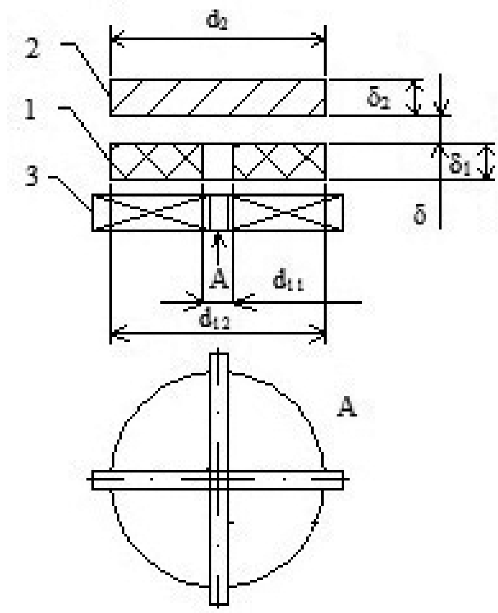

Fig. 1. A sketch of the "inductor-dishes" system: 1 – inductor; 2 – heated dishes; 3 – ferrite core

2) *The main electrical and energy indicators of the inductor and the system "inductor-dishes" are calculated.* The specific surface power in the dishes p_{02} is determined by the formula:

$$p_{02} = \frac{4P_2}{\pi(d_{12}^2 - d_{11}^2)}, \tag{4}$$

where P_2 denotes the given in initial data power released in heated dishes.

The magnetic field strength H_{02} on the surface of the heated dishes is calculated by the formula:

$$H_{02} = \sqrt{\frac{p_{02} \cdot 10^3}{\rho_2 \mu_2 f F_2}}, \tag{5}$$

where ρ_2 denotes the electrical resistivity of the steel of the dishes at the given maximum temperature of its heating T_2, μ_2 is the calculated value of the magnetic permeability of the dishes' steel at the given temperature T_2, F_2 is the correction factor.

Then, the coupling coefficient k_{12} is determined, which in fact represents the transformation coefficient under the assumption that the inductor and heated dishes are windings of an air transformer. The calculation of the coupling coefficient is performed using the corresponding expression.

The magnetic field strength on the surface of the inductor H_{01} is determined by the expression:

$$H_{01} = \frac{H_{02}}{k_{12}}. \tag{6}$$

Then, the active power in the inductor P_1 is calculated:

$$P_1 = \pi \cdot H_{01}^2 \frac{d_{12}^2 - d_{11}^2}{4} \sqrt{\rho_1 f} F_1 \frac{1}{k_{\mathrm{f}}}, \tag{7}$$

where ρ_1 denotes the electrical resistivity of the material of the inductor (copper), k_f the fill factor of the inductor, taking into account the presence of interturn insulation which is preselected (usually $k_f = 0.85 - 0.95$), F_1 the correction factor.

Reactive powers in the inductor P_{Q1}, in the dishes P_{Q2} and in the gap P_{Q3} are determined by the formulas:

$$P_{Q1} = P_1 \frac{G_1}{F_1}; \tag{8}$$

$$P_{Q2} = 0.6 P_2 \frac{G_2}{F_2}, \tag{9}$$

where G_1, G_2, F_1, F_2 denote correction factors;

$$P_{Q3} = \pi \cdot H_{01}^2 f \delta d_{12}^2. \tag{10}$$

Then, the active P_Σ and reactive $P_{Q\Sigma}$ powers of the "inductor-dishes" system as the sum of the corresponding powers as well as the total power of the system $P_{S\Sigma}$ are determined:

$$P_{S\Sigma} = \sqrt{P_\Sigma^2 + P_{Q\Sigma}^2}. \tag{11}$$

Then the calculation of the electrical efficiency η and power factor $cos\varphi$ is carried out:

$$\eta = \frac{P_2}{P_\Sigma}; \tag{12}$$

$$\cos\varphi = \frac{P_\Sigma}{P_{S\Sigma}}. \tag{13}$$

The calculation of the current in the inductor I_1 is performed by the formula:

$$I_1 = \frac{P_{S\Sigma}}{U_1}, \tag{14}$$

where U_1 denotes the given voltage on the inductor.

3) *The determination of the number of turns of the inductor and the calculation of the width of the turn are carried out.* The number of turns of the inductor w_1 is calculated by the formula:

$$w_1 = \frac{H_{01} \cdot 0.5(d_{12} - d_{11})}{\sqrt{2} I_1}, \tag{15}$$

and the width of the coil with insulation b_1 is determined as:

$$b_1 = \frac{d_{12} - d_{11}}{2 w_1}. \tag{16}$$

1.2 Initial data for calculations

In this work, the inductors of induction cookers for two variants of the initial data presented in Tab. 1 are calculated and designed. It is assumed that the dishes heated is a pot made of Steel 45 grade.

