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Injection of Iron-Bearing Concentrates Derived from Steel-Smelting Slag into the Converter Bath

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Abstract—Steel-smelting slags form a large proportion of metallurgical wastes. They are generated at a rate of 150–200 kg/t of steel, on average. At current rates of steel production in Russia, the annual output of smelting slag is 9 million t, of which 8–11% consists of metallic iron and 15–40% of iron oxides. The total iron content in the slag is 20–30 wt %. Steel-smelting slag represents a valuable source of iron, which should be processed and returned to production. The slag-processing system at AO EVRAZ ZSMK permits stepwise removal of iron-bearing inclusions from the slag by magnetic separation. The iron-bearing concentrate obtained consists of three fractions: 0–10 mm (for use in sinter production); 10–80 mm (for blast-furnace use); and 80–250 mm (for use in steel smelting). The use of the 0–10 and 10–80 mm fractions in steel production in 160-t converters is considered in the present work. A mathematical model permits multivariant calculations to investigate the smelting dynamics and the distribution of added iron-bearing concentrates in the metallic melt, for different trajectories and dosing protocols. Analysis of the results yields new information regarding the hydrodynamic processes when iron-bearing concentrates from the slag-processing system at AO EVRAZ ZSMK are injected in the converter bath.

Keywords: converters, steel-smelting slag, recycling, modeling, smelting, hydrodynamics

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Steelmakers have accumulated considerable quantities of wastes, most notably blast-furnace, converter, and electrofurnace slags [1–6]. The slag formed in the converter amounts to 10–12% of the metal charge, depending on the steel produced, the converter design, and the production conditions. Note that, besides oxides of silicon, calcium, magnesium, manganese, and aluminum and the iron oxides FeO, Fe_2O_3, Fe_3O_4, the slag contains metallic iron in the form of beads, which amount to 8–11 wt % of the slag [7]. In the course of steel production, slag tailings are stored over considerable areas of land; the slag mass amounts to tens of millions of tons. In particular, in the Kuznets Basin, the figure for AO EVRAZ ZSMK is more than 40 million t [8]. This waste may be regarded as a valuable source of iron. Obviously, it should be processed and returned to production.

A low-cost approach to processing steel-production slag is enrichment—for example, by magnetic separation. The magnetic fraction is used as iron-bearing batch [9–11]. In the processing of iron-bearing slag concentrate, we may obtain a product containing 40–80% Fe, consisting of three fractions: 0–10, 10–80, and 80–250 mm. Such concentrates may be added to the charge—for example, by injection—and may serve as a substitute for iron scrap, which serves as a coolant inn the converter [11].

In recycling such waste, we need to identify the best means of introducing the material and to fine-tune the blast and slag conditions in the converter. Preliminary numerical modeling of the smelting dynamics of the slag concentrate in the melt provides additional information for the development of a resource-saving converter technology. It is of great scientific and practical interest to study the hydrodynamics and mass transfer in the converter and the assimilation dynamics of slag concentrate in the bath. In studying the mass transfer and melting of the concentrate, we use the available information regarding the hydrodynamic and thermal behavior of the melt with top injection of the converter bath [12–16].

The mathematical model is based on collective motion of the particles in the melt; this approach is applicable when the disperse concentrate occupies less than 20% of the melt volume [17. 18]. We assume that the motion and conversion of the concentrate particles

do not depend on the motion and conversion of the other particles, whose influence is taken into account solely through the overall characteristics of the medium. In such conditions, our attention focuses not on an individual particle in the melt but on a whole group of particles: a conglomerate of particles of solid disperse phase β in the converter bath. One of the basic characteristics of the conglomerate is the bulk density. The spatial distribution of particles in the conglomerate at any instant depends not only on the mean velocity of the solid phase, corresponding to convective transfer, but also on the effective diffusion coefficient, which characterizes the particle dynamics. Specifically, the particle dynamics is associated with nonuniformity of the flow and circulatory fluxes in the bath.

To simplify the formulation of the problem and hasten the calculations, we make a number of assumptions in the mathematical model. In particular, since the particles of phase β are relatively small, we may neglect the relative velocity of the solid phase and the liquid phase (melt). Hence, we may consider a one-dimensional hydrodynamic problem: to find the velocity field of the medium as a whole [19]. Thus, the mathematical model only takes account of the melting of the iron-bearing concentrate in the converter bath and the consequent distribution of the material in the melt. The mechanical influence of the disperse slag-forming materials on phase β is disregarded, and the dynamics of slag formation is not considered. In this formulation of the problem, the slag-forming additives only have local thermal influence, on account of their initial heating to the melt temperature.

Besides the solid impurity phase β, we consider the liquid phase η formed by its melting products. We assume that phase η includes all the melting products of phase β. We also make allowance for the thermal effects associated with the interconversion of the components of phase η.

