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Physical Simulation of Magnetite Particle Motion in the Molten Steelmaking Slag

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The experimental technique is developed to study the motion of nonconducting particles in the conducting liquid in crossed electrical and magnetic fields and applied to simulate a process of magnetite particle separation, formed during oxidizing of steelmaking slags. The calculated velocity of magnetite particles under action of the electromagnetic buoyancy force in molten steelmaking slags is 0.1-0.5 mm/min.

Keywords: STEELMAKING SLAG, MAGNETITE, SELECTIVE RECOVERY, ELECTROMAGNETIC BUOYANCY FORCE

Introduction

The new selective salvage method of steelmaking slag components, based on increase of iron valency in oxides to magnetite state by oxidative treatment, is being developed at National Metallurgical Academy of Ukraine and Royal Institute of Technology (Stockholm, Sweden) [1]. The known method of metal extraction from cooled steelmaking slags by crushing with the subsequent magnetic separation is not effective in case when the magnetic particles are presented by disperse oxide phase inside silicate matrix, that is why searching for magnetite recovery methods, including from molten slag, is of current interest.

The task of present research is to investigate the possibilities of magnetite particle recovery from molten slag by crossed electrical and magnetic fields action on the melt.

The magnetite produced by additional oxidation method is in slag in the form of crystals sized from 10 to 100 microns [1]. Such size particles at slag viscosity 0.3-0.4 Pa·s [2] are suspended in slag. The metallurgical slags with specific conductivity 100-120 Ohm/m [2] are possible to represent as electrolyte with ionic conductivity. As investigation of real molten slag is an extremely complicated experimental problem, in this work we used a cold model. Considering that at molten slag temperatures (1450-1500 °C and above) magnetite loses magnetic properties, we used non-magnetic particles at simulation.

It is known [3] that motion of rigid body freely suspended in the electrically conducting liquid can be controlled by applied electric and magnetic fields by means of electric-magnetic-foretic mechanism. This possibility to run a direction and velocity is widely applied in various areas of engineering. It is possible to remove micron particles with high efficiency by electromagnetic separation method [4]. The application of this method in bio-engineering is considered in work [5].

Electromagnetic buoyancy force (EBF) for solid in the form of sphere has been counted for the first time in works by Leenov and Kolin [6]. EBF (F_B) is acting on the sphere (volume V) submerged in the electrolyte in the crossed electric and magnetic fields. EBF is directed perpendicularly to current density vector (j) and magnetic field induction vector (B)

$$F_B = \frac{3}{4} jBV = \pi jBr^3 \qquad \text{(Eq. 1)}$$

The expression obtained with the application of dimensional theory - particular case of π- theorem [8] for EBF is resulted in works [7, 3] for nonconducting solid of any shape

$$F_B = C_1 jBA^{\alpha}V \qquad \text{(Eq. 2)}$$

where $A = \frac{jB\rho_f (2r)^3}{\eta^2}$ - dimensionless parameter characterizing EBF action on nonconducting particle. The physical sense of dimensionless parameter A is presented in work [9] as an analogue of Reynolds number that characterizes the mode of particle motion. Numerical modeling shows that mode of particle motion is subcritical at $A \le 2{\cdot}10^3$ and postcritical at $2{\cdot}10^3$. Characteristic particle velocity (υ) in case of nonconducting sphere is as follows

$$\mathbf{v} = C_2 U_0 A^p \qquad \text{(Eq. 3)}$$

$$U_0 = \frac{jB(2r)^2}{\eta} \qquad \text{(Eq. 4)}$$

where C_1 = 0.75; a = 0 at $A \le 1{\cdot}10^6$, and $C_2 = \frac{1}{48\sqrt{3}} C_2 = \frac{1}{48\sqrt{3}}$ and p = 0 at $A \le 2{\cdot}10^3$; $C_2 = \frac{1}{4{,}507} C_2 = \frac{1}{4{,}507}$ and p =-0.415 at $A > 2{\cdot}10^3$.

