Criterial dependencies of the movement of the melt refractory material in the bath of an ore thermal furnace under electromagnetic influence

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Abstract. In this work, for the first time, criterion dependencies of the speed of movement of the melt in the bath of an ore-thermal furnace during electric arc melting of oxide refractory materials under external electromagnetic influence were obtained. The initial quantitative characteristics for generalization in the form of the dependence of the speed in the zone of intense movement of the melt on the currents in the electrodes and the electromagnetic device were taken on the electrolyte and mercury physical models of an ore-smelting furnace with an electromagnetic device. Physical modeling was carried out while maintaining the invariance of the derived similarity criteria: the electrovortex flow parameter π_μ and the external magnetic field parameter π_l. In order to extend the experimental results obtained to a whole group of similar phenomena, the dependences of the dimensionless speed of melt movement (Reynolds criterion) on the dimensionless parameters of the external magnetic field and electric vortex flow were obtained and constructed. Since for all similar processes the similarity criteria retain the same values, then the criterion dependencies for them will be the same, and the results obtained can be extended to all similar cases.

Keywords: ore-thermal furnace, electromagnetic device, refractory material, oxide melt, model liquid, movement speed, electrode current, electromagnetic device current, criterion dependence.

1. Introduction

During the process of electric arc melting of materials under external electromagnetic influence, a complex structural movement of the melt occurs in the bath of an ore-thermal furnace. As a result, the melting process is intensified, energy consumption is reduced, and the chemical and temperature homogeneity of the melt increases, which helps improve the quality of the final product. In this case, the effectiveness of the electromagnetic effect depends on both the structure and the speed of the resulting movement of the melt in the bath of the electric arc furnace [1-3].

The implementation of experimental work related to the study of heat and mass transfer phenomena in the bath of an ore-thermal furnace is complicated by the emerging powerful electromagnetic fields and high temperatures of more than 2000 °C. A serious reason limiting research on existing industrial units is the creation of interference with the production process, loss of production time and safety requirements. Due to the complexity of direct research and the lack of sufficiently reliable and reliable theoretical methods of study, when analyzing such complex phenomena it is convenient to use the method of physical modeling. Physical modeling is widely used to study magnetohydrodynamic processes occurring during melting of various materials in electric arc furnaces [4-10].

The experimental dependences of the speeds of movement of model liquids on the current of the electromagnetic device and the current strength in the liquid obtained using physical models are of limited value, since they are applicable only to this particular case. To extend the experimental results obtained to a whole group of similar phenomena, it is necessary to generalize them by presenting the dependencies between individual quantities in the form of a connection

between similarity criteria, i.e. in the form of criterion dependencies characterizing these processes. Since for all similar processes or phenomena the similarity criteria retain the same meaning, then the criterion dependencies for them will be the same, and can be extended to all similar phenomena [11-14].

Thus, it is necessary to study the dependence of the movement of the melt on the parameters of the ore-thermal furnace and the external electromagnetic field using the method of physical modeling with generalization of the research results to a whole group of similar phenomena, which is the goal of this work.

2. Research methods

The research consisted of two stages:

Stage 1. The study of the dependence of the speed of movement of the melt of oxide refractory material during their electric arc melting with electromagnetic influence was carried out by the method of physical modeling on electrolyte and mercury physical models of an ore-smelting furnace with an electromagnetic device.

Stage 2. As a result of processing data on the speed of movement of model liquids at various currents in the electrodes and in the electromagnetic device, the dependences of the dimensionless speed of liquid movement (Reynolds criterion) on the dimensionless external magnetic field and the dimensionless electric current force were obtained as universal quantitative characteristics.

Experimental studies were carried out on a physical model of an OKB-2126A ore-thermal furnace with an electromagnetic device specially developed for these purposes (Fig. 1), the parameters of which are given in Table 1 [3], [15].

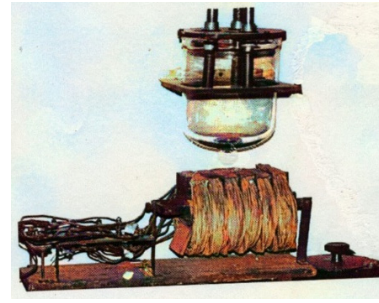


Fig. 1. Physical model of ore-thermal furnace OKB-2126A with electromagnetic device

Table 1. Parameters of the ore-thermal furnace of type OKB-2126A and its physical model

Parameter	Ore-thermal furnace OKB-2126A		Electromagnetic device	
	Original	Physical model		
1. Bath diameter	1,8	0,18	Parameter	Value
2. Bath depth, m	0,4	0,04		
3. Electrode decay diameter, m	0,8	0,08	Length x width, m	0,22 x 0,095
4. Electrode diameter, m	0,25	0,025	2. Phase voltage, V	220
5. Rated linear voltage, V	123-244	0-380	3. Phase current, A	20
6. Rated current, A	4300	250 (10*)	4. Total power, kA	13,27
7. Total power, kVA	1800	160 (5*)		
* – for electrolyte physical model				

Similarity criteria for physical modeling of processes occurring during electric arc smelting in an ore-thermal furnace of oxide refractory materials with electromagnetic mixing were derived by analyzing of equations the magnetic hydrodynamics that describe the processes.

