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# Application of Refractory Coatings to Converter Linings by Swirling Technology. 2. Motion of Slag Droplets

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**Abstract**—The use of swirling gas jets for more effective application of refractory coatings on the converter lining is considered. Numerical modeling is employed to analyze the aerodynamics of the working space and the motion of converter-slag droplets, in the case where neutral gas is supplied through a special lance with swirling elements. The description of slag-droplet motion to the converter lining is refined; the relation between the parameters of droplet motion and the characteristics of the swirling jet is established. The swirling of the jet mainly determines the trajectory of the slag droplets, regardless of their size. According to theoretical analysis, the use of swirling gas jets will permit more flexible slag-coating application to the converter lining.

*Keywords:* converter, swirling jets, aerodynamics, slag, gas injection, droplet size, droplet trajectory

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Information regarding the aerodynamics of gas–liquid flows and the hydrodynamics of liquid slag is essential in improving the application of refractory coatings to the converter lining [1–6].

Research on the dispersion of liquid slag by directed gas jets shows that the minimum size of the liquid-slag droplets is 300 μm; it may be reduced to 100 μm only in exceptional cases [6]. After separation of the droplet from the slag, it is accelerated by the gas flux. Its subsequent motion is determined primarily by its size, as well as by the parameters of the neutral gas supplied.

The small slag droplets rapidly reach the speed of the transporting gas flux, with which they travel; some droplets are removed from the converter by the ascending fluxes to the exhaust channel [7–11]. Larger droplets are also accelerated by the gas flux and move subsequently by inertia and also under the influence of the aerodynamic behavior of the flux. On acquiring sufficient momentum, the large particles move to the converter lining by inertia, encountering only the resistance of the medium. Since turbulent gas flow is typical for gas injection in the slag, Newton's law may be used to describe the gas flow around the slag droplet [9].

Consider the motion of a slag droplet along a trajectory from the dispersion zone to the lining in the converter's working space. The transporting gas flux, which carries the slag droplets, moves predominantly upward, along a spiral path. Then the droplet trajectory is described by the equations [12]

$$\frac{dW_\varphi}{dt} = \frac{W_r W_\varphi}{r} - \frac{(W_\varphi - V_\varphi)V_S}{L},$$

$$\frac{dW_r}{dt} = \frac{W_\varphi^2}{r} - \frac{(W_r - V_r)V_S}{L},$$

$$\frac{dW_z}{dt} = -\frac{(W_z - V_z)V_S}{L},$$

where $W_\varphi$ $W_r$, $W_z$ are the tangential, radial, and vertical components of the droplet velocity; $V_\varphi$, $V_r$, $V_z$ are the corresponding velocity components of the gas flux; $V_S$ is the relative flow velocity of the gas flux around the slag droplet; $L$ is the characteristic distance at which the slag droplet is accelerated by the flux of transporting gas.

Thus, the basic parameters determining droplet motion are the velocity acquired by the droplet on leaving the dispersion zone; and the characteristic distance $L$.

In this formulation, we may write [13]

$$L = \frac{4}{3}\frac{\rho_{sl} d}{C_f},$$

where $\rho_{sl}$ is the slag density; $\rho$ is the density of nitrogen at its temperature on injection in the slag; $d$ is the

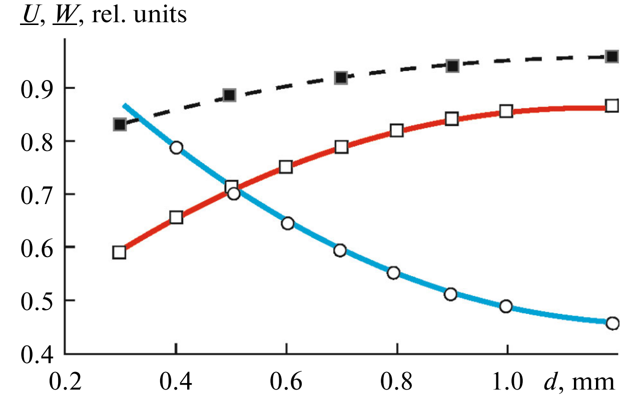


**Fig. 1.** Dependence of the droplet velocity on its diameter: (*1*) radial dimensionless velocity of the velocity after breakaway from the slag mass; (*2*, *3*) dimensionless droplet velocity at the converter lining, in normal conditions (*2*) and at 600°C (*3*).

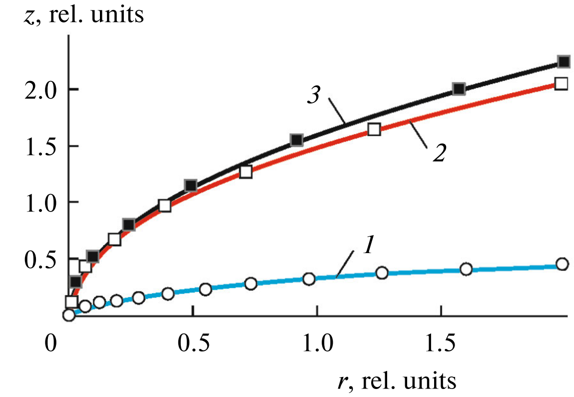


**Fig. 2.** Trajectory of slag droplets of diameter 1.2 (■), 0.3 (□), and 0.3–1.2 (○) mm in the acceleration region.

diameter of the slag droplet; and $C_f$ is the drag coefficient.

In turbulent gas flow (Re ≥ 500), $C_f = 0.44$.

The equation of droplet motion may be written in the simple dimensionless form [12]

$$dW/dt = -\underline{W}^2,$$

where $\underline{W}$ is the dimensionless speed of the slag droplet.

