

Article

Numerical Simulation of Motion and Distribution of Powder Particles Injected from a Nozzles-Twisted Oxygen Lance in BOF Steelmaking

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Abstract: The pulverized lime/limestone injection by top oxygen blowing lance during the basic oxygen furnace (BOF) process has gained much interest in recent years due to its advantages in helping slag formation and consequently in promoting refining reactions such as dephosphorization. In this pneumatic process, understanding the motion behavior and distribution of the powder particles in the furnace is of importance for regulating and designing this refining system reliably and efficiently. In this study, limestone powder top blowing through a novel nozzles-twisted oxygen lance during a BOF process is proposed and the process is simulated by establishing a multi-fluid flow model. The coupled fluid flow of gaseous oxygen and liquid steel is predicted by the volume of fluid (VOF) method, and the motion of the limestone particles is tracked by the discrete phase model (DPM). The results show that the powder injection has little effect on cavity depth of the oxygen-powder mixture jets of the nozzles-twisted lance, but decreases cavity width. During the blowing process, most of the powder particles gather around hot spots while the rest are taken out of the furnace by the reflecting oxygen stream or penetrate into the molten bath. The generated swirling flow of the nozzles-twisted oxygen lance enables a decrease in the amount of the powder particles carried by the reflecting stream and going into the molten bath, through changing the motion paths of the powder particles. As a result, the concentration distribution of the powder particles in the molten bath varies. It could be suggested that for the limestone powder injection the preferred nozzle twist angle of the oxygen lance is 10° due to the favorable conditions for dephosphorization.

Keywords: powder blowing; particle motion and distribution; nozzles-twisted lance; BOF

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1. Introduction

Phosphorus in steel is a detrimental element, and high phosphorus content in steel adversely affects the mechanical properties of the steel, such as ductility, toughness, formability, and embrittlement [1]. Therefore, dephosphorization of liquid steel is critical during the steelmaking process, in which the removal of phosphorus is achieved by slag/metal reactions. That is, phosphorus dissolved in liquid steel is oxidized by iron oxide and then goes into molten slag. Generally, specific valorizing paths and processes are then needed to recycle such phosphorus-containing slag either internally to the steelmaking cycle or externally due to the environmental concerns and its underlying economic value. This topic, however, is not the focus of the present work, and thus we will not go into detail here. More details in this regard can be found in refs [2,3]. To date, extensive efforts have been reported in the literature to efficiently remove phosphorus in liquid steel in various ways. Each of these has its own merits. For example, a recent reported approach by Barui et al. [4] is to use data driven modeling techniques. From the thermodynamic perspective of dephosphorization, it has been generally acknowledged that high basicity (e.g.,

CaO/SiO₂) and high FeO content of molten slag are favorable for dephosphorization. In this regard, a rapid dissolution and slagging of lime charged into the furnace as a slag former is desired during steelmaking. For this purpose, the pneumatic lime or limestone injection from the top oxygen blowing lance during the BOF steelmaking process is one of the promising solutions to achieving high dephosphorization efficiency due to its advantage in promoting dissolution of lime, and has gained much interest in recent years.

Understanding the underlying hydrodynamics of oxygen-powder mixture jets during the lime powder blowing in BOF is one of the main industrial concerns since it is important to govern and design the process. Extensive efforts have been made in this direction. Okuda and Choi [5] measured the particle motion velocity and evaluated the effect of particle motion on gas stream for gas-particle mixture flow in various types of convergent-divergent nozzle. Rather than by experimental measurement, Peng et al. [6] and Hatta et al. [7] numerically studied the effect of parameters such as the design Mach number of the nozzle and powder particle size on the powder particle motion velocity within a Laval nozzle. Further, the erosion to the nozzle wall induced by particle motion was predicted by Hu et al., [8] and Li et al. [9]. More recently, Miyata et al. [10] and Li et al. [11,12] developed their mathematical models of supersonic gas-powder mixture jets, revealing the particle motion velocity and concentration distribution in the supersonic oxygen stream, as well as the effects on gas stream velocity distribution.