Tab. 1 Initial data for calculation and design of inductors

Option number	**1**	**2**
Diameter of the bottom of the dishes d_2, m	0.12	0.24
Wall thickness of the dishes δ_2, m	0.003	0.004
Electrical resistivity of steel of dishes at 20°C ρ, Ω·m	$18.9 \cdot 10^{-8}$	$18.9 \cdot 10^{-8}$
Dishes heating temperature T_2, °C	100	280
Electrical resistivity of steel of dishes at given temperature T_2 for heating dishes ρ_2, Ω·m	$23.8 \cdot 10^{-8}$	$38.16 \cdot 10^{-8}$
Frequency of the electromagnetic field f, kHz	100	20
Inductor voltage U_1, V	220	220
Power released in the dishes P_2, W	2000	3300
Presence of a reactive power compensator	+	+

The calculations are carried out for large and small diameter pans (24 cm and 12 cm, respectively) for the minimum (20 kHz) and maximum (100 kHz) frequencies of the electromagnetic field, used in modern induction cookers [1]. According to the technical characteristics of induction cookers, the power released in the dishes (2.0 kW and 3.3 kW), as well as the temperature of heating the dishes (100°C and 280°C), also vary. Thus, in this paper, two inductors (of large and small diameters for heating of the corresponding dishes) are calculated and designed for use either in the corresponding single-ring induction cookers, or in one double-ring cooker with rings of different diameters.

1.3 Results of calculations and their analysis

The results of the calculation of inductors for both variants of the initial data are presented in Tab. 2. We analyze briefly the results obtained.

The basic geometric dimensions of the "inductor-dishes" system are calculated (see Fig. 1). The outer diameter of the inductor is taken equal to the diameter of the heated surface (diameter of the pan). The gap between the inductor and the dishes is tentatively assumed to be 1.0 cm (0.01 m) and will be specified in the design process of the induction cooker, based on the presence of thermal and electrical insulation, taking into account the features of the technological process of assembling the cooker.

Given in Tab. 2 the values of the inductor thickness calculated for both variants of the initial data are the minimum values that will also be refined during the designing the inductor. Among the calculated electric and energy quantities, the electric efficiency of the induction cooker is of most interest. The calculated values of the efficiency (about 50-70%, see Tab. 2 and section 4) are in good agreement with the results of experiments performed at the experimental workbench developed by the authors [7] for household induction cooker type VES V-HP6 (59-70% depending on the selected mode of heating of the pot with water). We also note that the measured values of the power factor are in the range of 0.98-1.00, in contrast to the calculation results (about 0.80, see Tab. 2 and section 4). This may be because the reactive power compensator is probably used in the structure of the induction cooker.

The designs of a 2-turn and a 12-turn inductor calculated (the initial data and the results obtained — see Tab. 1, 2, options 1 and 2, respectively) are presented in Fig. 2.

Tab. 2 Results of calculation and design of inductors

Option number	**1**	**2**
Outer diameter of the inductor d_{12}, m	0.12	0.24
Inner diameter of the inductor d_{11}, m	0.04	0.04
Gap between the inductor and the dishes δ, m	0.01	0.01
Inductor thickness δ_1, m	$0.29{\cdot}10^{-3}$	$0.5{\cdot}10^{-3}$
Specific surface power in the dishes p_{02}, W/m^2	$1.99{\cdot}10^5$	$7.5{\cdot}10^4$
Magnetic field strength on the surface of the dishes H_{02}, A/m	$1.55{\cdot}10^4$	$0.99{\cdot}10^4$
Magnetic field strength on the surface of the inductor H_{01}, A/m	$6.596{\cdot}10^4$	$4.213\ {\cdot}10^4$
Coupling coefficient k_{12}	0.235	0.253
Active power in inductor P_1, W	$2.058{\cdot}10^3$	$1.49{\cdot}10^3$
Reactive power in the inductor P_{Q1}, VAr	$2.058{\cdot}10^3$	$1.49{\cdot}10^3$
Reactive power in the dishes P_{Q2}, VAr	$1.2{\cdot}10^3$	$1.98{\cdot}10^3$
Reactive power in the gap P_{Q3}, VAr	$0.098{\cdot}10^3$	$0.161\ {\cdot}10^3$
Active power of the "inductor-dishes" system P_Σ, W	$4.058{\cdot}10^3$	$4.79{\cdot}10^3$
Reactive power of the "inductor-dishes" system $P_{Q\Sigma}$, VAr	$3.258{\cdot}10^3$	$3.47{\cdot}10^3$
Total power of the "inductor-dishes" system $P_{S\Sigma}$, VA	$5.204{\cdot}10^3$	$5.915\ {\cdot}10^3$
Electrical efficiency η	0.493	0.689
Power factor $cos\varphi$	0.78	0.81
Inductor current I_1, A	23.655	26.886
Number of turns of the inductor w_1	2	12
Width of coil with insulation b_1, m	0.02	0.0083

