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ESTIMATE OF THE ENERGY DISTRIBUTION OF A MULTIMODE uhf FIELD IN RESONATOR SYSTEMS BASED ON HEATING OF A LIQUID DIELECTRIC

A. G. Gasparyants, Yu. K. Gubiev,
V. V. Krasnikov, and G. I. Krikunova

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A method is presented for estimating the results of experimental investigations of the nonuniformity of the energy distribution of an electromagnetic field in the cavity of a "Slavyanka" uhf (microwave) furnace.

In processes of thermal treatment, for the power supply of uhf (microwave) energy as systems connecting sources of electromagnetic energy with the product being treated, use is made of cavity resonators, in which a multimode electromagnetic field is excited [1]. The resulting vector of the intensity of the electric component of the field in an arbitrary element of volume is determined by the vector sum of the intensity of all forms of oscillations at the given point [2]. The value of the resulting field intensity depends on the form of the resonator, the method of excitation of electromagnetic oscillations in it, the frequency of the source of excitation, and the coordinates of the point of observation: the value does not depend on the time. An analytic description of such an inhomogeneous field represents an extremely complicated mathematical problem.

To estimate the nonuniformity of the distribution and the efficiency of the systems being used for "equalizing" the electromagnetic field in the resonator chambers intended for the thermal treatment of the products, it is advisable to apply methods based on the actual absorption of electromagnetic energy at each element of the cavity volume by the material being treated. The main point of one of those methods consists in the determination of the quantity of heat transformed in the liquid enclosed in a calorimeter that is "transparent" to microwaves. (In our case the calorimeter consists of a double cylinder of capacity $125\cdot10^{-6}$ m^3, made of plastic.)

The energy absorbed by the liquid (distilled water) in the calorimeter, neglecting phase transformations, is determined by the equation of balance

$$dW = (c_w m_w + c_c m_c)\, d\overline{t}. \tag{1}$$

The diameter of the calorimeter and the thickness of its walls were considered with account of the skin effect and a relation between the mass of the calorimeter and the distilled water for which neglect of the term $c_c m_c$ in Eq. (1) introduces an error that does not exceed 4%.

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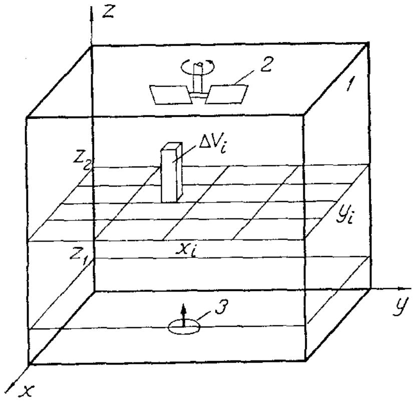

Fig. 1

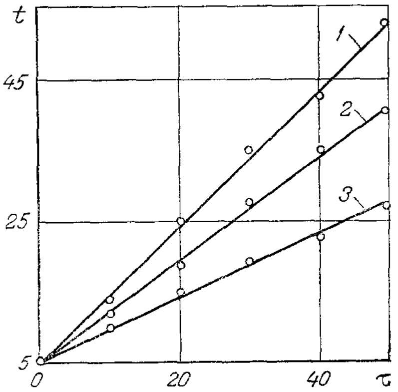

Fig. 2

Fig. 1. Volume element ΔV_i being investigated: 1) resonator cavity; 2) reflecting–balancing electromagnetic field system; 3) source of microwave energy.

Fig. 2. Dependence of the temperature of heating of distilled water t (°C) in a multimode microwave field on the time τ (sec) for various values of coordinates x and y for $z = 8\cdot 10^{-2}$ m: 1) x = 8, y = 8; 2) x = 3, y = 4; 3) x = 5, y = 3.

The total specific power of the multimode electromagnetic field absorbed by the dielectric, according to [2], can be represented in the form

$$p_{\mathrm{t}} = 0.55\cdot 10^{-10} f_{\mathrm{g}} E^2_{\mathrm{ef}} \varepsilon''_{\mathrm{t.w}} \tag{2}$$

Joint solution of Eqs. (1) and (2) gives an expression for the numerical value of the square of the resulting intensity of the electric component of the field

$$E^2_{\mathrm{ef}} = \frac{B}{\varepsilon''_{\mathrm{t.w}}}\,\frac{d\bar{t}}{d\tau}, \tag{3}$$

where $B = \rho_w c_w / 0.55\cdot 10^{-10} f_g$.

The working volume of the resonator cavity (Fig. 1) was divided into elements ΔV_i with coordinates x_i, y_i, z_i. (The division step in the directions of the x and y axes is given by the dimensions of the calorimeter, and in our case was equal to $3\cdot 10^{-2}$ m.) For fixed coordinates x_i, y_i, z_i, the specific power of scattering of the electromagnetic field, transformed in a liquid into the form of heat, is constant, since the generator operated in the stationary regime, and the geometric dimensions of the resonator did not vary. For arbitrary position of the calorimeter in the resonator, we plotted the heating curves of distilled water.