Instead of focusing on the hydrodynamics of the gas-particles mixture jet, Miyata et al. [13,14] carried out industrial trials to evaluate the thermodynamics and kinetics of dephosphorization when the lime powder was blown from the top oxygen lance during BOF steelmaking. They confirmed that this method was feasible for efficiently dephosphorizing. The authors reported that when the lime powder particles arrived at the molten bath surface, the FeO-CaO melt formed at a hot spot was capable of decreasing the phosphorus content of hot metal to an ultralow range even at the high temperature at the hot spot. Therefore, it can be said that the high iron oxide content at the hot spot is preferable for generating FeO-CaO melt and contributes to high dephosphorization efficiency. Early studies by Li et al. [15] demonstrated that a high iron oxide content in molten slag was obtained by employing a newly designed oxygen lance, named the nozzles-twisted oxygen lance [16]. The novel lance can generate swirling oxygen jets that have high tangential velocity; it not only creates a larger jet impacting area for the reaction between oxygen and liquid steel but also improves the dynamic conditions in the molten bath [15,17]. In this context, we proposed the limestone powder injection through a nozzles-twisted oxygen lance for dephosphorization during BOF steelmaking. It could be expected that this technology can create more beneficial conditions, such as high iron oxide content and intensive flow, for quickly-forming FeO-CaO melt at hot spots for dephosphorization. However, during the limestone powder blowing in such a process, what the motion behavior of the powder particles is and how the generated supersonic swirling oxygen stream of the novel lance influence the particle motion and distribution within the converter are not clear. This knowledge can provide a basis for designing the process parameters and driving further industrial application.

Therefore, this study presents an effort to modeling the limestone powder injection by a nozzles-twisted oxygen lance in a steelmaking BOF. Especial attention was paid to how the swirling oxygen stream of the lance influences the motion and distribution of the particles, so as to provide suggestions for the process design such as the novel lance parameters. To this end, a CFD model representing three-phase flow of oxygen gas, liquid steel and limestone powder during BOF steelmaking process was established by using the VOF method and DPM. With the help of the model, the design of nozzle twist angle for the novel lance was determined.

2. Mathematical Formulation

Prior to formulating the mathematical model, the following assumptions were made: (1) molten slag was ruled out and only liquid steel was considered; (2) oxygen gas was

regarded as a compressible ideal gas and followed the relation of $p = \rho RT$, while the liquid steel was regarded as an incompressible Newtonian fluid; (3) collisions of particle-particle and chemical reactions in BOF were neglected; (4) the interactions between the continuous phases (i.e., oxygen and liquid steel) and dispersed phase (i.e., powder particle) were two-way coupled, and (5) the heat transfer between the phases was neglected. The model is outlined below for completeness.

2.1. Governing Equations for Gaseous Oxygen and Liquid Steel Flow

The VOF model [18] is one of the prevalent approaches for modeling multiphase flows. In the model, phase volume fraction, wherein the sum of the volume fraction for all the phases in each cell is equal to one, is introduced for tracking the phase interface. A single set of governing equations was shared by all the phases and solved to determine the phase-shared field variables such as velocity and pressure. Therefore, the mass, momentum and energy equations for gaseous oxygen and liquid steel are as follows.

$$\frac{\partial(\rho_q \alpha_q)}{\partial t} + \nabla \cdot (\rho_q \alpha_q \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mu_{\text{eff}} [\nabla \mathbf{u} + (\nabla \mathbf{u})^T] + \rho \mathbf{g} + \mathbf{F}_\sigma + \mathbf{F} \quad (2)$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [\mathbf{u}(\rho E + p)] = \nabla \cdot (\lambda_{\text{eff}} \nabla T) \quad (3)$$

where α_q and ρ_q are the volume fraction and density of q th phase, respectively; $\mathbf{u}$ is the velocity vector; p is the pressure shared by all the phases; ρ is the volume-averaged density based on volume fraction of each phase in a cell; μ_{eff} is the effective viscosity, $\mu_{\text{eff}} = \mu + \mu_t$; μ and μ_t are molecular viscosity and turbulent viscosity, respectively; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{F}$ represents the momentum source induced by interactions of oxygen and liquid steel with limestone particles; $\mathbf{F}_\sigma$ is the surface tension and calculated by the continuum surface force model [19]. The energy E is treated as a mass-averaged variable; λ_{eff} is the effective thermal conductivity and shared by all the phases; T is the temperature.

The fluid turbulence was described by the standard k - ϵ model. The transportation equations for the turbulence kinetic energy (k) and the turbulence dissipation rate (ϵ) are expressed as follows.