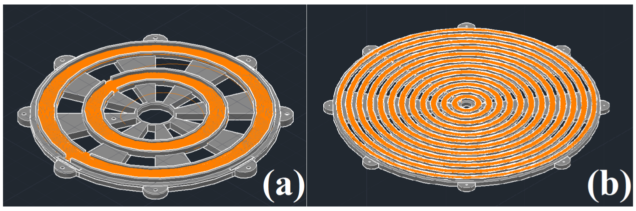

Fig. 2. Designs of 2-turn (a) and 12-turn (b) inductors of the household induction cooker

2 Calculation and design of magnetic cores of household induction cookers

2.1 A technique proposed

The most common type of magnetic core of induction cookers is a system of rods of rectangular cross-section, located under the inductor of the cooker and made of modern ferromagnetic material – ferrite of the appropriate brand with the desired electrophysical properties [8–11]. The corresponding structural elements of the induction cooker are shown in Fig. 3 [8–10].

Figure 3, a shows a ferrite magnetic core in the form of eight rods of rectangular cross-section, located under the inductor [8,9]. Another number of rods is also used (usually even from 6 to 12, Fig. 3, b) [10,11].

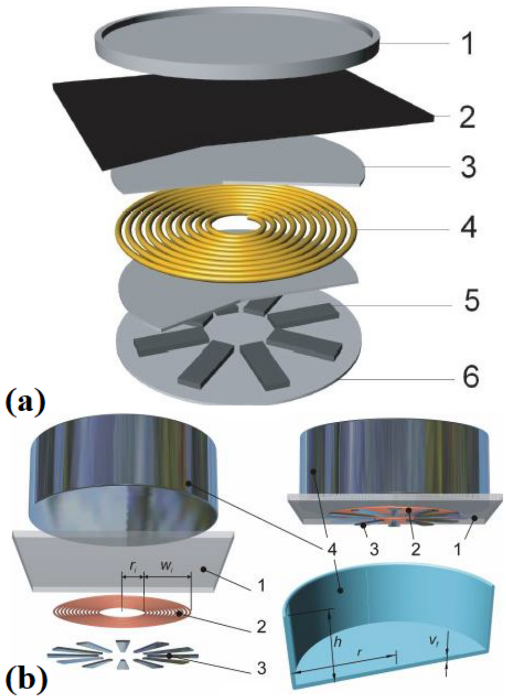

Fig. 3. Main structural elements of induction cookers: **(a)**: 1 – heated dishes (frying pan); 2 – cooking surface; 3 – electrical insulation (mica); 4 – inductor; 5 – ferrite magnetic core; 6 – aluminum plate [8, 9]; **(b)**: 1 – glass-ceramic cooking surface; 2 – inductor; 3 – ferrite magnetic core; 4 - heated dishes (saucepan) [10].

Magnetic cores of household induction cookers are made of modern magnetic materials – ferrites [8–11]. In the literature there is no information about the brands of ferrites used for the production of magnetic core rods of household induction cookers. The analysis of the information given on the sites of suppliers of the corresponding production allows to draw a conclusion that cores of magnetic conductors of household induction cookers are made of MnZn ferrites. The properties of these ferrites of different brands are given, for instance, in [12, 13].

The purpose of calculation and design of the magnetic core is the choice of material for its manufacture, determination of geometric and mass parameters of the magnetic core, as well as losses in it during operation of the plate. The following sequence of solving the problem is proposed.

1) *The choice of material for the manufacture of magnetic core rods.*

As mentioned above, the rods of magnetic cores of household induction cookers are made of MnZn ferrites. In [12] the main properties (initial magnetic permeability, saturation magnetic flux density, loss volume density at the conditions of its definition specified in [12], Curie temperature, electrical resistivity) of the specified ferrites are presented. Based on the given information, it is possible to pre-select the brand of MnZn ferrite focusing primarily on the range of operating frequencies (current frequency in the inductor of the induction cooker – 20-100 kHz) and, if possible, a small loss volume density. Therefore, among the ferrites for low and medium frequencies (10-300 kHz) we can select, for example, a new material PC95 manufactured by TDK Corporation, which meets these requirements.

Detailed description, characteristics and properties of MnZn ferrites produced by TDK Corporation are given by the manufacturer in [13]. This document confirms that the selected ferrites can be used in various electronic and electrical devices, including devices for electric heating. In addition to the values given in [12], the document [13] provides the most detailed information on the properties of the respective materials: it additionally gives density, coercive force, remanent flux density, as well as in graphical form the main magnetization curves $B(H)$ at different temperatures, the dependence of magnetic permeability on temperature and frequency, the dependence of the loss volume density on the amplitude of the magnetic flux density B_m, temperature and frequency. This detailed information is used in the subsequent stages of the calculation of the magnetic core of the household induction cooker.