The experimental data obtained show that the linearity of the heating curve in the temperature range 5-50°C ensures that the total loss factor $\varepsilon_{t.w}$ will be constant (Fig. 2), i.e., the region of anomalous dispersion of the distilled water is shifted into the region of short waves, not emerging for a narrow region of spectrum of frequencies excited in the resonator of the field. In this case, the phase transformations are practically absent.

To determine the magnitude of the rate of heating of the liquid, it is sufficient to know the initial and final temperatures and the time of heating:

$$v_{ti} = \Delta\bar{t}_i / \Delta\tau_i\,. \tag{4}$$

It is important to emphasize that with a calorimeter diameter equal to $3\cdot 10^{-2}$ m, and a height equal to two diameters, the deviation of the numerical values of the intensity of the electric component of the field from the maximum value along the radius of the cylinder for water temperature 1.5°C does not exceed 5%, and for temperature 85°C does not exceed 1%. Therefore, we can neglect the change in depth of penetration of the electromagnetic field in a liquid as a function of the temperature.

Using Eq. (3) for arbitrary x_i and y_i for fixed z_i, we can determine n values of the squares of the resulting intensity of the electric component of the field, the arithmetic average of which, with account of (4), is written in the form

$$E^2_{\text{ef.av}} = \frac{\sum\limits_{i=1} E^2_{i\ \text{ef}}}{n} = \frac{B}{\varepsilon''_{\text{t.w}}}\, v_{t\ \text{av}}. \tag{5}$$

The absolute value of the variation of the square of the field intensity for arbitrary x_i and y_i for fixed z_i with respect to $E^2_{\text{ef.av}}$ is determined by the modulus of the difference between the average and the i-th values:

$$\Delta E^2_{\text{ef.av}} = |E^2_{\text{ef.av}} - E^2_{\text{ef}\,i}| = \frac{B}{\varepsilon''_{\text{t.w}}}\, \Delta v_{ti}\,. \tag{6}$$

From all the values of ΔE^2_i we choose the maximum value, and with account of (2) we determine the maximum of the relative nonuniformity of the energy distribution of a multimode microwave field in a resonator (for fixed z), expressed in percent:

$$\varepsilon_{E^2} = \varepsilon_{\text{pt}} = \frac{\Delta p_{\text{t max}}}{p_{\text{t av}}} \cdot 100\,\% = \frac{\Delta v_{t\ \text{max}}}{v_{t\ \text{av}}} \cdot 100\,\%. \tag{7}$$

The accuracy of the calorimetric method of estimating the nonuniformity of the distribution of the electromagnetic field in the resonator cavity depends on the accuracy of measurement of temperature and time. For use as a thermomeasuring device of a differential gas thermometer [3], enabling us to measure temperature during heating with accuracy to 0.5°C (the time was measured with accuracy 10^{-1} sec), the error of the estimate of the nonuniformity of the distribution of the specific power in the resonator does not exceed 5%. (The error introduced by the calorimeter owing to heat exchange is less than the error in the measurement of temperature, since the change in temperature in the calorimeter 60 sec after the field has been switched off does not exceed 0.5°C, and the measurement of the temperature takes 10-15 sec.)

Using the described method we investigated the nonuniformity of the distribution of the total specific power p_t of the electromagnetic field in the resonator of a Soviet uhf furnace "Slavyanka" for arbitrary values of x_i and y_i for fixed $z_1 = 4 \cdot 10^{-2}$ m, $z_2 = 8 \cdot 10^{-2}$ m. The maximum spread of values of p_t from $p_{t\ \text{av}}$ for a rotating "reflecting—equalizing system" for z_1 was ±25% and for z_2 was ±36% (Table 1). The spread in the values of p_t over the cross section x_i, y_i for z_2 when the reflecting—equalizing system is switched off increases

