Journal of Engineering Physics and Thermophysics, Vol. 78, No. 3, 2005

MATHEMATICAL SIMULATION OF MASS-TRANSFER PROCESSES IN OFF-FURNACE DEGASSING OF METAL BY FLOATING INERT GAS BUBBLES

N. I. Zakharov,[a] **F. V. Nedopekin,**[b]
A. I. Trotsan,[c] **and P. S. Kharlashin**[d]

UDC 532.516.669

A mathematical model of mass-transfer processes in off-furnace degassing of metal in blasting by inert gas bubbles has been developed. The model allows for the effect of both the concentration of molten surfactants and the modes of floating of gas bubbles in the liquid bath on mass transfer and describes a wide class of mass-transfer processes in technologies, which differ in kind and composition of metals. The factor of resources and energy saving is determined.

The problem of removal of gases from metal is one of most urgent in metallurgy. As is known, the use of different methods of off-furnace treatment of melts is most promising for solving this problem. One of these methods is blasting of metal by argon through porous elements of the ladle bottom, which gives the best results in a nucleate flow of inert gas to the melt simultaneously with metal flow from the furnace to the ladle [1–3].

In economically developed countries (Japan, USA, and others), this method of liquid metal degassing has gained wide acceptance [4–6], especially in combination with evacuation. As the refractory industry of the CIS countries develops toward manufacture of reliable porous blocks (in foreign countries this trend is still present [7–9]), application of the considered method of metal degassing can be expected in these countries as well. Here, of practical interest is the use of this method in blasting at atmospheric pressure under the slag layer [10, 11]. Although the efficiency of the latter method is lower compared to the complex method, it is simple to maintain and does not require high material and service expenditures, by virtue of which it can be used in manufacture of some grades of steel. Thus, the development of theoretical principles of mass transfer of the considered processes can be considered urgent.

Cold modeling of mass-transfer processes in off-furnace hydrogen desorption of molten metal by inert-gas blasting through porous elements is, as is known, very problematic due to the difficulty of providing the equality of the similarity criteria under the real conditions and on the cold model. Mathematical simulation, the results of which are in quantitative agreement with the data of hot modeling and in qualitative agreement with the results of cold modeling, may appear to be more preferable.

Mathematical simulation of the processes under consideration allows one to reveal the reserves of the existing refining facilities and to develop energy- and resource-saving regimes of these processes.

The most complete mathematical description of such processes is presented in [12–14], although in [12] it is given in application to bubbles of carbon oxide. In [13], the influence of only the concentration of surfactants of the melt, rather than the regimes of floating of inert gas bubbles, on the coefficients of mass transfer is taken into account.

The suggested mathematical model generalizes the results of [14] to the case of continued blasting of the melt by the inert gas upon completion of discharge of metal from the surface to the ladle and thus allows prediction of degassing processes in the mixed mode of blasting (countercurrent, which changes over to a straight flow).

Let, at the time instant $\tau = 0$, the refining vessel be filled by liquid metal. At $\tau = \tau_0$, the melt is subject to blasting by inert gas. From the time instant $\tau = 0$, the table of the metal is covered by a layer of refining slag, which

---

[a] Donetsk National Technical University (DonNTU), 58 Artem Str., Donetsk, 83000, Ukraine; e-mail: lana@fizmet.dgtu.donetsk.ua; [b] Donetsk National University (DonTU), Donetsk, Ukraine; [c] I. N. Frantsevich Institute of Material Science Problems, National Academy of Sciences of Ukraine, Donetsk (Makeevka), Branch, Ukraine; [d] Priazov'e State Technical University (PSTU), Ukraine. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 3, pp. 68–71, May–June, 2005. Original article submitted November 26, 2003.

prevents the melt from overcooling and prevents entry of the gas from the atmosphere into it. The height of the metal in the refining vessel as a function of time is determined as

$$H_\mathrm{m}(\tau) = \begin{cases} (\dot{m}_\mathrm{m}/(\rho_\mathrm{m} S))\,\tau\,, \ 0 \le \tau \le \tau_\mathrm{d}\,; \\ H_0 = \mathrm{const}\,, \ \tau > \tau_\mathrm{d}\,. \end{cases}$$

The commonly adopted main assumptions used in construction of the mathematical model of mass-transfer processes in off-furnace degassing of liquid metal by floating bubbles of the inert gas are [3]:

(a) due to the mixing effect of gas bubbles the concentration of removed gases is homogeneous over the volume of the metal (except for nonmixed diffusion boundary layers on the gas–metal interfaces);

(b) the metal temperature is constant in space and time;

(c) the thermodynamic equilibrium is reached on gas–metal interfaces;

(d) gas mixing in bubbles is ideal;

(e) there is no gas transfer from the environment to the metal;

(f) the slag layer is permeable for floating bubbles of the inert gas.

