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Application of Refractory Coatings to Converter Linings by Swirling Technology. 1. Breakup of Liquid Slag with a Swirling Lance

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Abstract—The application of refractory coatings to the converter lining may be improved by means of special injectors, such as swirling lances, for most effective spraying of the slag melt. On the basis of the mechanics of gas–liquid systems, the breakup of liquid slag under the action of swirling jets is simulated. The size of the slag particles entrained from the interaction zone is determined by the speed of the gas flux and the gas flow rate. Decrease in slag viscosity tends to reduce the minimum particle size. At breakdown, foaming of the slag melt is possible. That reduces the speed of the slag particles and impairs the formation of a slag coating on the converter lining.

Keywords: converter, swirling lance, jet speed, liquid slag, breakup, drop size, injection, refractory coating

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In the past ten years, special lances and technologies for the application of slag coatings to converter linings have been used to extend lining life [1–4].

As we know, combined gas–liquid motion in metallurgical systems is extraordinarily complex [5–7]: it ranges from the motion of two parallel continuous fluxes interacting at one continuous interface to the motion of foam formed by two phases with a complex and unstable structure.

Forces, thermal fields, and mass transfer at the phase interface affect the velocity, pressure, temperature, and concentration fields in the different phases. Discontinuities of pressure, temperature, concentration, and flow velocity appear at the phase interface.

The behavior of gas–liquid systems is not well understood, despite extensive research [5–10]. Considerable theoretical and experimental difficulties have been encountered.

One option for optimizing the coating technology is to design lances such that swirling gas jets are obtained [8–11]. That ensures maximum spraying of the slag melt; the analysis is based on the mechanics of gas–liquid systems.

The operation of swirling lances and the interaction of swirling gas fluxes with slag melt were described in [11, 12]. It was found that, when the gas is supplied through a swirling lance, it moves downward and is reflected from the liquid surface [11]. Capturing slag particles, it moves to the upper levels of the converter [13].

In the center cross sections of the gas jet, when plotting a velocity curve at the beginning of the jet section (the initial speeds), we find that the radial flow velocity is zero. As the gas jet travels in the working space of the converter, it begins to expand on account of centrifugal forces. The axial velocity declines, while the velocity in the boundary layer increases. This process is intensified by vigorous interaction with the surroundings and by using swirling gas jets.

The quantity of slag melt entrained by the gas flux and applied to the converter's refractory lining depends on the diameter D of the slag particles formed on interaction with the swirling gas jets, as established in [11]

$$D \approx 6\frac{\tau^{1/3}}{\rho_g \Delta u^2}(\sigma + \mu_g \Delta u), \tag{1}$$

Here $\tau = Q_{li}/Q_g$ is the ratio of the bulk flow rates of gas and liquid; u is the tangential flow velocity, m/s; Δu is the velocity difference between the particle and the gas pulsations, m/s; σ is the surface tension, N/m; μ_g is the dynamic viscosity of the gas, Pa s.

If we divide both sides of Eq. (1) by the effective diameter d of the slag column (m), which is equal to

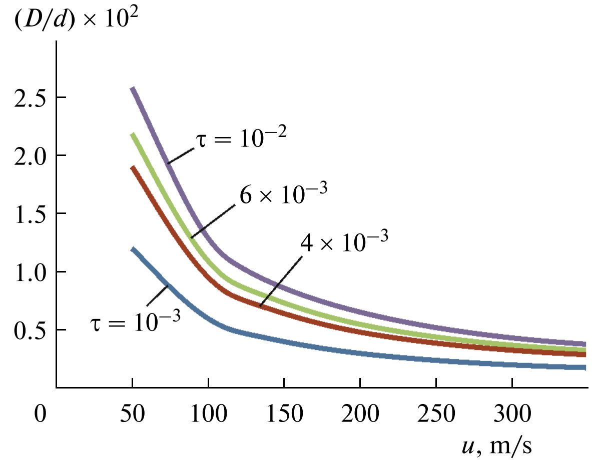

Fig. 1. Dependence of D/d on the velocity of the gas flow u, for various τ values.

the output-nozzle diameter of the swirling lance, we obtain the equation

$$\frac{D}{d} = 6\tau^{1/3}\left(\mathrm{We}^{-1} + \mathrm{Re}^{-1}\frac{\mu}{\mu_g}\right), \quad (2)$$

where We $= \rho_g \Delta u^2 d/\sigma$ is the Weber number; Re $= \rho \Delta u d/\mu_g$ is the Reynolds number; $\rho_g \Delta u^2$ is the analog of the pulsational kinetic energy of the gas, kg/m s^2; μ is the dynamic viscosity of the slag, Pa s.