2) *The choice of geometric dimensions of ferrite rods, the calculation of the mass of the magnetic core.*

In the process of designing magnetic cores in the form of ferrite rods of rectangular cross-section, located under the inductor [8–11], when choosing the geometry of ferrite rods of magnetic cores of induction cookers, we should focus on the range of relevant products on the market. According to the relevant catalogs, it is possible to purchase ferrite rods with cross-section $h \times b = 5\,\text{mm} \times 15\,\text{mm} = 5 \cdot 10^{-3}\,\text{m} \times 15 \cdot 10^{-3}\,\text{m}$, where h, b are the height and thickness of the rod, respectively. The length of the rod l is determined by the formula:

$$l = 0.5(d_{12} - d_{11}), \tag{17}$$

where d_{12}, d_{11} are the outer and inner diameters of the cooker's inductor, respectively.

The mass of the magnetic core m is calculated as:

$$m = \rho V N, \tag{18}$$

where ρ is the density of the material of the rods; N is the number of rods of the magnetic core of the cooker; V is the volume of one rod:

$$V = hbl. \tag{19}$$

Formula (19) can be applied when in the magnetic core of an induction cooker rods of "traditional" geometry shown in Fig. 3, a [2,3] are used. When using rods tapered in the direction of the inner diameter of the inductor (in order to obtain a kind of concentrators of the electromagnetic field [10,11], see Fig. 3, b), the volume of the rod is calculated accordingly.

3) *Calculation of power losses in the magnetic circuit.*

Losses P_C in the ferrite rods of the magnetic core are calculated by the formula:

$$P_C = p^*_{cv} V N, \tag{20}$$

where p^*_{cv} is the loss volume density which should be determined using graphs (dependence of the loss volume density on the amplitude of magnetic flux density B_m, frequency and temperature) for the corresponding brand of ferrites under appropriate operating conditions (specific values of magnetic flux density amplitude B_m, frequency and temperature). The required graphic information (see Fig. 4) is given, for example, in [13]. In the absence of this detailed information, it is possible to use the p_{cv} values given in [12] for "fixed" conditions (e.g., magnetic flux density amplitude 200 mT, frequency 100 kHz, temperature 100°C), but this can lead to errors in power losses calculations.

It should be note that the manufacturer also provides graphic information on the material's main magnetization curves $B(H)$ at different temperatures (Fig. 5) to be used in the process of numerical analysis of the distribution of the electromagnetic field of the induction cooker (see section 5).

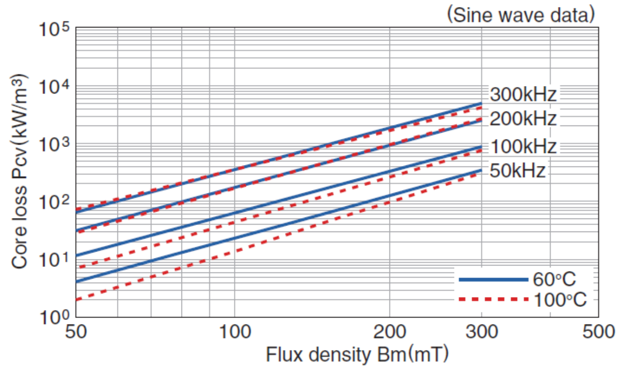

Fig. 4. Dependencies of the loss volume density on the magnetic flux density of the PC95 MnZn ferrite manufactured by TDK Corporation [13]

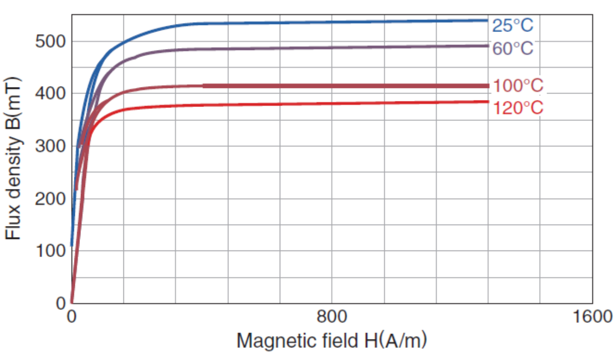

Fig. 5. Magnetization curves of the PC95 MnZn ferrite manufactured by TDK Corporation [13]

2.2 Initial data and results of calculations

Calculations of ferrite magnetic cores are carried out on the examples of two variants of inductors (see previous section of the paper, Fig. 2). The initial data for the calculations are given in Tab. 1, 2. Dishes (frying pans of different diameters and with different wall thicknesses) are heated to temperatures specified in Tab. 1 at different current frequencies in the inductor of the induction cooker.

It is intended to use the magnetic cores in the form of 8 ferrite rods of the corresponding geometrical sizes. The material of the rods is MnZn ferrite of the new brand PC95 manufactured by TDK Corporation, the detailed properties of which are given in [13]. The cross-section of the rods 5 mm × 15 mm is selected in accordance with the product catalog.