The generalized mathematical model of mass-transfer processes in off-furnace degassing of liquid metal by floating bubbles of the inert gas under the slag layer at atmospheric pressure has the form [15]

$$\varepsilon^i = \frac{1}{Q^i_\mathrm{in}} \int_x \int_y \int_z \int_\tau j_i\,(x, y, z, \tau)\; n\,(x, y, z, \tau)\; dx dy dz d\tau\,. \tag{1}$$

The character of relative motion of the melt and gas bubbles is different in various periods of blasting. Thus, when $\tau > \tau_\mathrm{d}$ argon bubbles monotonically approach the table of the metal (straight flow). When $\tau_\mathrm{in} < \tau < \tau_\mathrm{d}$ (metal discharge), the trajectories of motion of inert gas bubbles are complex due to interaction of bubbles with the discharged metal (countercurrent).

Since the gas injected into metal is inert, its mass in each bubble is constant during the whole way of its floating. This fact allows one to present the quantity n at the time instant τ as

$$n = \frac{\dot{m}\tau_\mathrm{r}}{m_0 V}\,. \tag{2}$$

In the calculation, it is expedient to use averaged characteristics for the countercurrent model [14], and successive mass transfer during the period τ' of floating of a registered bubble

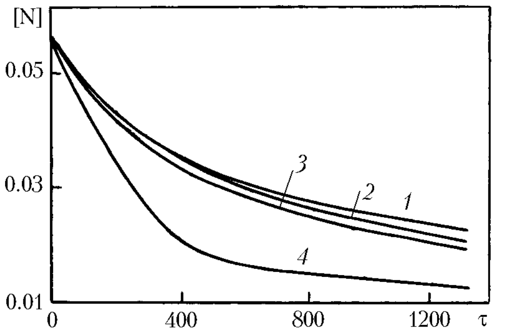
$$\tau_\mathrm{r} = \int_{\tau'} d\tau' \tag{3}$$

for the straight flow. In this case, Eq. (1) becomes

$$\varepsilon^i = \frac{1}{Q^i_\mathrm{in}} \int_{\tau_\mathrm{in}}^{\tau_\mathrm{d}} \frac{\dot{m}H_\mathrm{m}}{m_0}\,\overline{(j_i/U)}\; d\tau + \frac{1}{Q^i_\mathrm{in}} \int_{\tau_\mathrm{d}}^{\tau} \frac{\dot{m}}{m_0} \int_{\tau'} j_i(\tau, \tau')\; d\tau' d\tau\,. \tag{4}$$

Depending on the process parameters (e.g., rate of blasting), at fixed ε^i the unknown function τ is beyond the integration limits (the overbar denotes averaging over volume V). The complexity of solution of Eq. (4) is related to the variety of modes of gas bubbles floating in the liquid. Their own dependences j_i and U correspond to each mode [16].

Figure 1 shows the comparison of the results of the calculation based on the suggested mathematical model with the data of laboratory studies [17] on removal of solute nitrogen from liquid iron by argon in the presence of surfactants. The comparison of curves for the laboratory (1) and calculated (2 and 3) results indicates satisfactory



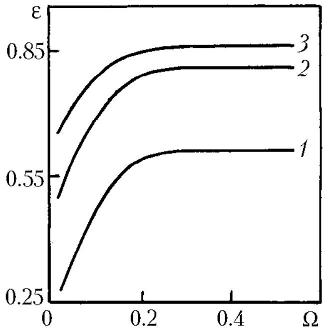


Fig. 1. Concentration of nitrogen in the melt as a function of the time of blasting.

Fig. 2. Degree of metal degassing as a function of the rate of blasting at different depths of the bath: 1) $H = 1$; 2) 2; 3) 3 m. [S] = 0.015%.

