Optimal microwave heating of biochar containing iron ore pellets

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Abstract. Process of microwave heating of a composite material consisting of a mixture of iron oxides (Fe₂O₃ / Fe₃O₄), a binder (bentonit), and a carbon-containing powder (biochar) was studied theoretically and experimentally. The values of complex permittivity and permeability of the samples under study were found according to effective medium approximation and enhanced Bruggeman expression in particular. Spatial distribution of temperature in the pellet of composite material was obtained when heated by an electromagnetic field with a frequency of 2.45 GHz, as well as the time dependencies of sample surface temperature.

1. Introduction
Investigation of the distribution of electromagnetic field in a composite material consisting of biochar and iron ore by microwave heating will improve the energy efficiency of existing technologies in the production of pure iron. Obtaining the experimental results of microwave heating with different field configurations, as well as numerical simulation of volume heating of the pellets, is necessary to control their heating rate and reduction temperature. When changing the parameters of microwave heating, it becomes possible to control the order of phase transitions, the ratio of CO/CO₂ and the residual content of OH-groups in samples.

Improving the performance of products, as well as environmental requirements for powder metallurgy processes, limits the use of traditional methods, such as high-temperature sintering in furnaces and hot pressing. The use of microwave processing allows to achieve fast, uniform and, with high accuracy, controlled heating, and also to exclude the possible influence of muffle material on composition of synthesized substances [1]. In the present work, microwave heating of a composite pellet, which is a mixture of iron ore, biochar and bentonite was studied.

In most of previous studies, the main attention was paid to the use of fine coal and coke for reduction of iron [2]. The structure and properties of the prepared material in this case are not effectively changed, which still leads to large emissions of SO₂, NOₓ and CO₂. Biochar is formed by pyrolysis of renewable biomass at high temperatures and has an unique characteristic of carbon neutrality in comparison with other types of fuel [3,4]. Biochar has a high fixed carbon content (30-90%), a low impurity content (S and P) [5] and a large surface area (60350 times more than that of coal [6] and 10 times more than coke with the same particle size [7]), which positively affects the reduction of iron from oxides in the green ore [8].
2. Objects and methods of investigation

The green composite pellets were prepared taking into account the requirements for their qualitative mechanical properties and surface impedance matching for effective microwave heating by selecting their composition, structure, and various parameters of pelletization [9].

Microwave heating of the studied samples was carried out in the installation of a rectangular waveguide (mode H10) with a cross section of 45x95 mm. Experimental studies were performed in the traveling-wave mode with a frequency of 2.45 GHz, and the sample temperature, depending on the heating time, was recorded by the contactless method using the modified AKIP-9311 pyrometer.

To calculate the properties of the material at different stages, the effective medium approximation was used. The characteristic sizes of the particles of the initial powders are about 1050 m [9], which is significantly less than the wavelength of the microwave radiation used in the work. Consequently, the conditions of the quasistationary approximation are satisfied and the application of the effective medium theory is justified here. The values of effective permittivity \( \varepsilon_{\text{eff}} \) and permeability \( \mu_{\text{eff}} \) in the case of high conductivity of biochar in initial and intermediate stages were derived from the Bruggeman formula for a material model consisting of spherical particles in the shell (for \( \mu_{\text{eff}} \) is identical):

\[
\begin{align*}
\left(1 - \sum_{i=1}^{N} p_i \zeta_i \right) (\varepsilon_g - \varepsilon_{\text{eff}}) \prod_{i=1}^{N} (2\alpha_i \varepsilon_{\text{eff}} + \beta_i \varepsilon_{\text{shell}}) + \\
+ (\varepsilon_g - 2\varepsilon_{\text{eff}}) \sum_{i=1}^{N} \left[ p_i \zeta_i \left\{ \zeta_i - 1 \right\} \left( \varepsilon_i + 2\varepsilon_{\text{shell}} \right) \left( \varepsilon_{\text{shell}} - \varepsilon_{\text{eff}} \right) + \\
+ 3\varepsilon_{\text{shell}} \left( \varepsilon_i - \varepsilon_{\text{eff}} \right) \right] \times \\
- \left(\varepsilon_g - 2\varepsilon_{\text{eff}}\right) \sum_{i=1}^{N} \left[ \frac{9}{2} p_i \zeta_i \varepsilon_{\text{eff}} \left( \varepsilon_i - \varepsilon_{\text{shell}} \right) \ln \left( 1 + l_i \right) \times \\
\prod_{j=1,j \neq i}^{N} (2\alpha_j \varepsilon_{\text{eff}} + \beta_j \varepsilon_{\text{shell}}) \right] = 0,
\end{align*}
\]

