R. PRZYŁUCKI, S. GOLAK, B. OLEKSIAK, L. BLACHA

ISSN 0543-5846
METABK 51(1) 67-70 (2012)
USD 669:669.3:66.067=111

INFLUENCE OF AN INDUCTION FURNACE'S ELECTRIC PARAMETERS ON MASS TRANSFER VELOCITY IN THE LIQUID PHASE

Received – Prispjelo: 2011-01-12
Accepted – Prihvaćeno: 2011-03-30
Preliminary Note – Prethodno priopćenje

This article is an analysis of the results obtained under the tests aimed at determination of the influence exerted by the current frequency of an induction furnace on the mass transfer coefficient for liquid metallic phase.

Key words: metallurgy, cooper, refining, alloy, induction melting, mass transfer.

Utjecaj parametara indukcijske elektro peći na brzinu masenog prijenosa u tekućoj fazi. U radu su analizirani rezultati dobiveni testiranjem provedenim s ciljem utvrditi utjecaj frekvencije industrijske peći na maseni koeficijent prijenosa u tekućoj metalnoj fazi.

Ključne riječi: metalurgija, bakar, rafinacija, slitina, indukcijsko taljenje, prijenos mase

INTRODUCTION

Comprehensive analysis of the chemical phenomena taking place in the liquid metal/gaseous phase systems typical for metallurgy requires knowledge of the mass transfer phenomena occurring in both the said phases. This results from the fact that in heterogeneous systems, the components of the individual phases react with one another only after penetrating the interface. The parameter characterising the mass transfer velocity in the given phase is the so-called mass transfer coefficient. Knowing its value with reference to both phases as well as knowing the constant velocity of the reaction taking place in the interfacial area enables calculation of the general mass transfer coefficient values characteristic for the given process but also identification of the stages determining the coefficient. This paper is an analysis of the results obtained under the tests aimed at determination of the impact exerted by the selected electric and geometric parameters of the furnace on the mass transfer coefficient for an induction-stirred liquid metallic phase.

MODELS OF MASS TRANSFER IN LIQUID PHASE

The first hydrodynamic model applied to describe the phenomenon of mass transfer in a liquid phase was the model of boundary film developed by Nernst [1]. The model was based on the assumption that concentrations of all components in the core of the phase are balanced by way of convection, and that only near the interfacial area, there is a motionless boundary film through which the transfer in question can take place by diffusion exclusively. According to this model, the mass transfer coefficient is described by the following dependence:

$$\beta_l = \frac{D_{AB}}{\delta_x} \tag{1}$$

The thickness of the boundary film marked as δ_x depends on the hydrodynamic conditions in the system, and it is a quantity particularly difficult to determine.

Among the models much more frequently used to describe the mass transfer in the liquid phase than the boundary film model one should mention the penetration models [2, 3]. The first of them (the so-called Higbie model) was based on the assumption that the liquid surface is composed of multiple elements, each being in contact with the gaseous phase for a specific period of time, passing deeper into the liquid afterwards. This means that the turbulent swirls occurring deeper in the liquid are not suppressed near the interfacial area and so they approach it causing its continuous restoration. In such a model, the time all elements of the liquid spend near the surface is identical and the dependence describing the mass transfer coefficient assumes the following form:

$$\beta_l = \left(\frac{D_{AB}}{\pi \cdot \tau}\right)^{0,5} \tag{2}$$

The second penetration model was proposed by Danckwerts who managed to modify Higbie's assump-

R. Przyłucki, S. Golak - Silesian Technical University Department of Management and Informatics, Katowice, Poland
B. Oleksiak, L. Blacha - Silesian Technical University Department of Metalurgy, Katowice, Poland

tion that time τ is not constant and random. According to Danckwerts, however, the constant quantity is the relation between the area restored in a unit of time and the liquid's overall area. In this model, the mass transfer coefficient is described by the following dependence [3]:

$$\beta_l = (D_{AB} \cdot s)^{0,5} \tag{3}$$

The penetration models use quantities that are difficult to determine. They include both time τ and proportionality factor s. Therefore, using these models to describe the mass transfer in a liquid metallic phase in hydrodynamic systems, usually occurring in metallurgical aggregates, is limited in scope. One of the exceptions to this principle is the liquid metal barbotage with gases. Therefore, for instance, Higbie's model can be efficiently applied in describing mass transfer in liquid metal for refining aluminium with gases [4] or evaporation of volatile components from a liquid alloy blown with gas [5, 6].

Among the solutions more and more commonly applied for the sake of describing mass transport, one must mention empirical correlations developed in accordance with the principles of the similarity theory [7].