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho k \mathbf{u}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \cdot \nabla k \right] + G_k + G_b - Y_k - \rho \epsilon \quad (4)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \epsilon \mathbf{u}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \cdot \nabla \epsilon \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (5)$$

$$\mu_t = C_\mu \rho \frac{k^2}{\epsilon} \quad (6)$$

where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients. G_b is the generation of turbulence kinetic energy due to buoyancy. Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. $C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$, σ_k , σ_ϵ and C_μ are model constants and their values are 1.44, 1.92, 0.8, 1.0, 1.3 and 0.9, respectively.

2.2. Equations for Particle Motion

The trajectories of the limestone particles are predicted by integrating the force balance acting on each individual particle in a Lagrangian reference frame using DPM. This force balance on a particle is written as follows.

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{u}_p \quad (7)$$

$$\frac{d\mathbf{u}_p}{dt} = \mathbf{F}_{\text{drag}} + \mathbf{F}_{\text{pressure}} + \mathbf{F}_{\text{mass}} + \mathbf{F}_{\text{gravity}} \quad (8)$$

where $\mathbf{x}_p$ is the position vector of the particles; $\mathbf{u}_p$ is the particle velocity vector; $\mathbf{F}_{\text{drag}}$, $\mathbf{F}_{\text{pressure}}$, $\mathbf{F}_{\text{mass}}$, and $\mathbf{F}_{\text{gravity}}$ represent drag force, pressure gradient force, virtual mass force, and buoyancy force, respectively. They are calculated as follows [20]

$$\mathbf{F}_{\text{drag}} = C_D \frac{\pi d_p^4}{4} \frac{\rho_g |\mathbf{u}_p - \mathbf{u}| (\mathbf{u}_p - \mathbf{u})}{2} \quad (9)$$

$$\mathbf{F}_{\text{pressure}} = \frac{\pi d_p^3}{6} \nabla p \quad (10)$$

$$\mathbf{F}_{\text{mass}} = C_v \frac{\pi d_p^3 \rho_g}{6} \frac{d(\mathbf{u}_p - \mathbf{u})}{dt} \quad (11)$$

$$\mathbf{F}_{\text{gravity}} = \frac{\pi d_p^3}{6} (\rho_p - \rho_g) \mathbf{g} \quad (12)$$

where d_p is particle diameter; C_v is the virtual mass force coefficient and is assumed to be 0.5 for a spherical particle; C_D is the drag coefficient and expressed as follows [20]

$$C_D = a_1 + \frac{a_2}{\text{Re}} + \frac{a_3}{\text{Re}} \quad (13)$$

where a_1 , a_2 , and a_3 are constants; Re is the Reynolds number of particle. In this turbulent flow system, the trajectories of the dispersed particles are influenced by the turbulent flow of the continuous phase. Consequently, the random walk model [21], which explains the stochastic effect of turbulent fluctuations on the particle motion, is invoked. In this model, the fluctuation of the particle velocity is estimated by a Gaussian distributed random number that is chosen according to the local turbulent kinetic energy. A new instantaneous velocity fluctuation is then produced by changing the random number at a frequency equal to the characteristic lifetime of turbulent eddy. The instantaneous velocity of the continuous phase is written as

$$\begin{aligned} \mathbf{u} &= \bar{\mathbf{u}} + \mathbf{u}' \\ \mathbf{u}' &= \zeta \sqrt{\overline{\mathbf{u}'^2}} = \zeta \sqrt{\frac{2k}{3}} \end{aligned} \quad (14)$$

where $\mathbf{u}'$ is the fluctuation velocity; $\bar{\mathbf{u}}$ is the time-averaged velocity; ζ is the Gaussian distributed random number.

2.3. Simulation Conditions

In this study, the process of limestone powder top blowing by a nozzles-twisted oxygen lance in a steelmaking BOF was simulated. Figure 1 illustrates the schematic diagram of this process and the reduced converter domain used for the simulations. The simulations were conducted against a 120-ton commercial BOF equipped with a 4-nozzles oxygen lance. The nozzle inclination angle of the oxygen lance was 14° . The lance height was fixed as 1300 mm in all the simulations. The molten bath depth was 1320 mm. The main parameters of the converter and the oxygen lance are listed in Table 1, in which the physical properties of each phase material are also included.