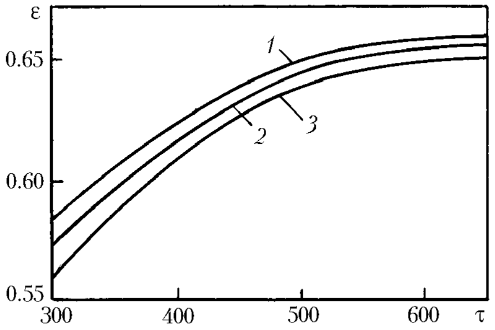


Fig. 3. Degree of metal degassing as a function of the time of blasting: 1) [S] = 0.025; 2) 0.030; 3) 0.035%. τ_d = 300 sec, Ω_{opt} = 0.3 m^3/sec.

agreement of them. In this case, the qualitative behavior of the curves is similar. The quantitative differences, which do not exceed 5–8%, are explained by the known deviation of the iron–nitrogen system from the state of thermal equilibrium which forms the basis of the mathematical model. Curve 2 corresponds to calculation by the refined model (4) and curve 3 by the averaged model when both the countercurrent and the straight flow are described by the first term of the right-hand side of Eq. (4). Curve 4 (Fig. 1) corresponds to the results of computer simulation of the degassing process with the assumption [18] on its limiting by gas diffusion in metal. As follows from the relative comparison of the curves, the account for adsorption of surfactants of the melt by the bubble surface gives a result which is in much better agreement with the experimental data.

Numerical calculation by the model at the initial data of [15] is given in Fig. 2, which shows that as the depth of the bath increases the corresponding curve lies higher since inert gas bubbles are saturated by hydrogen to a greater extent and thus, at the given rate of blasting, more hydrogen is removed from the metal upon completion of its discharge from the furnace. It is also seen from the figure that as the bath becomes deeper, the degree of saturation of bubbles by hydrogen increases, but only to a certain extent, which is indicated by the convergence of the curves with increase in H. The attainment of saturation by the curve $\varepsilon(\Omega)$ upon some Ω_{opt} dictates the necessity of choosing an optimum rate of blasting in each specific case of it, thus solving the problem of energy- and resource-saving.

In Fig. 3, we see the graph of the dependence of the degree of metal degassing on the time of blasting with continuation of degassing upon melt discharge from the furnace. Curves 1–3 correspond to different concentrations of sulfur surfactant in the bath. It follows from the graph that on continuing blasting at an optimum rate after the time instant $\tau = \tau_d$ a larger ε can be obtained, as a rule. However, when $\tau > \tau_d$ the efficiency of degassing $d\varepsilon/d\tau$ decreases. This is in qualitative agreement with the known data according to which the efficiency of degassing increases with an increase in the concentration of the removed gas and, correspondingly, decreases with its decrease [19]. It is also seen from this figure that as the concentration of sulfur increases the curve $\varepsilon(\tau)$ is lower, which is related to adsorption of this surfactant on the bubble surface and, correspondingly, blocking of a part of it for mass transfer of hydrogen removed through the phase interface. In this case, an increase in the concentration of sulfur leads, as is known, to an increase of the blocking area, which results in a decrease in ε [16, 20].

The results of the laboratory studies obtained by Zakharov et al. [21] are in qualitative agreement with the data of mathematical simulation which makes it possible to extend the developed program of computer calculation to the case of a real technological process of blasting through porous elements of the ladle bottom during metal discharge from the furnace (countercurrent) with continuation of blasting upon completion of this period.

The suggested mathematical model of mass transfer describes a wide class of processes of off-furnace degassing of melts, which differ in grade and composition of metals, by floating inert gas bubbles.

NOTATION

H_0 and H_{m}, steady-state and current values of the liquid bath depth, m; j_i, mass flux of the ith component of the gas mixture on the bubble surface, kg/sec; m_0, mass of the inert gas in an individual bubble, kg; $\dot{m}$, mass flow rate, kg/sec; $\dot{m}_{\mathrm{m}}$, mass flow rate of metal to the vessel, kg/sec; n, number of bubbles per volume unit of the melt, 1/m^3; Q^i_{in}, initial concentration of the ith component of the gas mixture (hydrogen, nitrogen, oxygen), kg/m^3; [S] and [N], concentration of sulfur and nitrogen in the melt, %; S, cross-section area of the vessel, m^2; U, velocity of bubble floating, m/sec; V, volume of the liquid bath, m^3; x, y, z, rectangular Cartesian coordinates, m; ε^i and ε, depth of metal degassing from the ith component and hydrogen; ρ_{m}, metal density, kg/m^3; τ, τ_{in}, τ_{d}, and τ_{r}, current, initial, metal discharge, and relaxation time, sec; Ω_{opt}, optimum rate of blasting, m^3/sec. Subscripts: d, discharge of metal from the furnace to the vessel; m. metal; in, initial; 0, steady-state; opt, optimum; r, relaxation.