Thus, mass transfer may be described by the following system of equations

$$\frac{\partial \beta}{\partial t} + \bar{v}(\beta \bar{v}) = \bar{v}(D_\beta \bar{v}\beta) + \Phi; \quad (1)$$

$$\frac{\partial \eta}{\partial t} + \bar{v}(\eta \bar{v}) = \bar{v}(D_\eta \bar{v}\eta) - \frac{\rho_\beta^\circ}{\rho_\eta^\circ}\Phi, \quad (2)$$

where $\bar{v}$ is the overall velocity of the medium; D_β and D_η are the effective diffusion coefficients of phases β and η; ρ_β° and ρ_η° are the true densities of phases β and η; Φ is the bulk density of the solid phase.

The thermal aspects of the process are described by the equation

$$C_e \frac{dT}{dt} = \vec{\nabla}\left(\lambda_e' \vec{\nabla} T\right) + L_e \frac{\rho_\beta^\circ}{\rho_0}\Phi + \Theta, \quad (3)$$

where

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + \bar{v}\vec{\nabla} T$$

is the material derivative of the temperature T of the medium; C_e is its effective specific heat; λ_e' is the effective thermal conductivity of the medium (divided by its mean density ρ_0); L_e is the effective specific heat of phase transition, taking account of the heat consumed in the melting of phase β and the thermal effect associated with the solution and chemical reactions of phase η; the coefficient Θ takes account of the thermal influence on the melt when the slag-forming additives are introduced.

Then

$$\Theta_e\left[(C_b + \varphi C_c)\left(T_b^0 - T_m\right) + \varphi L_c\right]\psi, \quad (4)$$

where C_b and C_e are the specific heats of solid lime and feldspar; φ is the relative content of feldspar in the slag-forming additives; T_b^0) is the initial temperature of the slag-forming additives; T_m is the melt temperature; ψ is the mass consumption of slag-forming additives at their point of introduction, by means of which their supply rate may be characterized.

The first term in square brackets in Eq. (4) takes account of the heat consumed in bringing the slag-forming additives to the melt temperature, while the second term takes account of the heat consumed in melting the fluorspar.

In this formulation of the problem, the bulk density of the solid phase Φ determines the kinetics of phase conversion. When iron-bearing concentrate is supplied to the melt, we assume that the disperse material is irregular in form, has a nonuniform fractional composition, and includes all the particles within unit volume [18]. Then

$$\frac{d\beta}{dt} = \Phi = -K'\beta^{1/3}\Delta_f T_f,$$

where

$$K' = \sqrt[3]{3(4\pi N)^2}\,\frac{\mathrm{Nu}\lambda_e}{2L\rho_\beta^0}$$

is the kinematic coefficient; N is the number of solid particles per unit volume; T_f is the melting point of the concentrate; ρ_β^0 is the density of concentrate particles; and Nu is the Nusselt number.

The boundary conditions for Eqs. (1) and (2) follow from the condition that the flow of phases β and η is zero at all the boundaries of the calculation region. (The supply of phase β to the melt is taken into account by means of the bulk density of the solid phase Φ.) The boundary conditions for Eq. (3) are selected as in [20].