The calculations are carried out by (17)-(20). Separately, let us describe the determination of the value p^*_{cv} – the loss volume density which is found using graphs (dependence of the loss volume density on the amplitude of magnetic flux density B_m, frequency and temperature, see Fig. 4) for the corresponding grade of ferrite under appropriate operating conditions (specific values of magnetic flux density amplitude B_m, frequency and temperature) [13]. Using the appropriate graphs presented in Fig. 4, we find the values of p^*_{cv} for frequencies of 100 kHz and 20 kHz (according to both calculation options), temperature 60°C (assuming that the magnetic core in the operation of the cooker is heated approximately to this temperature) and the amplitude of the magnetic flux density B_m on the surface of the magnetic core. Regarding the value of B_m, in accordance with the results of the previously performed computer simulation of the distribution of the electromagnetic field of the induction cooker (see section 5), we assume it to be approximately 0.125 T.

2.3 Results of calculations and their analysis

The results of the calculation of magnetic core are given in Tab. 3.

Tab. 3 Results of calculation and design of the magnetic core

Option number	**1**	**2**
Number of ferrite rods N	8	8
Cross-section of ferrite rods $h \times b$, m	$5 \cdot 10^{-3} \times 15 \cdot 10^{-3}$	$5 \cdot 10^{-3} \times 15 \cdot 10^{-3}$
Length of the rod l, m	0.04	0.1
Volume of the rod, m^3	$3 \cdot 10^{-6}$	$7.5 \cdot 10^{-6}$
Density of the material of the rods, kg/m^3 [13]	$4.9 \cdot 10^3$	$4.9 \cdot 10^3$
Mass of the magnetic core, kg	0.1176	0.294
Amplitude of the magnetic flux density B_m, T [1]	0.125	0.125
Loss volume density p^*_{cv}, W/m^3 [13]	10^5	$2 \cdot 10^4$
Power losses in the magnetic core, W	2.4	1.2

From the obtained results of calculations (see Tab. 3) it can be concluded that the calculated and designed magnetic cores should be used in the designs of induction cookers, because:

• The power losses in the rods of magnetic cores are insignificant (units of W, see Tab. 3) in comparison with the active power of the system "inductor-dishes" (see Tab. 2).

• The mass of the magnetic core (up to 300 g in the considered examples) is small in comparison with the mass of the whole structure (mass of one-ring induction cookers available for sale is from 2.3 kg).

Figure 6 shows the main structural elements of an induction cooker with a two-turn inductor and 8 ferrite rods designed according to the techniques developed by the authors.

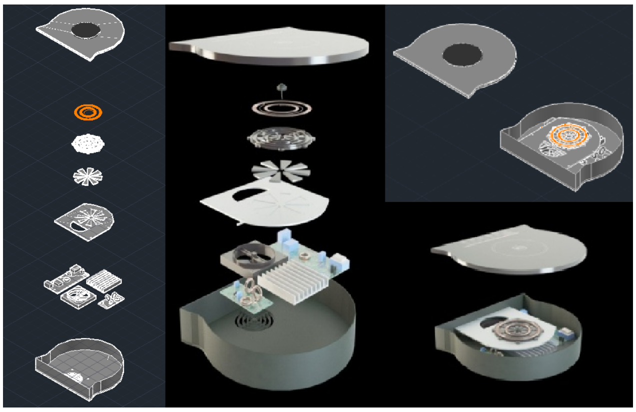

Fig. 6. Conceptual design of an induction cooker with 2-turn inductor and 8 ferrite rods

3 Experimental validation of the results obtained

Experimental investigations of the operation of the household induction cooker type VES V-HP6 have been carried out. Figure 7 shows a photo of its main structural elements – inductor and magnetic core. The photo was taken after disassembling of the induction cooker. Some examples of experimental results obtained are presented in Fig. 8 and Tab. 4.