REFERENCES

1. I. I. Bornatskii, V. I. Machikin, and V. S. Zhivchenko, *Off-Furnace Refinement of Iron and Steel* [in Russian], Tekhnika, Kiev (1979).
2. N. I. Zakharov, D. A. Dyudkin, and K. Kh. Okon, Prediction of the processes of degassing of metal melts by floating bubbles of inert gas, *Izv. Vyssh. Uchebn. Zaved.*, *Chern. Metallurg.*, No. 11, 103–104 (1990).
3. N. I. Zakharov, D. A. Dyudkin, and A. I. Trotsan, *Modeling of Thermophysical Processes of Off-Furnace Jet Degassing of Metal* [in Russian], Yugo-Vostok, Donetsk (1999).
4. A. Mariuyuki, *Improvement of the Efficiency of the Process of Liquid Steel Degassing*, Patent Application 57-200514, Japan, MKI C 7/10, C 22 B 9/04. Published on 08.12.83.
5. O. Khirosi, I. Masakhiro, and N. Katsukhiro, *Method of Liquid Metal Degassing*, Patent Application 459914, Japan, MKI C 21 C 7/10. Published on 26.02.92.
6. L. Wang, H. Lee, and P. Hayes, A new approach to molten steel refining using gas bubbles, *ISIJ Int.*, **36**, No. 1, 17–19 (1996).
7. R. Endel, R. Marr, and E. Pretorius, Refractory. Slag systems for ladles and secondary refining processes. Part VII. Refractory, *Iron Steel Mark.*, **23**, No. 10, 109–114 (1996).
8. A. Keizo and O. Tomohiro, *Refractory for Gas Flowing for Molten Metal Refining Vessel*, Patent Application 0577873, Japan MKI C 21 C 7/0172. Published on 12.01.94.
9. T. Mitsukhiro, A. Isidzaka, T. Khisaki, et al., *Porous Brick for Bottom Ladle Degassing of Metal*, Patent Application 3297537, Japan, MKI B 22 d 1/00. Published on 27.12.91.
10. V. S. Zhivchenko, N. F. Parakhin, and I. I. Bornatskii, *Ladle for Metal Degassing*, USSR Intentor's Certificate 827262, MKI B 22 c 141/00. Published on 07.05.81.
11. N. P. Lyakishev and A. G. Shalimov, *State-of-the-Art of the Technology of Steel Refining* [in Russian], ÉLIS, Moscow (2001).
12. V. I. Yavoiskii, V. P. Borzunov, and V. A. Sherbakov, Mathematical modeling of the process of hydrogen removal from liquid steel under vacuum in the ladle furnace, in: *Physicochemical Principles of Vacuum Processes in Ferrous Metallurgy* [in Russian], Metallurgiya, Moscow (1984), pp. 46–48.
13. S. Turkan and K. Lange, Entgasung von Metallschmelzen mit Blasenschwarmen, *Steel Res.*, **56**, 247–249 (1985).

14. N. I. Zakharov, I. I. Bornatskii, and A. I. Tuyakhov, Mathematical model of mass transfer for degassing of metal melts by floating bubbles of inert gas, *Izv. Vyssh. Uchebn. Zaved., Chern. Metallurg.*, No. 9, 30–33 (1989).
15. N. I. Zakharov, Process of mass transfer in off-furnace degassing of metal, *Protsessy Lit'ya*, No. 2, 3–6 (2000).
16. V. G. Levich, *Physicochemical Hydrodynamics* [in Russian], Fizmatgiz, Moscow (1959).
17. T. Masamitsu, M. Hiromu, and S. Masamichi, Rate of nitrogen desorption of molten iron by argon flowing, *Iron Steel Inst. Jpn.*, **72**, No. 3, 419–423 (1986).
18. M. A. Glinkov, R. I. Men'shikov, and L. I. Urbanovich, Mathematical model of liquid steel degassing by bubbles of inert gas and carbon oxide. Communication 1, *Izv. Vyssh. Uchebn. Zaved., Chern. Metallurg.*, No. 5, 162–164 (1973).
19. K. P. Bakanov, I. L. Barmotin, and N. N. Vlasov, *Steel Refinement by Inert Gas* [in Russian], Metallurgiya, Moscow (1975).
20. B. V. Linchevskii, *Thermodynamics and Kinetics of Interaction of Gases with Liquid Metals* [in Russian], Metallurgiya, Moscow (1986).
21. N. I. Zakharov, P. S. Kharlashin, and A. I. Trotsan, Experimental study of the processes of off-furnace jet degassing of metal, *Protsessy Lit'ya*, No. 4, 21–24 (2002).