This equation is in generalized form and written for the case of \( N \) particles with a shell. In the case of two types of particles, let us consider the following definitions: \( m \)-particles of iron oxides, and \( c \)-particles of biochar. Each of the particle types is covered with a bentonite shell \( b \), respectively, \( \varepsilon_{\text{shell}} = \varepsilon_b \), and parameters depending on the geometric sizes of the particles in the sample can be written as:

\[
\begin{align*}
\zeta_{m,c} &= (R_{2m,2c}/R_{1m,1c})^3 = (1 + l_{m,c})^3, \\
l_{m,c} &= (R_{2m,2c} - R_{1m,1c})/R_{1m,1c}, \\
\alpha_{m,c} &= (\zeta_{m,c} - 1)\varepsilon_{m,c} + 2(\zeta_{m,c} + 1)\varepsilon_b, \\
\beta_{m,c} &= (2 + \zeta_{m,c})\varepsilon_{m,c} + 2(\zeta_{m,c} - 1)\varepsilon_b.
\end{align*}
\]

(2)

here characteristics of iron ore particles - \( \varepsilon_m = 14.2 + 0.2i \) is permittivity, \( \mu_m = 1.8 + 0.9i \) is permeability; of biochar - \( \varepsilon_c = 3 + 4\pi\sigma_c i \), \( \mu_c = 1 \); of bentonite - \( \varepsilon_b = 1.2 \) and \( \mu_b = 1 \); and of gas in between of particles - \( \varepsilon_g = 1 \) and \( \mu_g = 1 \); \( R_{1m} \)-core radius of iron ore particle, \( R_{2m} \)-radius of entire iron ore particle with bentonite shell, \( R_{1c} \)-core radius of biochar particle, \( R_{2c} \)-radius of entire biochar particle with shell; volume fractions - of bentonite \( p_b = 0.023 \) and of biochar \( p_c = 0.9 - p_b - p_m \).

Obtained values of complex effective permittivity and permeability were used to calculate electromagnetic field distribution within the pellet consisting of mixture of particles above. Considering this field distribution as heating sources, the temperature distribution within the pellet was calculated by finite element method as well. So that, the coupled electrodynamics and heat transfer task was studied.
3. Results and discussion

The obtained dependencies of surface impedance and imaginary part of permittivity of the material under study on the volume fraction of iron ore and the conductivity of biochar (figure 1) allow us to solve the problem of optimization the penetration of microwave radiation into the pellets under study. So, based on them, we can conclude that for the most efficient heating of the green pellet it is recommended to use biochar with conductivity $\sigma_c = 10^{11} \text{s}^{-1}$ and to ensure a gradual decrease of iron ore fraction in the pellet from the surface to the center for best matching of surface impedance.

Taking into account the data obtained, the finite element method was used to simulate the heating of pellet samples under study in a rectangular waveguide with calculation of the temperature and reflection coefficient (figure 2, a). The temperature distribution inside the pellet changes significantly when the impedance is matched as described above (figure 2, b, c) - it is possible to create conditions for the volume uniform heating of composite pellet by microwave radiation with a frequency of 2.45 GHz.

The obtained experimental data on the time dependence of the sample surface temperature are qualitatively correlated with the calculated values with an approximate account of the thermal conductivity of the sample holder and the surrounding gaseous medium (argon) (figure 2, d).

4. Conclusion

In this work, a microwave heating of composite pellet consisting of iron ore and biochar was studied. Experimental data and theoretical approaches that allow the calculation of electrodynamic properties of powders mixture and the simulation of microwave heating, are presented.

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Figure 2. Simulation of microwave heating in a rectangular waveguide - a, temperature inside the pellets for a uniform distribution of iron ore in the volume - b and with a decrease to the surface - c. Comparison of the time dependence of heating the composite pellet obtained numerically - d, 1 and experimentally - d, 2.

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