In the calculations, we assume the following numerical values [13]: $\rho = 3 \times 10^3$ kg/m^3; $\mu = 0.1$–0.3 Pa s at $T = 1450°$C; kinematic viscosity $\nu = (0.3–1.0) \times 10^{-4}$ m^2/s; $\sigma = 0.5$–0.6 N/m at 1400–1600°C. The slag viscosity depends on its chemical composition and the temperature. The gas used in breaking up and spraying the slag is nitrogen, for which we assume that $\rho_N = 1.25$ kg/m^3; $\mu_N = 2.1 \times 10^{-5}$ Pa s. Preliminary calculations when the velocity of the gas–liquid flow $u = 100$ m/s show that the action of surface tension is no more than 2% of the effect of friction and decreases with increase in the velocity. Accordingly, we only take account of the viscous friction in the subsequent calculations.

The use of lime–magnesite fluxes during gas injection in the converter increases the slag viscosity. Therefore, the second term in Eq. (2) is much greater than the first. Hence, we may write Eq. (2) in simpler form

$$\frac{D}{d} = 6\tau^{1/3}\left(\mathrm{Re}^{-1}\frac{\mu}{\mu_g}\right). \quad (3)$$

In Fig. 1, we show the relative diameter of the slag droplet obtained in spraying according to Eq. (3), when the relative bulk flow rate of the liquid phase $\tau = 10^{-3}$–10^{-2}. We find that, when the output-nozzle diameter of the swirling lance is $d = 0.2$ m and the gas flow velocity is 300 m/s, the droplet diameter is about 600 μm.

Obviously, the droplet size is determined not only by the gas flow velocity but also by the gas flow rate. In preliminary calculation of the slag-particle size, we assume that $\tau \sim 10^{-3}$; that corresponds to $G_{li}/G_g = 2.4$, where G_{li} is the mass flow rate of the liquid slag particles, kg/s; G_g is the mass flow rate of the gas, kg/s. With decrease in G_{li}/G_g to 0.5, the minimum size of the slag droplet will be around 300 μm, with the maximum viscosity of the slag melt. Reducing the slag viscosity to a third of its initial value reduces the minimum particle size to about 100 μm.

We may adopt an analogous approach in describing the dispersion both in the central zone and at the interaction boundary of the gas flux, the slag melt, and the converter lining at breakdown. Hence, we may estimate the droplet size as follows [11]: in Eq. (3), we may adopt the diameter d_{int} of the interaction zone from which the gas jet displaces liquid slag as the scale factor. Hence, we may use a correction factor $k = D/d_{int}$. The tangential velocity declines on the basis of the typical $1/r$ distribution (where $r = d/2$) [14]. That is also the diameter ratio; in other words, the correction is determined as $(D/d_{int})2$. The pulsational component of the interaction declines in the same manner. Therefore, when gas injected into the slag melt around the bath periphery, increase in diameter of the slag particles is likely.

The size of the particles formed at the boundary of the slag melt is limited, on account of the formation of a two-phase flux of slag particles and gas in that region. That results in some foaming of the gas–slag emulsion. Accordingly, slag particles are displaced from the interaction zone at a speed no greater than the velocity of sound in the mixture. For a mixture of nitrogen and liquid slag, the velocity of sound a_{mi} is determined from the expression [15]

$$\frac{1}{a_{mi}^2} = \frac{\partial \rho_{mi}}{\partial P} = \rho_{mi}\left(\frac{\varphi}{\rho_g a_g^2} + \frac{1-\varphi}{\rho_{sl} a_{sl}^2}\right),$$

$$\rho_{mi} = \rho_{sl}(1-\varphi) + \rho_g \varphi.$$

Here $a_g^2 = \partial\rho_g/\partial P$ is the velocity of sound in nitrogen; $a_{sl}^2 = \partial\rho_{sl}/\partial P$ is the velocity of sound in slag; ρ_g is the density of nitrogen; ρ_{sl} is the density of the slag; P is the pressure; φ is the gas content of the flow.