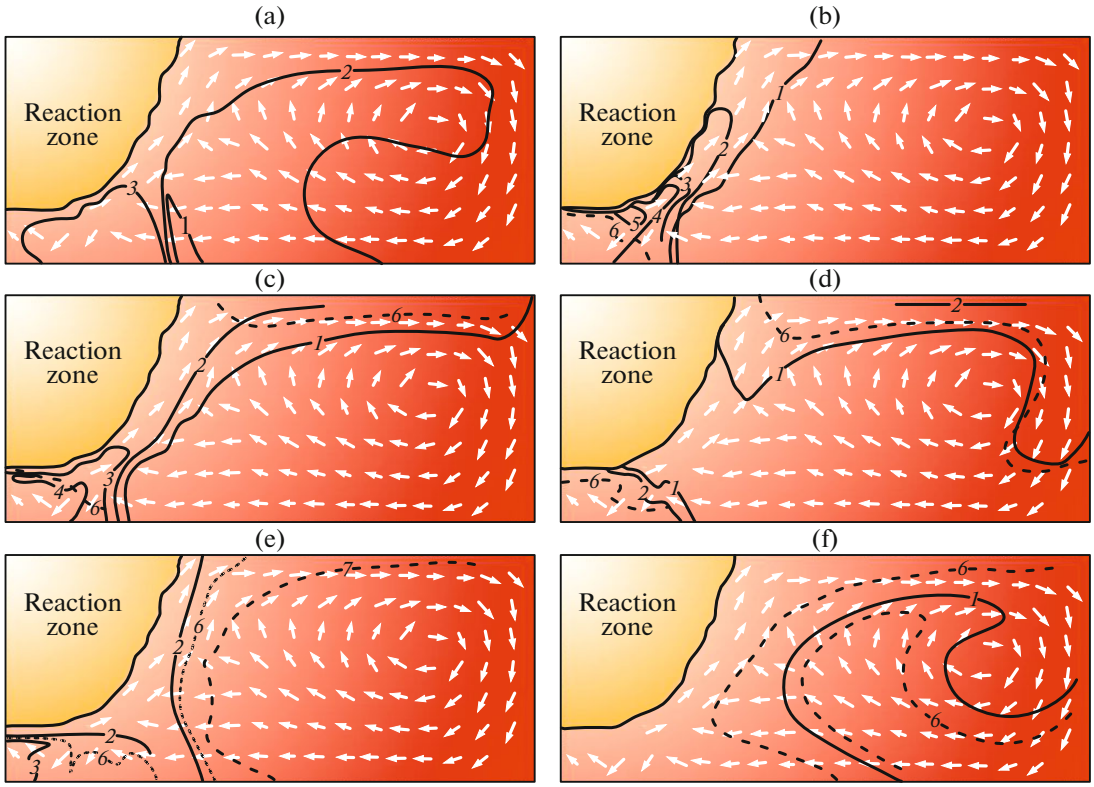

Fig. 1. Concentration fields of the phases within the converter at the end of concentrate supply (a) and after 20 (b), 40 (c), 60 (d), 100 (e), and 110 (f) s: (*1*) 0.05% phase β; (*2*) 0.2% phase β; (*3*) 1% phase β; (*4*) 4% phase β; (*5*) 6% phase β; (*6*) 10^{-4}% phase η; (*7*) 10^{-3}% phase η.

Numerical solution is based on an explicit difference scheme, with approximate terms for the effective diffusion coefficients and thermal conductivity [17].

The mathematical model permits multivariant calculations to investigate the smelting dynamics and the distribution of added iron-bearing concentrates in the metallic melt, for different trajectories and dosing protocols. The converter geometry assumed corresponds to the 160-t units at AO EVRAZ ZSMK. The quantity of concentrate introduced in the melt is 4–6 t or 3.5–7.5 kg/t of steel produced. The supply trajectory of the material is determined by the design of the supply channels and, when using loading scoops, by the distribution of the material within the bath in the reaction zones with the oxygen jets. The concentrate is introduced within 30–40 s; it is introduced at a distance of 0.2 m from the converter's symmetry axis. The hydrodynamic conditions in the converter are taken from [20].

In Fig. 1, we illustrate the results of mathematical modeling. The arrows indicate the direction of the circulating melt fluxes; the continuous and dashed local curves correspond to constant concentrations of the β and η phases, respectively.

When iron-bearing concentrate is supplied to the converter, it may be captured by the melt fluxes ascending along the reaction zone and the turbulent eddies rotating under the reaction zones (Fig. 1a). At the end of concentrate supply (Fig. 1a), as a rule, the concentrate is distributed in two portions: the first is captured in the global vortex and travels over the whole bath volume; the second remains within the zones of action of the local vortices under the reaction zones. This pattern determines the distribution of phase β when iron-bearing concentrate is supplied to the bath.

As phase β is distributed in the bath, it also melts. As a result, phase η is formed (Fig. 1b). Melting on account of local heating is relatively intense [19]. In Fig. 1b, we show the concentration isolines for phase η in the lower part of the converter bath (under the reaction zones). In Fig. 1c, we present the analogous isolines in the upper part of the bath. The melting of phase β reduces its total volume. For example, after 110 s (Fig. 1f), phase β disappears from the region below the reaction zones. We also note increase in the content of phase η, which occupies an ever larger share of the bath volume in the course of injection.

As a result of intense motion of the melt during concentrate supply, the material is distributed over the whole bath and continues to melt. In the course of injection, phase η is distributed practically uniformly over the whole bath volume.

CONCLUSIONS

A mathematical model permits analysis of the hydrodynamics in the converter bath when iron-bearing concentrates from the slag-processing system at AO EVRAZ ZSMK are injected. (The 10–80 mm fraction of the concentrate is introduced.)

As a result of intense motion of the melt during concentrate supply, the concentrate particles are distributed practically uniformly over the whole bath and continue to melt.