Based on the penetration models, Machlin [7] succeeded in preparing a mass transfer model for an induction-stirred liquid metallic phase. Under this model, commonly referred to as a "streamline flow model", it was assumed that the liquid elements move as a rigid solid body along the contact surface between the bath and the gas, or between the bath and the melting pot, and the velocity gradient normal towards the surface is close to zero. In accordance with Machlin's theory, the mass transfer coefficient is described by the following dependence:

$$\beta_l = \left(\frac{8 D_{AB} \cdot v_m}{\pi \cdot r_m} \right)^{0,5} \tag{4}$$

Machlin's model was frequently used in kinetic analyses of the evaporation process for volatile contaminants of iron as well as lead [8-10].

Assuming that one applies dependence (4) to calculate the value of coefficient β_l, a particularly important aspect would be the correct determination of the metal's velocity near the surface. According to Machlin, this value depends to a slight extend on the electric parameters of the furnace as well as on its dimensions. However, it has occurred that the nature of the metal motion in an induction furnace as well as its circulation and intensity are the functions of numerous variables, such as the furnace geometry, density of the power emitted or frequency of the current [11-13].

In order to determine the value of velocity v_m, one can apply a numerical method based on the so-called electromagnetic flow model [14, 15]. The model comprises the following two subsequent elements:

- analysis of the electromagnetic field generated in the liquid metal,
- analysis of the velocity field occurring in the liquid metal.

Let us then elaborate on the last method, by applying it to determine the velocity of a liquid, inductively stirred Cu-Pb alloy.

The basic furnace operating parameters as well as the physical and chemical quantities characterising the liquid metal, that were used in the respective calculations, have been summarised in Table 1 below.

The electromagnetic field calculations were conducted in two dimensions, by applying a commercially available numerical programme, Flux. The programme was supplemented with certain procedures enabling determination of the mean value for the period of the forces volumetric density. Figure 1 is the analytical model diagram. The respective computational areas as well as the model boundaries have been marked as well.

Table 1 **Furnace operating parameters and selected properties of the Cu-Pb alloy**

Furnace operating parameters		Liquid metal properties (Cu alloy + 2 % wt. of Pb)	
Frequency	3 kHz	Temperature	1 473 K
Power	20 kW	Metal density	7,9 Mg·m^{-3}
Melting pot internal diameter	0,1 m	Metal viscosity	0,0015 Pa·s
Inductor current intensity	155 A	Specific conductance	1,25·10^{-6} H·m
		Electric conductivity	4·10^{6} S·m^{-1}

In the individual computational areas, the following differential equations of magnetic potential were solved for sinusoidal input functions:

$$\Omega_1: \quad \nabla \times \left(\frac{1}{\mu} \nabla \times \mathrm{A} \right) = 0 \tag{5}$$

$$\Omega_2: \quad \nabla \times \left(\frac{1}{\mu} \nabla \times \mathrm{A} \right) + \mathrm{j}\omega\sigma \, \mathrm{A} = \mathrm{J}_{\dot{z}} \tag{6}$$

$$\Omega_3: \quad \nabla \times \left(\frac{1}{\mu} \nabla \times \mathrm{A} \right) + \mathrm{j}\omega\sigma \, \mathrm{A} = 0 \tag{7}$$

where: j – imaginary unit $\left(j = \sqrt{-1} \right)$.

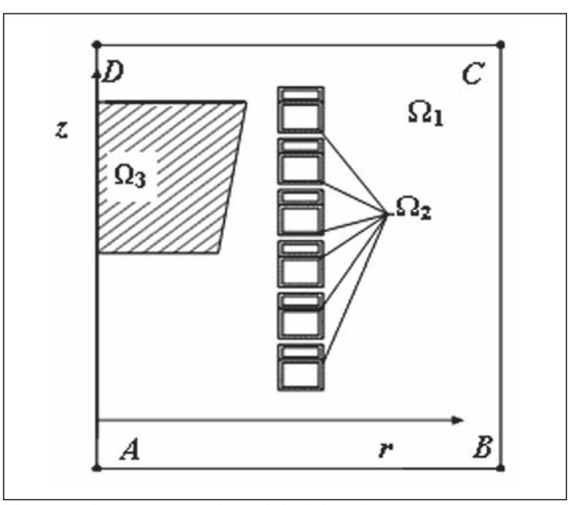

Figure 1 Computational model of the electromagnetic part of calculations: Ω_1 – air; Ω_2 — inductor winding; Ω_3 – charge material (liquid metal)

At the boundaries of the computational area: $\overline{AB}, \overline{BC}, \overline{CD}, \overline{DA}$, the Dirichlet boundary condition of A=0 was assumed.