With the initial condition $\underline{t} = 0$, $\underline{W} = 1$, the solution may be written in the form [12]

$$\underline{W} = (\underline{t} + 1)^{-1},$$

where $\underline{t}$ is the dimensionless time.

In Fig. 1, we show the calculated radial velocity component of the droplet after it breaks away from the slag mass and also the total dimensionless droplet velocity close to the converter lining. The radial velocity $\underline{U}$ of the droplet is calculated with respect to the radial velocity of the swirling jet; the dimensionless velocity $\underline{W}$ is calculated with respect to the maximum droplet velocity on acceleration.

The temperature of the nitrogen jet emerging from the lance is relatively low. However, the jet is rapidly heated as it moves in the converter's working space. As we see in Fig. 1, the dimensionless velocity of droplets of different size as they leave the dispersion zone and encounter the gas jet is only slightly different from that in the vicinity of the converter lining. In that case, we may conduct the baseline calculations for normal conditions (for cold gas in the converter), and the main calculations for conditions with heating of the transporting gas to 600°C. Even for particles of diameter 0.3 mm, the relative velocity at the wall is 0.83. For dimensionless velocity particles of diameter 1.0–1.2 mm, the error is 4–6%. We may expect little change in velocity of the droplets as they move through the high-temperature gas in the converter.

The droplet size considerably affects its acceleration by the high-speed flux of transporting gas. In Fig. 1, we show the radial velocity of droplets of different diameter relative to the radial velocity of the transporting gas flux. Large slag particles move more slowly, and therefore their height at application to the lining is less than that of the small droplets on account of the greater inertia in interaction with the gas flux.

In Fig. 2, we show the trajectory of slag droplets (diameter 0.3–1.2 mm) during acceleration by the transporting gas flux: the dimensionless height $z$ to which the droplet rises is plotted against the dimensionless distance $r$ of the droplet from the dispersion zone. The results correspond to gas jets with moderate ($\sigma = 1$) and intense ($\sigma = 0.2$) swirling; here $\sigma$ is the ratio of the unswirled and swirled components of the flow velocity. This range is mainly used in practice in slag injection by swirling jets. As we see in Fig. 2, $\sigma$ markedly affects the droplet trajectory. Intensely swirling jets permit effective application of slag coatings to the lower levels of the converter lining; slightly swirling jets may be used to direct the slag droplets to the upper levels of the converter lining. The results for droplets of different size are very similar, thanks to the dimensionless formulation of the problem.

To assess how the slag droplet is affected by the structure of the transporting gas flux, we calculate the relative Reynolds number for gas flow around the droplet (Fig. 3). The Reynolds number is determined from the difference in dimensionless velocities of the droplet and the gas flux [14]

$$V_S = [(V_\varphi - W_\varphi)^2 + (V_r - W_r)^2 + (V_z - W_z)^2]^{1/2}.$$

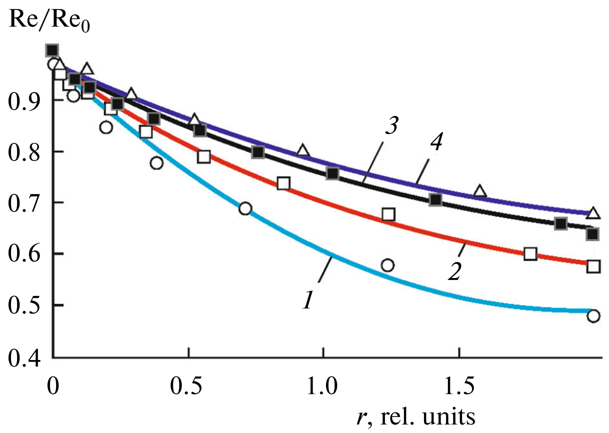


**Fig. 3.** Relative Reynolds number in the acceleration region for slag droplets of diameter 0.3 (*1*), 0.6 (*2*), 0.9 (*3*), and 1.2 (*4*) mm.

Thus, the relative Reynolds number takes the form

$$\frac{\mathrm{Re}}{\mathrm{Re}_o} = \left\{\frac{1}{r^2} + \left[\frac{P^2\tau^3}{3} - \left(1 - \frac{1}{r^2}\right)^{1/2}\right]^2 + (\sigma - z^{(1)})^2\right\}^{1/2},$$

where $P$ is the pressure of the medium.

Since

$$(\sigma - z^{(1)})^2 = \sigma^2\exp(-2P\tau),$$

we find that [15]

$$\frac{\mathrm{Re}}{\mathrm{Re}_o} = \left\{\frac{1}{r^2} + \left[\frac{P^2\tau^3}{3} - \left(1 - \frac{1}{r^2}\right)^{1/2}\right]^2 + \sigma^2\exp(-2P\tau)\right\}^{1/2}.$$

Analysis of the decrease in $\mathrm{Re}/\mathrm{Re}_o$ with increase in the dimensionless distance $r$ traveled by the slag droplet indicates that the droplet velocity gradually approaches that of the transporting gas flux. With decrease in droplet diameter, $\mathrm{Re}/\mathrm{Re}_o$ declines. Thus, the velocity of small particles is hardly different from that of the surrounding gas. Small droplets actually reach the velocity of the gas flux; for large droplets, the influence of the swirling gas is not so great and it continues to move by inertia to the converter lining.

## CONCLUSIONS

We have analyzed the motion of slag droplets formed when swirling gas jets are injected into the slag melt in an oxygen converter. We have established the relation between the parameters of droplet motion and the characteristics of the swirling jet. The aerodynamic behavior of the transporting gas flux considerably affects the motion of small slag droplets. The motion of the large slag droplets only depends on the velocity of the transporting gas flux in the early stages. The trajectory of the slag droplets, regardless of their size, is mainly determined by the swirling of the jet. Thus, the use of swirling gas jets will permit much more effective slag-coating application to the converter lining.

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