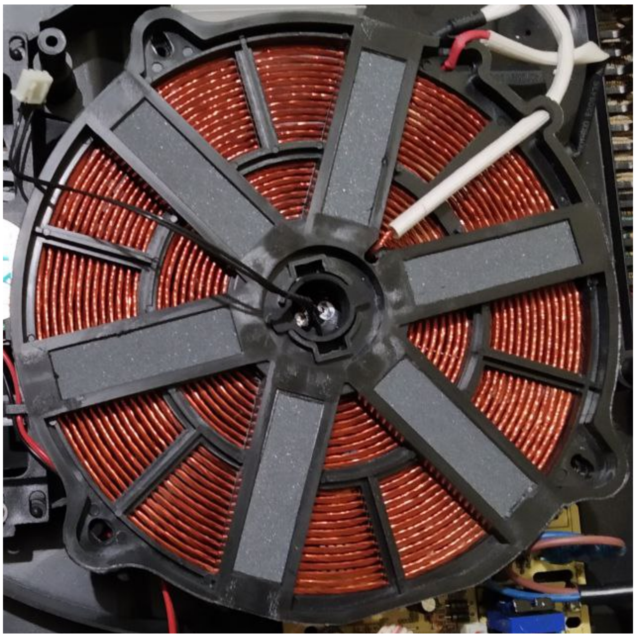

Fig. 7. Magnetic core of the household induction cooker type VES V-HP6

The study of water heating rate (1 liter of water in a special pot for induction cookers) from the initial temperature of 20°C to the boiling point of 100°C at different power of the induction cooker has been carried out. The thermocouple of the digital thermometer was immersed in a pot with heated water. The obtained results are summarized in Fig. 8. It is established that at small power of heating of water (and, accordingly, food) in the pot, boiling is impossible. The reason for this phenomenon is heat exchange with the environment (cooling by cool air).

The temperature of the work surface, digital display and control panel of the induction cooker was also measured using a pyrometer. Based on the obtained results, it can be concluded that the induction cooker is safe and comfortable to use in terms of low temperature of the control panel (not exceeding 28°C).

Experiments to measure the electricity consumed by the induction cooker in the process of bringing 1 liter of water to a boil included the reading of a digital multimeter in time during operation of the induction cooker. The results obtained are given in Tab. 4. The following values have been measured: network voltage U, current I, total power consumption P, active power Q, reactive power S, power factor $cos\varphi$. The analysis of the obtained results shows that at relatively low power (up to 1 kW) the induction cooker operates in the mode of periodic switching on the inductor. At high power (starting from 1 kW) the inductor of induction cooker operates in a continuous mode for providing fast enough heating of dishes. It should also be noted that during the operation of the induction cooker, the value of $cos\varphi$ is almost 1, which can be caused by the fact that the induction cooker design includes a reactive power compensator.

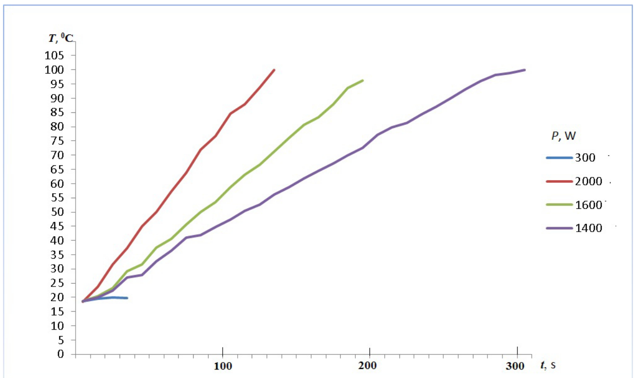

Fig. 8. Heating 1 liter of water to boiling point depending on the power of the induction cooker

Tab. 4 Results of measurements

Measured quantities	Induction cooker's power								
	0.3	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
U, V	224.5	219.0	220.0	221.0	220.0	219.4	220.2	219.7	222.0
I, A	0.2	3.2	3.2	3.2	3.7	4.2	4.5	5.0	5.3
P, kW	0.7	0.74	0.7	0.7	0.81	0.92	0.98	1.09	1.17
Q, кW	0.72	0.74	0.7	0.7	0.81	0.92	0.99	1.07	1.17
S, кVAr	0.29	0.1	0.1	0.1	0.1	0.1	0.09	0.09	0.09
$cos\varphi$	0.98	0.989	0.988	0.988	0.995	0.993	0.995	0.996	1.00

Above just a brief description and analysis of experimental results obtained are presented. The more important fact is that this experimental information allows to confirm results of calculation and design of induction cooker's structural elements obtained using the technique proposed. The design of the magnetic core of a commercially available induction cooker, shown in Fig. 7, differs from the design options proposed and calculated in this work (see Tab. 1-3), by the number of rods of the magnetic core (6 and 8, respectively) and the cross-section of each of the magnetic core rods. Nevertheless, the total cross-sectional area and the total volume of the rods of a factory-made household induction cooker (see Fig. 7) practically coincide with one of the proposed options (see option 2 in Tab. 1-3). This makes it possible and permissible to compare integral energy indicators, namely the efficiency of these induction cookers. The experimental data processing and comparison of the results show that the calculated value of the efficiency (68.9%, see Tab. 2, option 2) is in good agreement with the results of experiments performed for household induction cooker type VES V-HP6 (70% at the maximum powerful mode of heating of the pot with water).

4 Household induction cooker electromagnetic field computer simulation

4.1 Problem definition

There are publications [2–5] and many others devoted to household induction cookers' electromagnetic field computations using various formulations and approaches. In this work the authors do not intend to develop new or improve existing numerical techniques for induction cooker computer simulation. The goal of this section is to carry out just "preparatory" computations of the distribution of the electromagnetic field of the induction cooker to estimate the amplitude of magnetic flux density B_m required to calculate and design the induction cooker magnetic core (see section 3). To do this, the finite element analysis of induction cookers' electromagnetic and field is carried out in common 2D formulation. A simplified computational model of the household induction cooker including main elements such as an inductor, a heated pan and a ferrite magnetic core is developed and analyzed.