The resulting four defining criteria π_μ, π_σ, π_ω, π_l have the form:

$$\pi_\mu = \frac{\mu_0 I^2}{\rho^{-1}\eta^2}, \quad \pi_\sigma = \frac{\sigma\eta^3}{I\rho^2}, \quad \pi_\omega = \frac{\omega\eta^3}{B^2 I^2 \rho}, \quad \pi_l = \frac{BIl}{\rho^{-1}\eta^2}. \tag{1}$$

When modeling turbulent motion, viscous forces and, together with them, complexes π_σ, π_ω are insignificant and can be neglected. Thus, there remain two similarity criteria, the invariance of which must be observed:

– parameter of electric vortex flow – $\pi_\mu = \mu_0 I^2/\rho^{-1}\eta^2$ = idem;

– external magnetic field parameter – $\pi_l = BIl/\rho^{-1}\eta^2$ = idem, where B – is magnetic induction; I – current strength in the melt; μ_0 – magnetic constant;

– ρ melt density; η – dynamic viscosity; ℓ – characteristic linear size.

Based on the obtained similarity criteria and based on convenience, an electrolyte in the form of a 25 % NaCl solution and mercury were used as model liquids, a physical model was selected on a scale of 1:10 for the OKB-2126 A ore thermal furnace and in relation to forsterite-chromite and corundum materials.

The study of the flows and structure of fluid movement was carried out using video and photography at various currents in the electrodes and an electromagnetic device. Due to the boiling of the 25 % NaCl solution, the current value in the bath was limited to $I = 10$ A. Moreover, in the considered range $I =$ 1-10 A, the values of the defining criteria are π_μ = 6,2×10^2-6,2×10^3, π_l = 1,4×10^6-5,9×10^7. On the mercury physical model, the currents in the electrodes varied in a wide range $I =$ 50-500 A. In this case, the considered range of defining similarity criteria was π_μ = 1,8×10^7-1,8×10^9 and π_l = 3,4×10^8-3,4×10^9. The upper limit of currents is limited by the fact that when the currents in the electrodes increase more than $I =$ 500 A, i.e. When the criterion value of electric vortex flow is $\pi_\mu \geq$ 2×10^9, electric vortex flows excited as a result of the interaction of currents in the bath with their own magnetic fields become significant.

3. Research results

The motion structures on the surface of a bath of 25 % NaCl and mercury solution that arise when the electrodes and electromagnetic device are turned on are shown in Fig. 2.

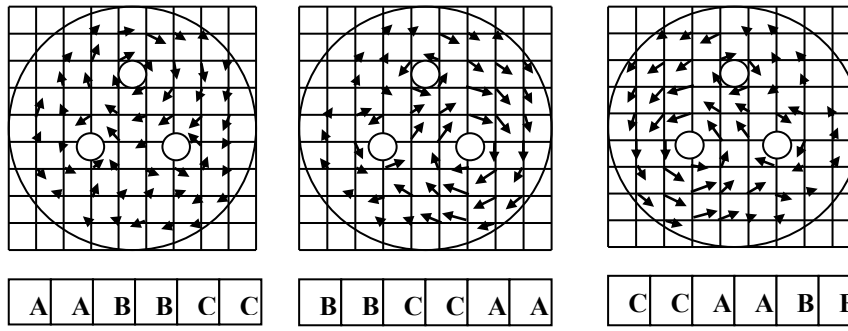
The dependences of the speed in the zone of intense movement of model liquids at different values of currents in the electrodes and electromagnetic device are given in Table 2.

Table 2. Speed of movement of the electrolyte NaCl (in the numerator) and mercury (in the denominator) at various currents in the electrodes and electromagnetic device

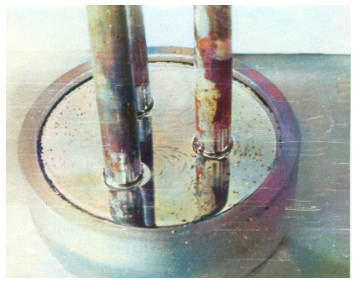
Electromagnetic device current, A	Current in electrodes, A			
	1/100	3/200	5/300	7/500
5/3	1.1/1.2	1.5/2.0	2.5/3.0	3.4/4.0
10/5	1.3/1.5	2.1/3.1	3.2/4.4	4.2/6.0
15/7	1.7/2.2	2.9/4.2	4.2/6.0	5.3/8.0
20/8	2.4/2.5	4.0.4.6	5.7/6.7	6.7/9.1

As can be seen from Table 2, when the current of the electromagnetic device increases from 5 to 20 A and the currents in the electrodes from 1 to 7 A, the speed of movement of the electrolyte increases from 1.1·10^{-3} to 6.7·10^{-3} m/s. The speed of movement of mercury in the zone of intense mixing with currents of the electromagnetic device $I =$ 3-8 A and electrodes $I =$ 100-500 A varies within the range of 1.2×10^{-2}-9.1×10^{-2} m/s.