The values of electromagnetic buoyancy force (EBF) acting on electrically conducting and spherical dielectric particles in synthetic slag are experimentally determined in work [3]. It is shown that the force acting on conducting body at small stress on electrodes is comparable to EBF acting on the dielectric body. But at high stress it alternates in signs, which authors explain by start of chemical reaction on the sphere surface under electrolysis effect. Here it is possible to assume that magnetite particles in slag also can appear as nonconducting (at low stress) and as conducting (at high stress) component, which is necessary to consider when modeling magnetite recovery from molten slag.

Numerical modeling

At numerical modeling the authors accepted that:

1) Particle density is close to liquid density, effect of gravitation and Archimedes` forces is negligible;
2) The particle does not conduct electric current;
3) Magnetic permeability of particle and liquid is almost same as in vacuum;
4) Bath sizes are more than particle sizes;
5) The liquid stream is characterized by small magnetic Reynolds number;
6) The magnetic field created at electric current flow in liquid is negligible;
7) The particle shape is sphere or cube;
8) The particle charge is negligible, since the particle is almost not displaced under effect of electric field without magnetic field application.

In case of spherical nonconducting body submerged in electrolyte solution, EBF is computed by formula (1). If sphere resistance force under EBF action is proportional to sphere velocity (υ), fluid dynamic viscosity (η) and sphere radius (r),

$$F_d = \lambda \eta \upsilon r \qquad \text{(Eq. 5)}$$

Having equated medium resistance force (5) to EBF expressed from formulas (3-4) for $A > 1{\cdot}10^6$, we determine the steady velocity of sphere motion

$$\upsilon = \frac{4\pi C_1}{3} \frac{jBr}{\lambda\eta} \qquad \text{(Eq. 6)}$$

Having equated formulas (6) and (3), we find the coefficient $\lambda = \frac{\pi}{4C_2}$, where $C_2 = \frac{1}{48\sqrt{3}}$.

Velocity of sphere motion is:

$$m\frac{d\upsilon}{dt} = F_B - F_d \qquad \text{(Eq. 7)}$$

After force substitution and transformation we obtain

$$\frac{m}{\lambda\eta r}\frac{d\upsilon}{dt} = \frac{jBr^2}{6\eta} - \upsilon \qquad \text{(Eq. 8)}$$

Assume $a_0 = \frac{m}{\lambda\eta r}$, $\upsilon_0 = \frac{jBr^2}{6\eta}$, then

$$a_0\frac{d\upsilon}{dt} + \upsilon = \upsilon_0 \qquad \text{(Eq. 9)}$$

Solving this equation, we obtain steady velocity of the sphere for experimental installation

$$\upsilon = \frac{(\upsilon_0)}{1 - \frac{a_0}{\tau\left(1 - \exp\left(-\frac{\tau}{a_0}\right)\right)}} \qquad \text{(Eq. 10)}$$

where $\langle \upsilon_0 \rangle = \frac{l-2r}{\tau}$ - average sphere velocity, l - the distance per time, τ.

Experimental Research

Physical modeling experiments are carried out using laboratory facilities of National Technical University (KPI). In the experiments we used: NaCl, purity 98 %; nickel electrodes produced from Ni-plate, purity 99.99 %; acrylic plastic bath; plastic balls of different diameter; acrylic plastic cube with edge of 2.1 mm.

We put two nickel electrodes into acrylic plastic bath, each electrode occupied the whole lateral face of the bath. The bath is filled with water solution NaCl prepared in advance. Solution density is selected equal to density of sphere (cube) to ensure suspension of particles in the liquid.

The experimental plant is illustrated in **Figure 1**. The bath with a sphere (cube) is placed in the front gap of electromagnet ЭМ3 (РЭ/306) creating a homogeneous constant magnetic field in the air-gap (55x55 mm) between vertical flat tips (each diameter 190 mm), then electric current is passed through solution. Average sphere velocity through the bath under EBF action is defined on the basis of videorecording data and counted by formula (10).

Viscosity of electrolyte is measured by means of capillary glass viscosity gauge of ВПЖ-2 type according to GOST 10028-62. Its operating principle is based on measuring time of certain liquid volume flow through a round capillary of set cross-section. Thus kinematic viscosity of liquid is directly proportional to flow time

$$\mu = 0{,}03221 \cdot t \cdot g \,/\, 980{,}7 \qquad \text{(Eq. 11)}$$

where t - flow time of liquid, s; g - gravitational acceleration in measure point (981.54 cm/s^2).

