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SIMULATION OF THE MICROWAVE FIELD INFLUENCE ON WASTES MELTING

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Abstract: *The paper determines the influence of the microwave field on the temperature produced in the melting crucible during the recovery process of nonferrous metals from industrial wastes. The particularities of the practical system are taken into account. An entire energetic layout, including the wave generation, wave propagation and the wave interaction with the SiC crucible, was performed using the MatLab simulation program.*

Key words: *microwave, model, waste, heat, melting.*

1. Introduction

Microwave processing of materials is a complex tool that implies a broad range of electromagnetic equipment and materials variables, which fluctuates with temperature.

The microwaves usage is a new technology that improves the physical properties of materials, reduces the impact on environment by saving energy, time and space and produces new materials and structures that can't be obtained by other methods.

Microwaves are electromagnetic waves with a frequency between 300 MHz and 300 GHz and wavelengths between 1 mm and 1 m. As a result, part of the electromagnetic field is transformed in thermal energy, which is transferred to the melted material molecules [1].

In this process, a heating effect of the dielectric material is generated by the electric field of high frequency (hysteresis losses) and partially by the Joule effect [2], [3], [4].

Microwave heating is an important component of the modern melting technology, because of its commercial advantages. Compared to conventional methods, microwave heating is performed directly without the intermedia of a slow thermal transfer process from the source element to the melting crucible [10]. The volumetric heating of the crucible minimizes the heating time, reduces the energy consumptions and improves the diffusion rate, while the electromagnetic energy is converted in heat, as a result of the interaction with the material. Therefore, the waste material will receive the heat

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produced in the crucible mainly by conduction, in a direct manner. Therefore, it is important to analyse the influence of the microwave field on the temperature produced in the melting crucible [8], [9]. To determine the temperature at which the charge is heated in the microwave furnace, the amount of heat generated by the microwave in the crucible was determined by the wave - material energy balance [7].

In their research work, Chandrasekaran et al. [3] studied the influence of microwave heating on the processing of waste material, function of system characteristics. Experimental and modelling work was provided in the paper. The application of energy balance equations generated a differential function of non-dimensional parameters, that were solved for quadratic solutions. In order to determine the coefficients of the final equation a Gaussian iteration method was implied. The experimental results matched partially the developed model. The differences were assumed to be provoked by the inherent heat losses and temperature gradients between the SiC susceptor, melting crucible and the charge [5]. A detailed heat transfer, as taking into account the area heated by the microwave and the actual heat transfer between the system components, was not performed in the paper [4].

Present paper proposes a model that describes the heating capacity of a practical system designed to process metal waste by the contribution of new microwave technology. The system includes electrical, magnetic and thermal transport phenomena, resulting in a multidisciplinary treatment with a high complexity, which implies the use of specialized MatLab modelling and simulation programs [6]. The model provides a step by step calculation process to determine the expected time for heating a certain area from SiC crucible by microwaves.

2. Simulation Method

The simulation process was performed with the Matlab software. The process was divided in three stages: microwave generation, wave propagation and wave-crucible interaction.

The first stage of the energetic layout is the microwave generation (depending on power and frequency), which describes the characteristics of the wave produced by the magnetron and the calculus of the wave energy propagated before its interaction with the guideway subassembly system.

In compliance with the producer specifications, the wave generated by the magnetron has the power, P = 1 kW and frequency f = 2.460 GHz. In order to determine the wave propagation model, there should be calculated: the wavelength (Equation 1), wave impedance (Equation 2) and the electric and magnetic energies [7]:

$$\lambda = \frac{c}{f} = \frac{299792458\frac{m}{s}}{2460000000\frac{1}{s}} = 0.122\,m\,, \tag{1}$$

where: c - light speed [m/s]; f - wave frequency [1/s].

A remarkable property of the electromagnetic wave is the ability to transfer an equal amount of electrical and magnetic energy in the considered isotropic environment. The wave impedance can be determined using Equation (2):

$$\frac{E_x}{H_y} = Z = \left(\frac{\mu_0 \mu^`}{\varepsilon_0 \varepsilon^`}\right)^{1/2}, \tag{2}$$

where: E_x - wave electric energy; H_y - wave magnetic energy; μ’, μ_0 (4π x 10^{-7} H/m) - relative magnetic and standard permeabilities; ε’, ε_o (8.854 x 10^{-12} F/m) - relative electric and standard permeabilities.