As a result of processing data on the speed of movement of model liquids at various currents in the electrodes and in the electromagnetic device, the dependences of the dimensionless speed of liquid movement (Reynolds criterion) on the dimensionless external magnetic field and the dimensionless electric current strength, presented in Fig. 3, were obtained as universal quantitative characteristics.



a)



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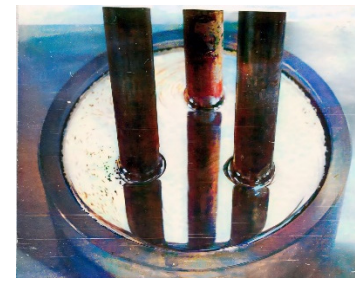
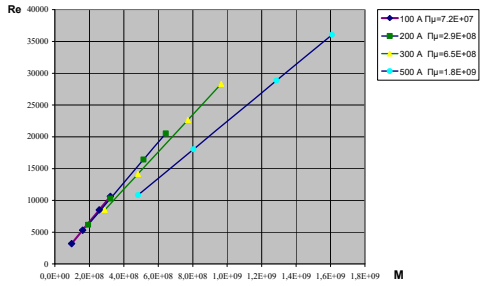
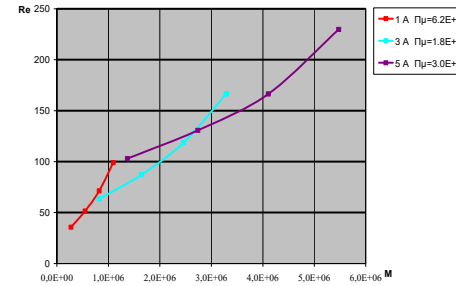


c)

Fig. 2. a) Movement patterns on the bath surface of 25 % NaCl and b), c) mercury solution, occurring when the electrodes and electromagnetic device



a)



b)

Fig. 3. Dependencies of Reynolds motion criteria 25 % solution of NaCl a) and mercury b) from external criteria magnetic field and electric vortex flow

With an increase in the criteria of the external magnetic field and electric vortex flow in the $\pi_\mu = 6.2\times10^2\text{-}6.2\times10^3$, $\pi_l = 1.4\times10^6\text{-}5.9\times10^7$, the dimensionless speed of movement (Reynolds number) of a 25 % NaCl solution increases from 36 up to 230, and mercury in the range $\pi_\mu = 1.8\times10^7\text{-}1.8\times10^9$ and $\pi_l = 3.4\times10^8\text{-}3.4\times10^9$ from 3190 to 36100. Thus, in studies on the electrolyte physical model, the Stokes regime takes place electromagnetic mixing, and on the mercury physical model – a developed turbulent regime.

Comparison of traces of movement on the free surface of the mercury bath with the structure of movement of the electrolyte NaCl, as well as the melt on the operating plants shows their identity and confirms the reliability and validity of the obtained results of physical modeling.

Since generalized dependencies are purely experimental, they are applicable only within the limits of changes in the argument confirmed by experiments, extrapolation of them both towards large and smaller values of the argument requires additional research.

4. Conclusions

As a result of processing data on the speed of movement of model liquids at various currents in the electrodes and in an electromagnetic device, the dependences of the dimensionless speed of liquid movement (Reynolds criterion) on the dimensionless external magnetic field $\pi_B$and the dimensionless electric current force π_I were obtained for the first time as universal quantitative characteristics.

With an increase in the criteria of the external magnetic field and electric vortex flow in the range $\pi_\mu = 6.2\times10^2\text{-}6.2\times10^3$, $\pi_l = 1.4\times10^6\text{-}5.9\times10^7$, the dimensionless speed of movement (Reynols number) of a 25 % NaCl solution increases from 36 up to 230, and mercury in the range $\pi_\mu = 1.8\times10^7\text{-}1.8\times10^9$ and $\pi_l = 3.4\times10^8\text{-}3.4\times10^9$ from 3190 to 36100. Thus, the electrolyte physical model allows us to simulate the Stokes mode of electromagnetic mixing, and the regime studied on the mercury physical model is a developed turbulent one.

Since the generalized dependencies are purely experimental, they are applicable only within the limits of changes in the argument, confirmed by experiments, extrapolating them both towards larger and smaller values of the argument for additional research.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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