REFERENCES

1. Kuznetsov, S.N., Volynkina, E.P., Protopopov, E.V., and Zorya, V.N., *Metallurgicheskie tekhnologii pererabotki tekhnogennykh mestorozhdenii, promyshlennykh i bytovykh otkhodov* (Metallurgical Technologies for Processing of Technogenic Deposits, Industrial and Household Wastes), Novosibirsk: Sib. Otd., Ross. Akad. Nauk, 2014.
2. Kuhn, M., Drissen, P., and Schrey, H., Successful treatment of liquid BOF slag at Thyssen Krupp Steel works to solve the problem of volume stability, *Proc. 3rd European Oxygen Steelmaking Conf., October 30–November 1, 2000*, London: IOM Commun., 2000, pp. 521–531.
3. Sahay, J.S., Nadpal, O.P., and Prasad, S., Waste management of steel slag, *Steel Times Int.*, 2000, no. 2, pp. 38–40.
4. Barella, S., Gruttadauria, A., Magni, F., Mapelli, C., and Mombelli, D., Survey about Safe and Reliable Use of EAF Slag, *ISIJ Int.*, 2012, vol. 52, no. 12, pp. 2295–2302.
5. Balajee, S.R., Callaway, P.E., and Keilman, L.M., Production and BOF recycling of waste oxide briquettes at inland steel, *Iron Steelmaker*, 1995, vol. 22, no. 8, pp. 11–21.
6. Weber, R., Steel production with optimized energy and raw material input, *ASM Congr. Cincinnati, Ohio*, Materials Park: ASM Int., 1992, pp. 21–27.
7. Kudrin, V.A., *Teoriya i tekhnologiya proizvodstva stali. Uchebnik dlya vuzov* (Theory and Technology of Steel Production: Manual for Higher Education Institutions), Moscow: AST, 2003.
8. Anashkin, N.S. and Pavlenko, S.I., *Martenovskie shlaki i ikh ispol'zovanie v metallurgii i drugikh otraslyakh narodnogo khozyaistva* (Marten Slags and Their Use in Metallurgy and Other Branches of the National Economy), Novosibirsk: Sib. Otd., Ross. Akad. Nauk, 2006.
9. Gladkikh, V.I., Gostenin, V.A., Bochkarev, A.V., Sukinova, N.V., and Murzina, Z.N., Processing of steelmaking slags at the AMCOM plant, *Stal'*, 2009, no. 10, pp. 107–108.
10. Golov, G.V., Sitnikov, S.M., and Kalimulina, E.G., Technology for extracting the metals from dump slag, *Stal'*, 2001, no. 8, p. 83.
11. Tarabrina, L.A., Kurgan, T.A., and Ignat'eva, N.S., Processing steelmaking slags at the Magnitogorsk Metallurgical Combine, *Metallurgist*, 2000, vol. 44, nos. 9–10, pp. 458–460.
12. Bulgakov, V.G., Bondarev, Yu.A., and Ageev, E.E., Use of briquettes from metallurgical waste for partial or complete replacement of pig iron in steelmaking, *Izv. Vyssh. Uchebn. Zaved., Chern. Metall.*, 1985, no. 9, p. 72.
13. Katsnhiko, N., Mitsugu, T., and Yoshimasa, M., Necessity of scrap reclamation technologies and present conditions of technical development, *ISIJ Int.*, 1997, vol. 37, no. 3, pp. 27–31.
14. Trentini, B., Scrap consumption in the oxygen converter, *Steel Times Int.*, 1985, no. 2, pp. 608–610.
15. Goodman, N., Slag splashing of BOF converters, *Iron Steel Inst.*, 1996, no. 30, pp. 24–33.
16. Singh, V.A., Lenka, S.N., Ajmani, S.K., Bhanu, C., and Pathak, S., Novel bottom stirring scheme to improve BOF performance through mixing and mass transfer modeling, *ISIJ Int.*, 2009, vol. 49, no. 12, pp. 1889–1894.
17. Samokhvalov, S.E., *Teplofizicheskie protsessy v mnogofaznykh sredakh: teoreticheskie osnovy komp'yuternogo modelirovaniya* (Thermophysical Processes in Multiphase Environments: Theoretical Foundations of Computer Modeling), Kiev: Inst. Sist. Issled., 1994.
18. Kutateladze, S.S. and Styrikovich, M.A., *Gidrodinamika gazozhidkostnykh sistem* (Hydrodynamics of Gas-Liquid Systems), Moscow: Nauka, 1976.
19. Protopopov, E.V., Chernyatevich, A.G., Samokhvalov, S.E., Ganzer, L.A., and Kosukhina, E.S., Numerical modeling of mixing and heat transfer in a converter bath with combined blowing, *Izv. Vyssh. Uchebn. Zaved., Chern. Metall.*, 1997, no. 12, pp. 3–8.
20. Protopopov, E.V., Mokrinskii, A.V., Chernyatevich, A.G., and Zhibinova, I.A., Converter-bath hydrodynamics with injection in a liquid-reduction unit, *Steel Transl.*, 2006, vol. 36, no. 6, pp. 1–4.

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