In Fig. 2, we show the calculated velocity of sound for gas–slag emulsion. Over practically the whole range of φ, the velocity of sound is no more than 30 m/s. It only increases in the extreme cases (with a low gas content or with practically no slag in the emulsion): to 69.8 m/s when $\varphi = 0.01$ and to 68.0 m/s when $\varphi = 0.99$.

When the gas flux leaves the lance, swirling flux is formed above the slag surface, as established in [11]. There is a region of reduced pressure in the axial zone. If we assume that the tangential velocity declines in proportion to $1/r$ on moving away from the center of the eddy, the pressure above the surface is determined by the equation [10]

$$\frac{1}{\rho_g}\frac{dP}{dr} = \frac{\Gamma^2}{r^3}, \quad (4)$$

where Γ is the circulation.

The solution is

$$P = P_0 - \frac{\rho\Gamma^2}{r^2},$$

where P_0 is the atmospheric pressure.

As the gas flows out of the swirling lance, the pressure in the vicinity of the gas output is considerably less than in the surroundings. The same is true of the overall pressure above the surface of the slag bath. As a result, on account of the pressure difference, the slag melt in the interaction zone moves from the periphery to the center. Note that such slag flow is only observed at a certain height of the gas lance with respect to the slag surface. The slag motion under the action of the pressure difference above the bath is described by the equation

$$V\frac{dV}{dr} = -\frac{1}{\rho_{sl}}\frac{dP}{dr},$$

where V is the flow velocity of the slag.

We disregard the slag viscosity. As a result, the melt velocity is overestimated. Substituting the pressure from Eq. (4), we obtain

$$\frac{V^2}{2} = \frac{\rho_g}{\rho_{sl}}\frac{\Gamma^2}{2r^2}.$$

Hence

$$V = \frac{2\Gamma}{d\left(\frac{\rho_g}{\rho_{sl}}\right)^{1/2}}.$$

Then the flow rate of the slag supplied to the interaction zone may be estimated as

$$Q = \frac{\pi\xi^2 d_0\Gamma\left(\frac{\rho_g}{\rho_{sl}}\right)^{1/2}}{2},$$

where the parameter ξ characterizes the position of the eddy boundary with below-atmospheric pressure.

The position of the eddy boundary is determined by the lance parameters ($\xi \sim 0.5$–0.6). In these conditions, the slag velocity at the lance outlet is about 4 m/s, while the flow rate of the entrained slag is 0.016 m^3/s (or 57 m^3/h).

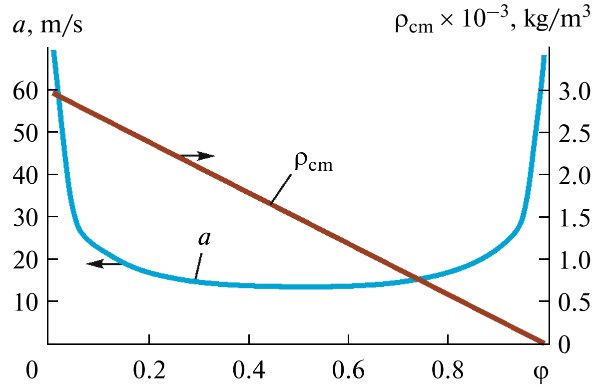

Fig. 2. Dependence of the velocity of sound in the gas–slag emulsion and the mixture density on the gas content.

CONCLUSIONS

In the application of slag coatings to the converter lining by means of swirling lances, the size of the slag particles entrained from the interaction zone is determined by the speed of the gas flux and the gas flow rate. Decrease in slag viscosity tends to reduce the minimum particle size. At breakdown, foaming of the slag melt is possible. That reduces the speed of the slag particles and impairs the formation of a slag coating on the converter lining.

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