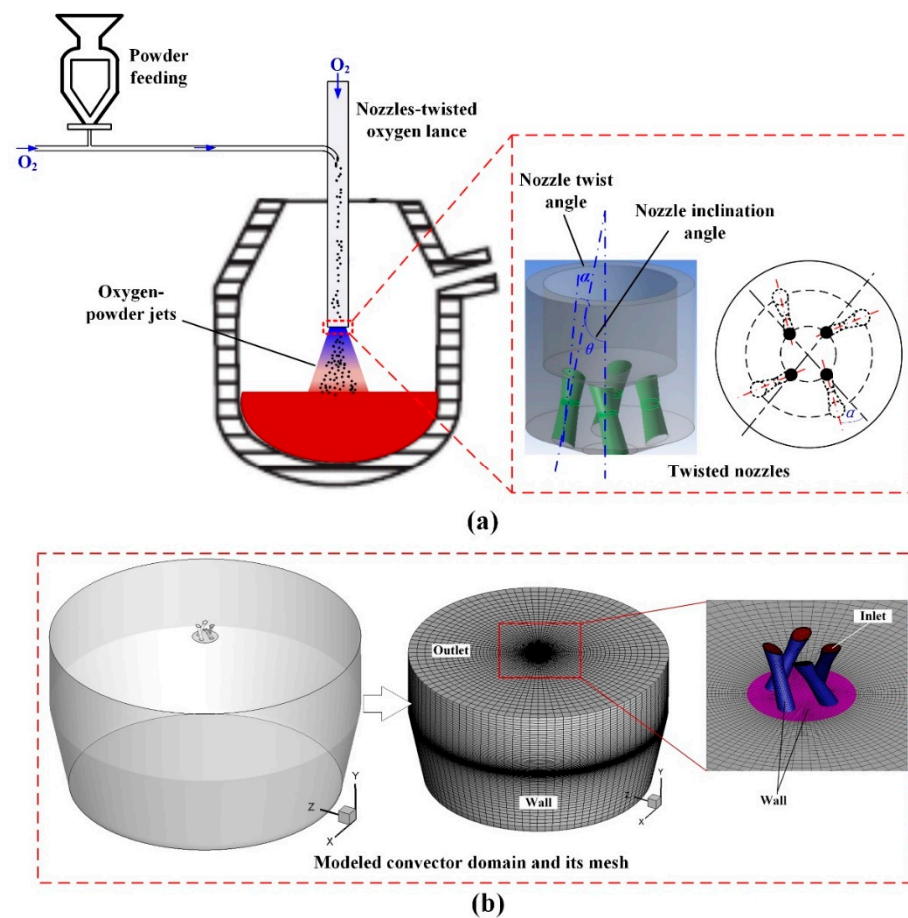


Figure 1. (a) Schematic diagram of flux powder top blowing by nozzles-twisted oxygen lance, and (b) reduced converter domain and its mesh for simulations.

Table 1. Geometric parameters of the converter and physical properties of materials.

Geometrical parameter	Nozzle throat diameter, mm		51.21
	Nozzle exit diameter, mm		66.54
	Nozzle number, -		4
	Nozzle inclination angle, °		14
	Mach number, -		2.0
	Bath diameter, mm		4870
	Bath depth, mm		1320
	Lance height, mm		1300
Physical properties	steel	limestone	oxygen
Density, kg/m ³	7000	2700	p/RT
Viscosity, Pa·s	0.005	-	1.19×10^{-5}
Surface tension, N/m	1.6	-	-
Heat capacity, J/(kg·K)	670	590	919.31
Conductivity, W/(m·K)	40	1.16	0.0246
Temperature, K	1873	300	-

2.4. Numerical Solution Strategies

Table 2 lists the boundary conditions used for the simulations. A pressure boundary condition was used at the outlet, where the gauge pressure was set to zero while the local atmospheric pressure was set to 0.1 MPa. A pressure boundary condition was applied to the nozzle inlets with the oxygen pressure of 0.8 MPa. The oxygen temperature at the

nozzle inlets is 300 K. A no-slip wall condition with the standard wall function was used to model the velocity near the wall.

Table 2. Boundary conditions and parameters for simulations.