TABLE 1. Deviation of Total Specific Power p_t from Average Value

Coord.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
$z = 4 \cdot 10^{-2}$ m, reflecting system included									
y_1	+2,3	—12,6	—22,9	—18,9	+4,9	—18,7	—23,4	—16,2	—7,9
y_2	+5,4	+10,5	—10,5	+2,8	+22,3	—17,3	—5,9	+6,4	+5,9
y_3	+4,9	+19,3	+5,9	+3,9	—2,8	+16,1	+19,3	+4,8	+4,9
y_4	+10,5	+4,9	—4,9	—12,1	—13,2	—14,2	+18,2	+11,6	+9,5
y_5	+15,2	+13,1	+6,9	—6,9	—6,9	—4,4	+14,7	+6,4	+7,5
y_6	+7,0	+4,9	—3,2	+14,2	—1,2	—1,3	—0,8	+7,9	—1,3
y_7	—1,6	—3,8	—13,6	—7,4	+21,3	—5,4	—12,1	+4,4	+12,1
y_8	—8,5	—21,8	—24,3	—17,22	+11,1	—13,2	—21,8	—8,94	—5,9
$z = 8 \cdot 10^{-2}$ m, reflecting system included									
y_1	—4,5	+36,2	+28,7	—17,1	—25,9	—5,6	+15,9	—4,3	—24,5
y_2	—9,0	+0,4	—17,8	—21,8	—14,8	—31,4	—18,9	—17,4	—8,6
y_3	—11,9	+30,7	+5,1	+27,3	+12,2	—5,7	+14,4	+5,4	—2,6
y_4	+4,2	—0,9	+1,7	—7,0	—10,7	—16,1	—11,9	+16,5	+51,8
y_5	+26,8	+26,3	—11,6	—5,6	—4,9	—2,3	+21,2	+27,3	—0,9
y_6	+4,3	+28,7	+0,4	—18,7	—12,8	—3,6	—27,0	+2,8	—12,2
y_7	+12,1	+1,1	—21,4	—20,5	—5,1	—13,6	—3,6	—2,4	—12,2
y_8	+11,8	+25,6	+19,4	—27,7	—37,9	—24,7	+21,0	+10,6	+0,6
$z = 8 \cdot 10^{-2}$ m, reflecting system excluded									
y_1	+7,4	+62,3	—19,6	—31,9	—38,2	+14,72	+49,9	+6,1	—51,6
y_2	—11,1	—6,3	—24,2	—52,2	—42,0	—16,8	—11,5	—19,4	—41,9
y_3	+17,2	+41,4	—10,7	—27,0	—26,3	—31,2	—4,2	+0,7	—15,6
y_4	+2,6	—17,2	—25,5	—12,0	—20,7	—43,2	—10,7	+27,6	+104,4
y_5	+61,9	+29,7	—42,31	—34,0	—37,4	—33,4	+13,1	+48,8	+64,0
y_6	+91,3	+43,8	—10,3	—47,6	—54,3	+25,7	+47,8	+18,0	+13,7
y_7	+47,5	+1,0	—33,9	—33,9	—16,4	—22,2	—2,6	+3,4	—3,2
y_8	+20,1	+83,4	+13,1	—25,0	—20,6	+38,1	+78,6	+54,3	+42,6

up to 104%. Hence, the reflecting—equalizing electromagnetic field system available in the "Slavyanka" furnace only partly solves the problem of the elimination of the nonuniformity of the field distribution of the resonator, which is one of the basic products in the processes of thermal treatment. Evidently, the methods of "equalization" of a multimode uhf field of standing waves should be combined, providing simultaneous displacement of the product and the field with respect to each other.

NOTATION

dW, energy released in the calorimater; $d\bar{t}$, average temperature variation; c_w and c_c, specific heats of the water and of the calorimeter; m_w and m_c, masses of the water and of the calorimeter; p_t, total specific power of the multimode electromagnetic field (the energy generated in an element of volume ΔV during time dτ); f_g, frequency of the generator; E_{ef}, effective vector of the intensity of the electric component of the field in the volume element ΔV; $\varepsilon''_{t.w}$, total loss factor of the water; ρ_w, density of water; B, a quantity that depends on the frequency of the generator; v_t, rate of heating of the liquid; ε_{E^2} and ε_{pt}, relative nonuniformities in the distribution of the square of the intensity and the total specific power in the resonator.

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CALCULATION OF THE TEMPERATURE PATTERNS IN CONTINUOUS CASTING OF CERAMIC COMPONENTS FROM THERMOPLASTIC SLIP

E. V. Nomofilov, Yu. V. Dvinskikh,
R. Ya. Popil'skii, V. V. Kulagin,
and S. I. Morozova

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A method is given for calculating the parameters and temperature patterns in continuous hot casting of ceramic components. The calculations are in satisfactory agreement with experiment.

Continuous casting of ceramic components from thermoplastic slip is widely used [1, 2]. This method is mainly used when one requires long tubular precision components of multilayer type with single or multiple channels. The thermophysical processes occurring in this form of casting are similar to those in the continuous forming of metals and alloys [3], but they are more rapid and occur on the shorter parts of the system, while the thicknesses and the temperature gradients are much smaller than those in forming metals. This causes certain difficulties in examining the solidification of the slip, which is necessary in choosing or calculating the parameters.

The basic parameters determining the throughput are the casting rate and the cooling rate. It is therefore necessary to know the temperature distributions.

Existing analytic methods are complicated or of low accuracy [3-5]. Here we give a method of calculating the temperature distributions in solidifying the solidified slip.

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