4.2 A mathematical model

The transient distribution of electromagnetic field is described by equation [14–16]:

$$curl\left(\frac{1}{\mu}curl\mathbf{A}\right)+\gamma\frac{\partial\mathbf{A}}{\partial t}=\mathbf{J}_{ext}, \tag{21}$$

where A denotes the magnetic vector potential, μ the magnetic permeability, γ the electric conductance and J_{ext} the harmonic current density applied to the inductor. Parameter γ is generally a function of the temperature T whereas μ is a function of the temperature T and magnetic flux density B. However, in case of a relatively small temperature rise that takes place at the heating of dishes using induction cookers, the temperature dependencies are disregarded.

In fact, the complete solution of the parabolic equation (21) is unfeasible due to relatively long time of the heating process. That is why we simplified the model by considering harmonic magnetic field. Now equation (21) can be rewritten in terms of the phasor $\underline{\mathbf{A}}$ of the magnetic vector potential A [14–16]:

$$curl\frac{1}{\mu}curl\underline{\mathbf{A}}+j\omega\gamma\underline{\mathbf{A}}=\underline{\mathbf{J}}_{ext}, \tag{22}$$

where j denotes the imaginary unit, $\omega=2\pi f$, f the frequency of the current in the household induction cooker inductor.

Equation (22) is solved in the axisymmetrical formulation by the Finite Element Method using one of the available in-house or commercial computer codes. In this work, in-house computer code EleFAnT2D [1] is used. The computations are carried out iteratively, the magnetic permeability μ in each element containing ferromagnetic material is adjusted in accordance with the corresponding main magnetization curve.

4.3 A computational model and numerical results obtained

In Fig. 9 the axisymmetrical model of the induction cooker developed in the EleFAnT2D code environment is presented. We consider a copper inductor, a MnZn ferrite magnetic core, and a modern pan designed specifically for induction cookers: an aluminum pan with a thin bottom ferromagnetic layer which is needed to obtain proper distributions of the electromagnetic field and eddy currents in the bottom of the pan.

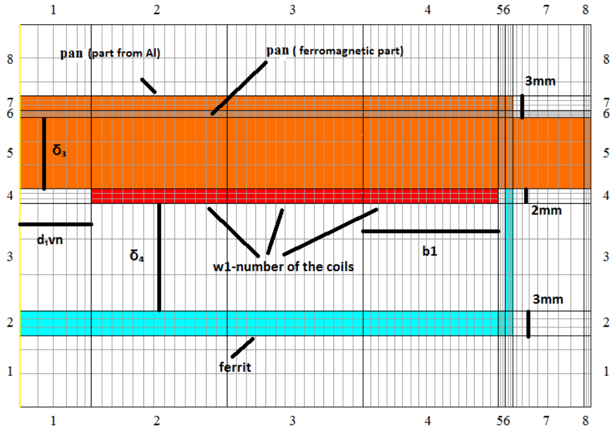

Fig. 9. Computational model of the induction cooker

Initial data for numerical analysis includes all necessary information on material properties namely the values of electric conductance of all materials used in the design of the induction cooker as well as magnetization curves of ferromagnetic materials (the PC95 MnZn ferrite's magnetization curve is shown in Fig. 5).

An example of obtained spatial distributions of electromagnetic is presented in Fig. 10. This is magnetic flux density distribution in the model with geometrical parameters (see Fig. 9) d_{1vn}=10 mm, b_1=16 mm, δ_3=10 mm, δ_4=2 mm and frequency of current in the inductor of 20 kHz. It can be seen that the amplitude of the magnetic flux density B_m on the surface of the magnetic core is about 0.125 T, and this value is used in section 3 to calculate and design the induction cooker magnetic core.

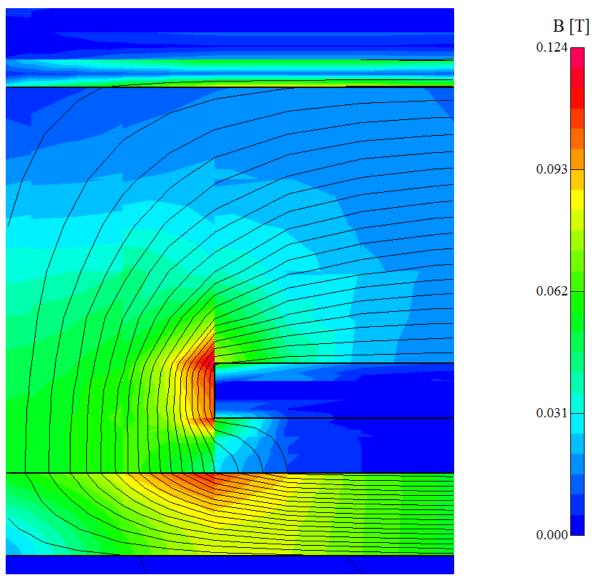

Fig. 10. Electromagnetic field distribution

Conclusion

• A developed technique for calculation and design of inductors of household induction cookers is described. The technique consists of two stages: the first one has been developed on the basis of engineering methods for calculating inductors of industrial induction heaters, taking into account the design features and operating modes of induction cookers, and the second one represents an engineering approach for the calculation and design of magnetic cores made of MnZn ferrites.