Because during generation process the wave propagates in the air, it can be considered that ε` = μ` = 1 and the wave impedance becomes (Equation 3):

$$Z = \sqrt{\frac{4 * \pi * 10^{-7}\ \mathrm{H/m}}{8.854 * 10^{-12}\ \mathrm{F/m}}} = 377\ \Omega. \tag{3}$$

The energy of an electromagnetic wave is proportional with its square amplitude (E^2 or B^2). The amplitude is the peak of the electric and magnetic field of the wave (Figure 1):

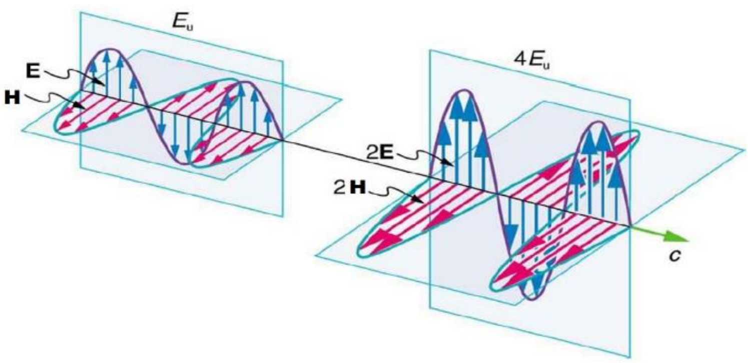

Fig. 1. *Electrical and magnetic components of the microwave* [11]

Knowing the wave generating power and the wave propagation transversal surface area, it can be determined the intensity of the wave, using Equation (4):

$$I = \frac{P}{S} = \frac{1000\ W}{0.0032\ m^2} = 312500\ \frac{W}{m^2}. \tag{4}$$

Wave operating surface is determined by transversal surface area of the propagation guide. In the present case, the guide is of parallelepipedal shape, with the dimensions of 40 x 80 x 165 mm (Figure 2) and the area of 3200 mm^2:

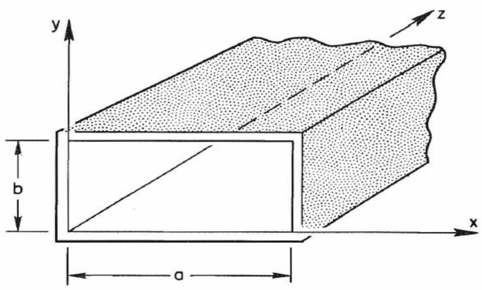

Fig. 2. *Waveguide model* [5]

For a continuous sinusoidal wave, the average intensity can be written using Equations (5) and (6):

$$I = \frac{c * \varepsilon_0 * E_0^2}{2}, \tag{5}$$

$$I = \frac{c * H_0{}^2}{2\mu_0}, \tag{6}$$

where: E_0 - maximum energy of electric field; B_0 - maximum energy of magnetic field.

Solving Equations (5) and (6), were calculated amplitudes E_0 = 15344.75 V/m and $H_0 = 5.12 \cdot 10^{-5}$ T. Applying the obtained data in MatCalc program, there can be described the wave generated in the furnace (Figure 3):

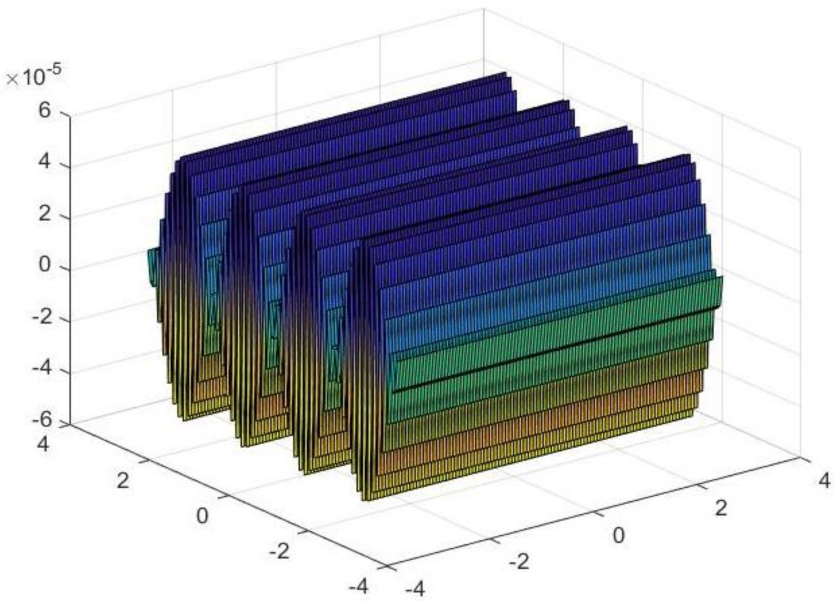

Fig. 3. *3D model of the wave generated in the furnace*

The second stage of the energetic layout consists of the wave propagation, where the waves generated by the magnetron will enter the waveguides with a wavelength λ = 0.122 m, intensity I = 12500 W/m^2, impedance Z = 377 Ω and amplitudes E_0 = 15344.75 V/m and $B_0 = 5.12 \cdot 10^{-5}$ T.