The components of the volumetric density of electromagnetic forces (mean values for the whole period) were calculated according to the vector potential based on formulas 8 and 9.

$$f_r = \frac{1}{2}\{\mathrm{Re}(\underline{J})\mathrm{Re}(\underline{B_z}) + \mathrm{Im}(\underline{J})(\underline{B_z})\} \quad (8)$$

$$f_z = -\frac{1}{2}\{\mathrm{Re}(\underline{J})\mathrm{Re}(\underline{B_r}) + \mathrm{Im}(\underline{J})(\underline{B_r})\} \quad (9)$$

where:
$J = j\omega\sigma A$,
$B = \nabla \times A$,
Re, Im – real and imaginary part of the complex vectors' components,
$\underline{B_r}$, $\underline{B_z}$ – components of the magnetic induction vector.

Components of the forces were determined in area Ω_3 for a uniform, rectangular mesh of 181 x 199 nodes (in line with axes *r* and *z* respectively).

The areas of flows were calculated numerically using the Fluent 6,2 software. The model entailed axial symmetry of the system.

Specific boundary conditions were introduced into the model in the form of two walls (the melting pot's bottom and generator) without any skid (i.e. with a zero velocity by the wall), an axis of symmetry and a free surface of the metal simulated by a wall free of friction with the liquid.

The impact of the electromagnetic field forces was introduced into the model by setting user defined functions. The functions used the field of force previously established by means of the Flux2D programme. Since the structure of the force field mesh developed using Flux2D differed from the mesh of the flow model, it was necessary to interpolate the results. However, as the meshes only differed in the radial direction and the input mesh of forces was more dense than the mesh of flows, the interpolation error could be considered negligibly small.

In order to calculate the velocity and turbulence, a second order discretisation was applied [16]. The pressure was determined based on the standard method proposed by Rhie and Chow [17]. The analysed method of calculating the velocity of induction-stirred liquid metal was also applied to liquid Fe-Cu alloys [18].

INFLUENCE OF THE CURRENT FREQUENCY ON THE METAL VELOCITY

Further analysis of the influence exerted by the furnace's electric parameters on the velocity of mass transfer involved determination of how the metal velocity near the surface as well as the mean velocity depend on the value of the current frequency. The exemplary fields of velocity have been depicted in Figures 2-3.

The simulation performed implied that for the current frequency up to 3 kHz, as the frequency increases

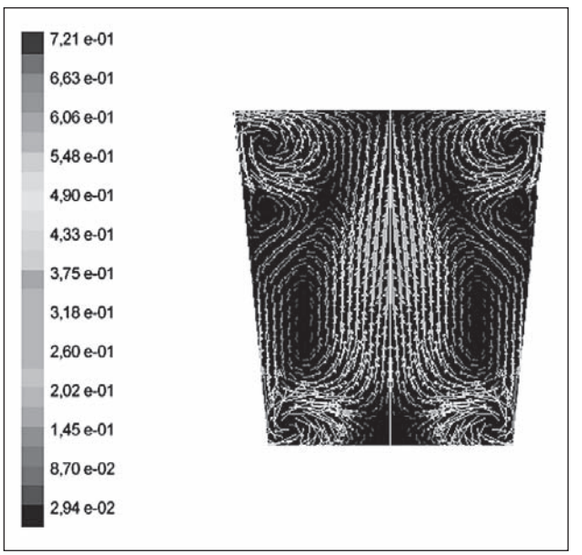

Figure 2 Velocity field obtained for the frequency of 1 Hz

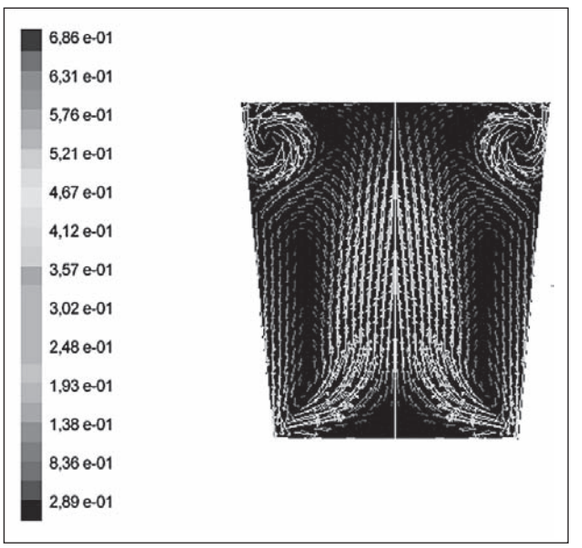

Figure 3 Velocity field obtained for the frequency of 5 Hz

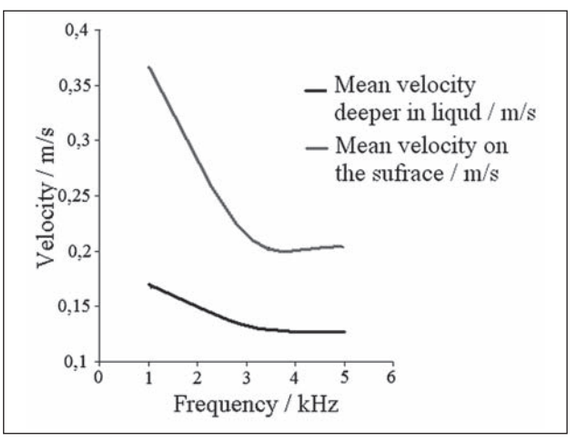

Figure 4 Influence of the current frequency on the liquid metal velocity

also the value of the velocity near the surface increases considerably. Further increase of the frequency value causes virtually no changes in the velocity - Figure 4.