Knowing liquid density, $\rho_f\,\rho_f$, g/m^3, dynamic viscosity is computed by formula

$$\eta = \mu\rho_f \qquad \text{(Eq. 12)}$$

$$\mu = 0{,}03221 \cdot t \cdot g \,/\, 980{,}7 \qquad \text{(Eq. 11)}$$

Results and Discussion

During the research we carried out approximately 200 experiments - five experiments for each value on diagrams. Results of experiments are summarized in **Table 1**.

To consider the effect of electromagnetic field and liquid churning round particle, we introduce dimensionless correction index k that characterizes particle motion under EBF action. Factor k is defined experimentally, we compare it to theoretical value C_2 obtained in work [9] and express by the following formula

$$k = \frac{P_1 \eta}{B r^2} = 4C_2 \qquad \text{(Eq. 13)}$$

where P_1 - tangent of tilt angle of dependence $\upsilon_0(j)$, defined by least square method. The error of dimensionless parameter k is defined by formula 14

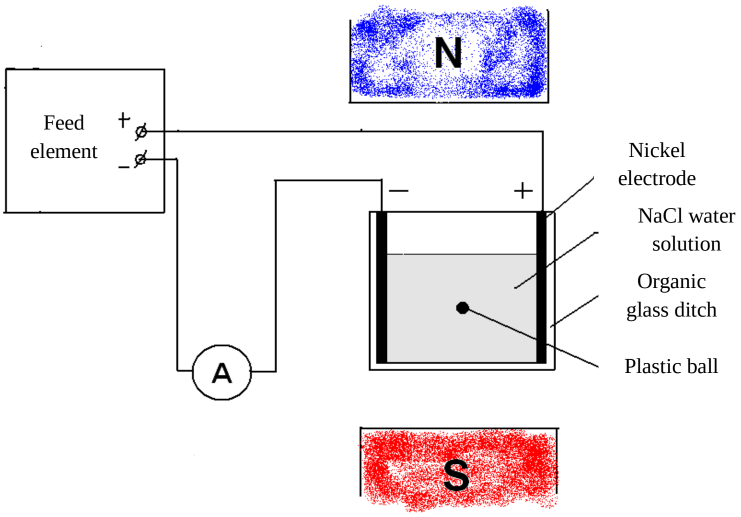

Figure 1. Experimental plant

$$\sigma_k = k\sqrt{\left(\frac{\sigma_{P_1}}{P_1}\right)^2 + \left(\frac{\sigma_\eta}{\eta}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 + \left(\frac{2\sigma_r}{r}\right)^2}$$

(Eq. 14)

When studying effect of current density on particle velocity (experimental mode No. 1 in **Table 1**, **Figure 2a**) we obtained the following values - k = 0.043 and C_2^e = 0.0108±0.0004. Deviation of this value C_2^e from theoretical values defined in [9] C_2^t = 0.0120 is $\frac{C_2^e - C_2^t}{C_2^t}100\% = 11\%$ $\frac{C_2^e - C_2^t}{C_2^t}100\% = 11\%$.

Values k and C_2 are counted in a similar way for experimental modes No. 2 and No. 3 (**Table 1**), that characterize the effect of magnetic intensity and particle radius on spherical particle velocity.

Till now, cube motion in the electrolyte under EBF action has not been studied. Other factors being equal, effect of electric current density on dielectric particle velocity is featured by tilt angle tangent P_1 of dependence $\upsilon_0(j)$. By results of experiments (mode No. 4 in **Table 1**) tilt angle tangent in **Figure 2b** is $P_1 = (3{,}09 \pm 0{,}09)\cdot 10^{-5}$.

Calculation of cristalline magnetite particle velocity under EBF action in the real slag system

There is a set of chemical, electrochemical, magnite-hydrodynamic reactions in molten metallurgical slag under effect of crossed electric and magnetic fields. According to ionic slag theory, both ionic and covalent bonds are possible in the steel-making unit in molten slags between slag components. Thus, metallurgical slag can be presented as an electrolyte with ionic conductivity.