According to Figure 2, the waveguide has a parallelipipedic section. The way of transmitting electromagnetic waves through waveguides of various shapes and dimensions has been extensively studied in the past and specific relations for the calculation of the wave propagation characteristics have been determined [2]. Transmission modes in perpendicular waveguides have been divided into several types, characterized by the value of critical wavelength, λ_c.

If the incident wavelength has a value higher than 2a, the waveguide acts like a filter and prevents the passage of the wave. In the present case, the incident wave has the value of λ = 0.22 m and the waveguide has the largest side of 0.08 m. The type of waveguides with an optimal wave transmission is TE_{10} (transverse electric component of the order 10) and characterizes the waves with wavelength values between $2a = 0.16$ m and $2a/[(1+(a/b)^2]^{1/2} = 0.09$ m.

For TE waveguides, the most important variables are the wavelength, λ_g and wave impedance (Z_{TE}). Their calculus is simplified by defining some coefficients dependent of the propagation environment, $k_1 = 2\pi f(\varepsilon'\varepsilon_0\mu'\mu_0)^{1/2}$ and the waveguide geometry, $k_c = [(m\pi/a)^2+(n\pi/b)^2]^{1/2}$. For TE_{10} waveguide, $\mu' = 1$, $\mu_0 = 4\pi \times 10^{-7}$H/m, $\varepsilon' = 1$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, $m = 1$, $n = 0$, so it results that $k_1 = 51.6$ and $k_c = 39.27$.

$$\lambda_g = {}^{2\pi}\Big/_{\sqrt{(k_1^2 - k_c^2)}} = 0.1881\, m' \tag{7}$$

$$Z_{TE} = f\mu_0\mu'\lambda_g = 581.4\,\Omega\,. \tag{8}$$

From the obtained results it can be observed that, at least theoretically, the wave is not attenuated by waveguide configuration, $\lambda_{initial} = 0.122$ m and $Z_{inițial} = 377\ \Omega$, maintaining the intensity from the generation moment.

Depending on the material from which the waveguide is built, wave can be attenuated by absorption and reflection phenomena. The general formula of the attenuation factor for a TE_{10} type waveguide depends on the largest transversal section of the waveguide and the threshold frequency (propagation limit). The threshold frequency can be calculated using Equation (9):

$$f_c = \frac{c}{2a} = 1873.7 * 10^6\, Hz. \tag{9}$$

Knowing resistivities for copper and stainless steel, $\rho_{cu} = 1.68\text{x}10^{-8}\ \Omega$m and $\rho_{ss} = 7.2\text{x}10^{-7}\ \Omega$m, power transmission attenuation factor of the wave can be calculated using Equation (10):

$$\alpha_c = \frac{0.01107}{a^{3/2}}\left[\frac{\frac{a}{2b}(\frac{f}{f_c})^{3/2}+(\frac{f}{f_c})^{-1/2}}{\sqrt{\left(\frac{f}{f_c}\right)^2-1}}\right]\sqrt{\frac{\rho_{cu}}{\rho_{ss}}} = 0.1891\, dB/m. \tag{10}$$

Therefore, the power of the wave is reducing with a 0.1891 factor for each meter of the waveguide. Having a length of 165 mm, then the transmitted power, P_g, is (Equation 11):

$$P_g = \frac{P}{10^{\alpha_c/10}} = 957{,}4\, W. \tag{11}$$

The third stage of the energetic layout is the wave - crucible interaction. Microwave heating is an energy transfer process from the incident waves to the receiver, by wave -

material coupler, that depends on the material characteristics of the receiver. The electric component of the wave energy has the most important effect on materials heating process. [6] Considering the power calculated at the waveguide output (P_g), it can be calculated the value of the electric field on the interface wave - crucible (E_c) using formula (12):

$$E_c = \sqrt{\frac{2P_g}{(1-S_{11}^2)*10^{-4}}} = 4168\ \frac{V}{m}, \tag{12}$$

where: S_{11} = 0.25 (resonance factor on 2460 MHz frequency).

