Effective electrodynamical parameters and microwave heating of radially heterogeneous pellets containing EAF dust and biochar

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Abstract. In this work, we investigated the effect of microwave radiation with radially heterogeneous pellets consisting of electric arc furnace (EAF) dust and biochar. We reviewed the possible content of EAF dust in terms of permittivity and permeability of its components and calculated effective permittivity and permeability of EAF dust by an effective medium approach. Using obtained values we calculated dependencies of effective permittivity and permeability of EAF dust - biochar composite mixture on the volume fraction of EAF dust and conductivity of biochar. Taking into account these dependencies we simulated electromagnetic field and temperature distribution within pellet with a radial dependency of volume fraction of EAF dust and effective permittivity correspondingly.

1. Introduction

Dust formation in electric arc furnaces can reach up to 30 kg per 1 ton of steel. The need to reduce dust formation and dust disposal technology is due to the negative impact of dust on the environment and human health [1]. Under these conditions, it is necessary to find ways to reduce dust formation and use dust as a secondary raw material in order to extract valuable components, primarily Fe, Zn, Pb.

In addition, millions tons of products of the pulp and paper industry are manufactured, waste in the form of hydrolytic lignin or biochar is at least 35\% of this mass [2].

Also, in recent years, much attention has been attracted by the technology of direct reduction of iron from iron-containing compounds, the advantages of which are temperatures below the melting point, reduced slag formation, low requirements for fuel [3]. The use of microwave energy makes it possible to carry out all stages of this process, and to regulate the course of the process by changing the power of the microwave generator.

The chemical composition of the dust of electric arc furnaces varies greatly from specific manufacturer, but over 90\% by weight are 4 substances: Fe\textsubscript{3}O\textsubscript{4}, Fe\textsubscript{2}O\textsubscript{3}, ZnO, ZnFe\textsubscript{2}O\textsubscript{4} [4, 5].

The main chemical processes occurring during the direct reduction of iron with solid carbon C depend on the initial composition of the EAF dust, but generally correspond to reduction reactions.
2. Calculation of effective permittivity and permeability

We used effective medium approximation to calculate effective permittivity and permeability of EAF dust itself as well as of mixture of EAF dust and biochar. For this purpose Bruggeman equation was generalized for a mixture of N types of spherical particles [6]:

\[
\sum_{i=1}^{N} p_i \frac{\varepsilon_i - \varepsilon_{eff}}{\varepsilon_i + 2 \varepsilon_{eff}} = 0
\]  

Bruggeman equation was derived in quasi-static approximation. However it is valid for our case because particle size (around 3-30 \(\mu m\)) is much less than wavelength.

For the model volume fractions and electrodynamic parameters of components of EAF dust on table 1, and according to Bruggeman equation calculation, effective permittivity and permeability of EAF dust are \(\varepsilon_{eff} = 10.69 + 2.6022i\) and \(\mu_{eff} = 0.8723 + 0.0975i\). Taking into account these values of effective electrodynamic parameters of EAF dust, dependencies of effective permittivity and permeability of EAF dust - biochar mixture on volume fraction of EAF dust and conductivity of biochar were calculated and are shown on figure 1. In fact, these are typical curves of the percolation transition [7, 8]. In addition, these dependencies are qualitatively consistent with experimental results in [9] for particular type of biochar.

| \(\varepsilon'\) | \(\sigma, \frac{Sm}{m}\) | \(\mu'\) | \(\mu''\) | Weight fraction | Model volume fraction |
|-----------------|--------------------------|--------|--------|-----------------|----------------------|
| ZnFe\(_2\)O\(_4\) | 3.7 | 0.17 | 1.25 | 0.55 | 1 – 20% | 10% |
| ZnO | 5.822 | \(2 \times 10^{-5}\) | 1 | 1 | 1 – 20% | 10% |
| Fe\(_3\)O\(_4\) | 57.355 | 1.2 | 0.2 | 0.2 | 10 – 23% | 15% |
| Fe\(_2\)O\(_3\) | 14.922 | \(1 \times 10^{-5}\) | 1 | 1 | 10 – 23% | 15% |
| SiO\(_2\) | 6 | \(1.125 \times 10^{-9}\) | 1 | 1 | 6 – 34% | 10% |
| CaMgSiO\(_4\) | 8.5 | \(7.7 \times 10^{-11}\) | 1 | 1 | 22 – 60% | 30% |

3. Electromagnetic fields and temperature distribution

It is possible to prepare pellets with radial distribution of EAF dust volume fraction so that permittivity and permeability within pellet can depend on radia. This approach may allow to achieve better impedance matching and optimal microwave heating of pellet under investigation. Electromagnetic field and temperature distribution as well as temperature curves were simulated by finite element method and are demonstrated on figures 2 and 3.

The following model parameters have been considered: electromagnetic wave frequency - 2.45 GHz, microwave power - 450 W, heat capacity of EAF dust - 1050 J/(kg*K), thermal conductivity of EAF dust - 0.3 W/m/K*(T/300K). Maxwell equations and heat equation were simulated by finite element method for the law of conservation of energy in a differential form when the heat source depends on time and taking into account thermal conductivity and convection. Electromagnetic heat sources were taken as following:

\[
Q = \frac{\omega}{8\pi}(\varepsilon''_{eff}|E|^2 + \mu''_{eff}|H|^2)
\]

\(Q\) -- electromagnetic heat source
Figure 1. Real and imaginary part of permittivity and permeability of EAF dust - biochar powders mixture on volume fraction of EAF dust $v_{eaf}$ and conductivity of biochar $\sigma_{biochar}$.

Figure 2. Permittivity and permeability linearly increases from 1 to 10 on radius. a - spacial distribution of imaginary and real parts inside pellet; b - electric field distribution in rectangular waveguide (mode H10); c - time dependence of maximum temperature inside pellet with radially heterogeneous distribution of EAF dust; d, e, f - spacial distribution of temperature inside pellet.
4. Conclusion
On the figure 2 we can see that if EAF dust is concentrated in the core of pellet than it is possible to achieve higher temperature. However the temperature distribution is less uniform and pellet better heats in the shell layer. On the figure 3 the EAF dust is concentrated in the shell of pellet and temperature distribution more uniform. However, maximum temperature is less than on figure 2.

Thus, spatial distribution of EAF dust inside pellet drastically affects on process of microwave heating of pellet. Adjusting pelleting process so as to achieve heterogeneous distribution of EAF dust on radius of pellet decreasing from core to shell will lead to more optimal microwave heating and reduction of EAF dust.

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