Having accepted typical parameters of slag system (density 3000 kg/m^3, specific conductivity110 Ohm/m, dynamic viscosity of slag 0.3 kg/m·s) and radius of magnetite particle 0.05 mm, and electrode distance 0.1 m we count magnetite velocity provided that magnetite does not conduct electric current. Magnetite velocity is presented by equation (3).

For given slag system, particle motion will take place in the subcritical mode, as dimensionless factor is $A \leq 2\cdot 10^3$. Dependences of calculated magnetite velocity in the real slag system under EBF action are shown in **Figure 3**.

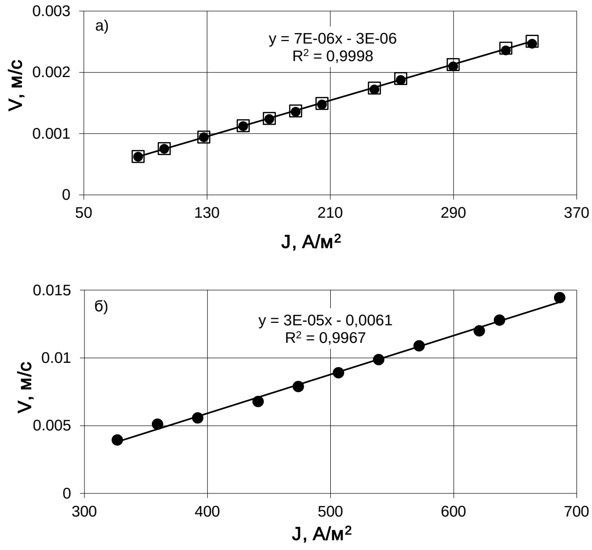

Figure 2. Dependence of dielectric particle velocity on current density: *a* - sphere; *b* - cube

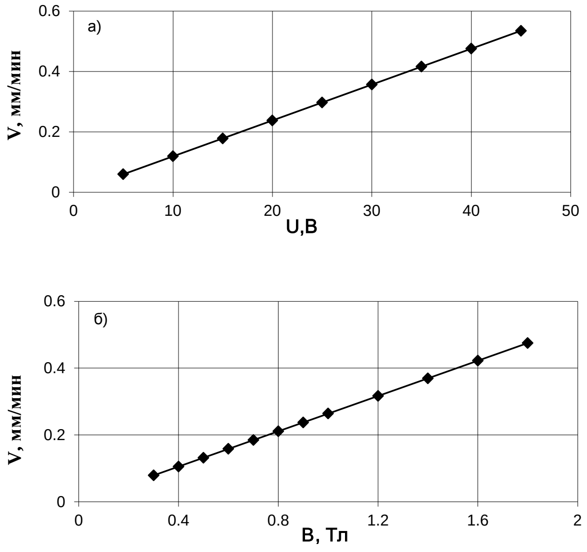

Figure 3. Dependence of magnetite particle velocity in slag system on: *a* - potential difference on electrodes at magnetic intensity 1.8 T; *b* - magnetic intensity at potential difference on electrodes 40 V

Conclusions

Cold simulation method shows the possibility of cristalline magnetite particle recovery from molten steelmaking slags under action of electromagnetic buoyancy force in the crossed electric and magnetic fields. Obtained dependences enable to predict particle behavior in the real slag system with various values of magnetic intensity, potential difference on electrodes and particle sizes. It is shown by calculation that magnetite particle velocity in the molten steelmaking slag is 0.1-0.5 mm/min, and the motion takes place in subcritical mode.

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Физическое моделирование движения частиц магнетита в расплавленных металлургических шлаках

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Разработана методика экспериментального исследования закономерностей движения непроводящих частиц в электропроводящей жидкости под действием выталкивающей электромагнитной силы в скрещенных электрическом и магнитном полях. Выполнено моделирование процесса магнитной сепарации кристаллических частиц магнетита, образующихся при окислительной обработке сталеплавильных шлаков. Показано, что скорость перемещения частиц магнетита под действием выталкивающей электромагнитной силы в расплавленном сталеплавильном шлаке составляет 0,1-0,5 мм/мин.