Since the material of the crucible is made of silicon carbide (SiC), the dielectric constant (ε' = 9.66) and the loss factor (tanδ = 0.003) can be extracted from existent databases. With these values we can determine the average power per unit of volume transformed into heat with the relation:

$$P_{heat} = \pi f \varepsilon_0 \epsilon' tan\delta E_c^2 = 8{,}75 * 10^3\ \frac{W}{m^3}. \tag{13}$$

The surface effect produced by the interaction of the microwaves with a solid material is influenced by its magnetic properties. The penetration depth is defined as the distance at which the field strength is reduced to 1/e (approximately 37%) of the initial value. Since SiC is a ceramic material, it has the relative permeability 1 and the electrical resistivity of 10^5 Ωcm.

$$d_s = \left(\frac{\rho}{\pi f \mu_0 \mu'}\right)^{1/2} = 32.1\ cm. \tag{14}$$

The thickness of the SiC crucible used for experiments (15 mm) is much lower than the calculated penetration depth (Figure 4). Therefore, the crucible is heated simultaneous in the entire volume, without requiring a heat transfer.

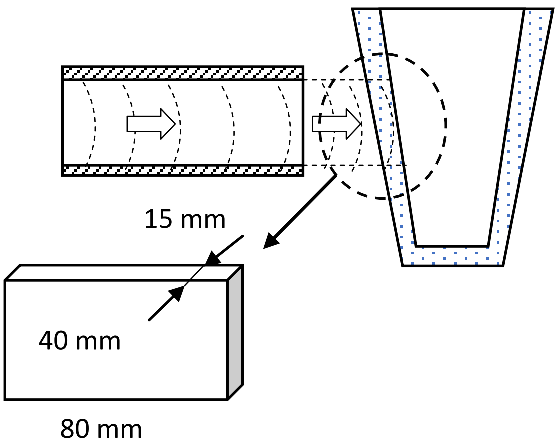

Fig. 4. *Representation of the microwave area*

The crucible area heated by microwaves is a parallelepiped, with dimensions of 40x80x15 mm and volume of $4.8 \cdot 10^{-5}$ m^3. Knowing the theoretical density of SiC (ρ_{SiC} = 3.21 g/cm^3), specific heat (C_p = 650 J/kgK), room temperature (T_0 = 293 K) and heating temperature of the crucible (T_c = 1873 K), one can determine the heat quantity generated in the crucible (Q) with the following expression (Equation 15):

$$Q = \rho_{SiC} V_C C_p (\mathrm{T}_c - \mathrm{T}_0) = 1.58 * 10^5\, J. \qquad (15)$$

The time necessary for microwave to heat the crucible area is determined with the Equation (16):

$$t = \frac{Q}{P_{heat}} = 18\, sec. \qquad (16)$$

Because the volume heated directly by the microwaves is one third of the entire crucible volume, a mixed heat generation and heat transfer process has to be considered in order to determine the heat generated by the microwave source in the entire crucible. Therefore, the complete heating of the crucible requests additional time, influenced by the heat transfer in the crucible.

3. Conclusions

In this article was presented a simulation of heating processes in the microwave furnace for the melting of non - ferrous waste, using MatLab program. In this context, there were analyzed the microwave generation stages, transmission and propagation through waveguides and wave - crucible interactions, respecting the characteristics of the furnace.

Main parameters of the generated wave (medium intensity, I, electrical and magnetic amplitudes, E_0 and H_0, wavelength λ and characteristic impedance, Z) were calculated using specific equations. The obtained data have contributed to the graphical representation of the wave generated in the furnace.

The geometry of the transmission waveguides and the characteristics of the incident wave aided in the definition of the microwave propagation, identifying the attenuation factor, α, the intensity, I, and the power of the wave, P at the output of the waveguide. Calculated equation system showed that the waveguide dimensions were optimized for a minimum attenuation of the power of the wave.

The interaction of microwaves with SiC crucible walls was studied, according to the waveguide distribution. For the analyzed case, due to special material characteristics of SiC, the microwave absorption generates a high thermal power, with a theoretical penetration depth higher than the crucible thickness. The specific time necessary to heat the crucible area, powered by microwaves, it was determined from energy balance calculations, using appropriate modelling equations. Due to the heat losses from the furnace atmosphere and to the large sizes of the crucible, the obtained values may show significant deviations from actual results. In this case, it is necessary to further the model by studying the thermal transfer from the furnace active area to the rest of the crucible.

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