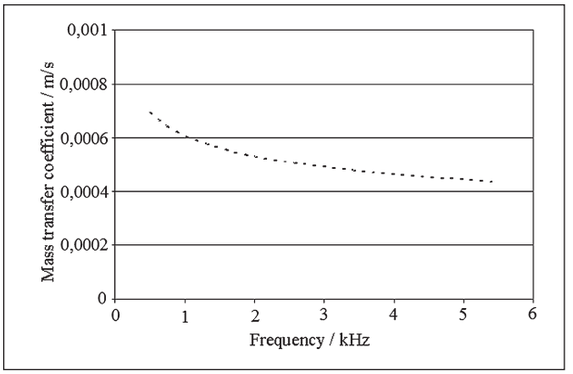

Figure 5 Influence of the current frequency on the mass transfer coefficient for the liquid metal phase (Cu-Pb alloy, 1 473 K)

The values obtained for the velocity near the surface were then used to determine the value of the mass transfer coefficient for the liquid phase by application of Machlin's dependence (6). The values obtained varied from $6.15 \cdot 10^{-4}$ m·s^{-1} for 1 Hz to $4{,}57 \cdot 10^{-4}$ m·s^{-1} for 5 kHz (Figure 5).

CONCLUSIONS

The tests conducted implied a considerable impact of the current frequency on the mass transfer coefficient for the induction-stirred liquid metallic phase. This is caused by the change of the stirring intensity along with the said parameter and thus the stirring velocity as well. Using a numerical method based on the so-called electromagnetic flow field enabled determination of the metal velocity near the surface and the mean velocity deeper in the metal. For the current frequency change from 1 kHz to 5 kHz, a decrease in both velocity values was observed, this, however, being more noticeable for the velocity near the surface.

REFERENCES

[1] D. R. Poirier, G. H. Geiger: Transport Phenomena in Materials Processing, TMS, Warrendale (1994).
[2] R. Higbie: Trans AICHE 31 (1935), 365 - 368.
[3] P. Danckwerts: Trans. Faraday Soc. 46 (1950), 101 - 103.
[4] J. Botor: Prace IMN 1 (1978), 12-16.
[5] B. Oleksiak: Metalurgija 47(2008)2, 87 - 90.
[6] J. Benavidies, I. Gokhan: Metall. Trans.B 32 (2001), 285 - 295.
[7] J. Botor: Podstawy metalurgicznej inżynierii procesowej, Wyd. Pol. Śl.., Gliwice (1999).
[8] R. Ward: Journal Iron and Steel Inst. 201 (1963), 920 - 923.
[9] R. Ohno, T. Ishida: Japan Inst. Met. 31 (1967), 1164 - 1169**.**
[10] J. Łabaj, J. Botor, R. Sosnowski: Archives of Metallurgy 47 (2002), 307 - 320.
[11] J. Szekely, K. Nakanishi: Metall. Trans. B 6 (1975), 245 - 256.
[12] J. Szekely, K. Nakanishi: Metall. Trans. B 6 (1975), 245 - 256.
[13] E. D. Tarapore, J. W. Evans J: Metall. Trans. B 7 (1976), 343 - 351.
[14] S. Golak, R. Przyłucki: A simulation of the coupled problem of magnetohydrodynamics and a free surface for liquid metals, Transactions on Engineering Science, WIT 63 (2009).
[15] S. Golak: Application of image analysis for the measurement of liquid metal surface, Transactions on Modelling and Simulation, WIT 48 (2009).
[16] T. J. Barth, D. Jespersen: The design and application of upwind schemes on unstructured meshes, Technical Report AIAA-89-0366, AIAA 27th Aerospace Sciences Meeting, Reno (1989).
[17] C. M. Rchie, W. L. Chow: Numerical Study of the Turbulent Flow past an Airfoil with Trailing-Edge Separation, AIAA Journal 21 (1983), 1525 - 1153.
[18] J. Łabaj: Kinetyka parowania miedzi z ciekłego żelaza, Wyd. Oldprint, Katowice (2010).

Note: Nowak P. is responsible for English language, Katowice, Poland