• Two-turn and multi-turn inductors of induction cookers for two variants of the initial data are calculated and designed.

• The magnetic core in the form of 8 rectangular rods made of MnZn ferrite is calculated and designed. In view of low mass and power losses they can be used in the designs of household induction cookers.

• Conceptual designs of household induction cookers are developed on the base of the techniques proposed.

• The developed techniques can be used in the process of promising research and design work on the development of household induction cookers.

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Розрахунок та проектування конструктивних елементів побутових індукційних плит

Пантелят М. Г., Грищук Ю. С., Чепелюк О. О., Єлоєв А. К.

Запропонована методика розрахунку та проектування основних конструктивних елементів побутових індукційних плит - індукторів та магнітопроводів. Техніка складається з двох етапів. Перший етап був розроблений на основі інженерних методів розрахунку мідних індукторів промислових індукційних нагрівачів з урахуванням конструктивних особливостей та режимів роботи індукційних плит, зроблених на таких етапах, як вибір геометричних розмірів індуктора, розрахунок основних електричних та енергетичних показників індуктора, розрахунок системи "індуктор-тарілки", визначення кількості витків індуктора та розрахунок ширини витка. Другий етап являє собою інженерний підхід для розрахунку та проектування магнітних осердь з феритів MnZn, виконаний на таких етапах, як вибір матеріалу для виготовлення стрижнів з магнітопроводом, вибір геометричних розмірів ферритових стрижнів, розрахунок маси магнітопроводу і розрахунок втрат потужності в магнітопроводі. Представлені та проаналізовані результати розрахунків та конструкції індукторів та магнітопроводів щодо ряду режимів нагрівання посуду різних геометричних розмірів. Розроблені методики та результати, отримані на їх основі, доповнюються та підтверджуються попереднім чисельним аналізом розподілу електромагнітного поля в індукційних плитах та посуді з підігрівом, а також експериментальними дослідженнями на розробленому експериментальному стенді. Концептуальні проекти індукційних плит, розроблені з використанням запропонованих підходів, ілюструють представлені методи. Розроблені методики можуть бути використані в процесі дослідження та проектування конструктивних елементів побутових індукційних плит, а також у навчальному процесі для підготовки бакалаврів та магістрів за відповідними освітніми програмами.

Ключові слова: побутова індукційна плита; індуктор; магнітопровід; ферит; розрахунок; проектування

Расчёт и проектирование конструктивных элементов бытовых индукционных плит

Пантелят М. Г., Грищук Ю. С., Чепелюк А. А., Елоев А. К.

Предложена методика расчета и проектирования основных конструктивных элементов бытовых индукционных плит - индукторов и магнитопроводов. Методика состоит из двух этапов. Первый этап разработан на основе инженерных методик расчета медных индукторов промышленных индукционных нагревателей с учетом конструктивных особенностей и режимов работы индукционных плит и включает следующие шаги: выбор геометрических размеров индуктора, расчет основных электрических и энергетических показателей индуктора, расчет системы "индуктор-тарелка", определение количества витков индуктора и расчет ширины витка. Второй этап представляет собой инженерный подход к расчету и проектированию магнитопроводов из MnZn ферритов и включает следующие шаги: выбор материала для изготовления стержней магнитного сердечника, выбор геометрических размеров ферритовых стержней, расчет массы магнитопровода и расчет потерь мощности в магнитопроводе. Приведены и проанализированы результаты расчета и конструкции индукторов и магнитопроводов применительно к ряду режимов нагрева посуды различных геометрических размеров. Разработанная методика и полученные на ее основе результаты дополнены и подтверждены предварительным численным анализом распределения электромагнитного поля в индукционных плитах и нагреваемой посуде, а также экспериментальными исследованиями на разработанном экспериментальном стенде. Концептуальные проекты индукционных плит, разработанные с использованием предложенных подходов, иллюстрируют представленные технологии. Разработанные методики могут быть использованы в процессе исследований и проектирования конструктивных элементов бытовых индукционных плит, а также в учебном процессе для подготовки бакалавров и магистров по соответствующим образовательным программам.

Ключевые слова: бытовая индукционная плита; индуктор; магнитопровод; феррит; расчет; проектирование