Conditions	Value
Oxygen temperature at nozzle inlets, K	300
Oxygen pressure at nozzle inlets, MPa	0.8
Pressure at outlet, MPa	0.1
Particle temperature, K	300
Powder feeding rate, kg/s	2.0
Particle diameter, μm	425
Nozzle twist angle, $^{\circ}$	0, 10, 20, 30

The pressure-velocity decoupling was achieved using the SIMPLE algorithms. The PRESTO scheme was employed to interpolate the pressure values at the cell faces from the surrounding cell nodes in the solution of the momentum equations. Additionally, the geometric reconstruction was used to track the free surface deformation. The second-order upwind scheme was employed for the discretization of the mass, momentum, and energy conservative equations. The convergence condition of the simulated solution is that the residual of energy was smaller than 10^{-6} , and the residual of other dependent variables were smaller than 10^{-4} .

In order to ensure the stability of solution, firstly a steady calculation for the oxygen-steel two-phase flow was accomplished using the VOF method. After obtaining a steady gas-liquid flow field, the limestone powder was injected at the nozzle inlets, and simultaneously transient calculation was enabled with a fixed flow time step size of 5×10^{-5} s and a particle time step size of 2×10^{-4} s. In order to reduce the computational cost induced by the accumulation of particles inside the furnace, when the tracking time of the particles was over 0.1 s the calculation for these particles stopped. As shown in Table 2, the nozzle twist angle of the oxygen lance was varied to evaluate its influence on the motion behavior and distribution of powder particle in the molten bath, so as to provide suggestions for optimizing the lance design.

2.5. Model Applicability

It is necessary to verify the validity of the mathematical model before applying it to numerical experiments, but it is difficult to perform trials on a commercial BOF because of extremely harsh environmental conditions. This case is especially true for the present process. In this process, most of the hydromechanics phenomena generated in the furnace, such as the motion and distribution of the powder particles, were driven by oxygen jetting of the top lance and were dominated by the coupled flow of oxygen-liquid steel. Therefore, reasonably predicting the main phenomena related to the coupled flow of the oxygen-liquid steel is vital for verifying the model applicability. The present model included a main model accounting for the coupled oxygen-liquid steel flow in BOF operated with a nozzles-twisted oxygen lance, and a sub-model accounting for the motion of the particles in the coupled flow field. For the main model, the validation was done in an earlier study [15], where the predicted key parameters such as jets penetration depth and jets impinging width were compared with experimental measurements, and reasonable agreement was obtained. Thus the present model could successfully be used to reproduce the key phenomena associated with the powder injection by the nozzles-twisted oxygen lance in BOF, at least qualitatively.

3. Results and Discussion

3.1. Impacting Characteristics of Swirling Oxygen-Powder Mixture Jets

Figure 2 shows the evolution of the molten bath surface profile with the blowing time as the oxygen-powder mixture is blown from the oxygen lance with the different nozzle twist angles. Note that (Figure 2a) the surface profile at the time of $t = 0$ s is created

by the oxygen jets without limestone powder injection, and the nozzle twist angle of 0° represents the conventional oxygen lance. Obviously, the surface profile is in an extremely unstable state. This can be attributed to the instability of the oxygen-powder mixture jets that are influenced by the stochastic motion of the powder particles. The flow at the bath surface induced by the oxygen-powder mixture jets of the nozzles-twisted oxygen lance is weak compared with that of the conventional oxygen lance, and this becomes increasingly obvious when the nozzle twist angle of the nozzles-twisted lance is increased. When the oxygen-powder mixture jets strike onto the steel level, one or several cavities are created, depending on the distance between each individual jet. The shape and distribution of the cavities are, to some extent, related to the contact area of oxygen and steel in the BOF. Figure 3 shows the shape and distribution of the cavities created by the oxygen-powder mixture jets. As can be seen, the distribution of the cavities created by the oxygen-powder mixture jets of the nozzles-twisted lance is scattered compared with that of the conventional oxygen lance. This is especially true when the nozzle twist angle is large; each individual jet of the swirling jets generated by the nozzles-twisted oxygen lance has a larger space relative to each other than that of the conventional oxygen lance because the nozzles are twisted [15–17]. It is also found that there seems to be little effect of the powder injection on the molten bath surface profile and the cavity distribution.

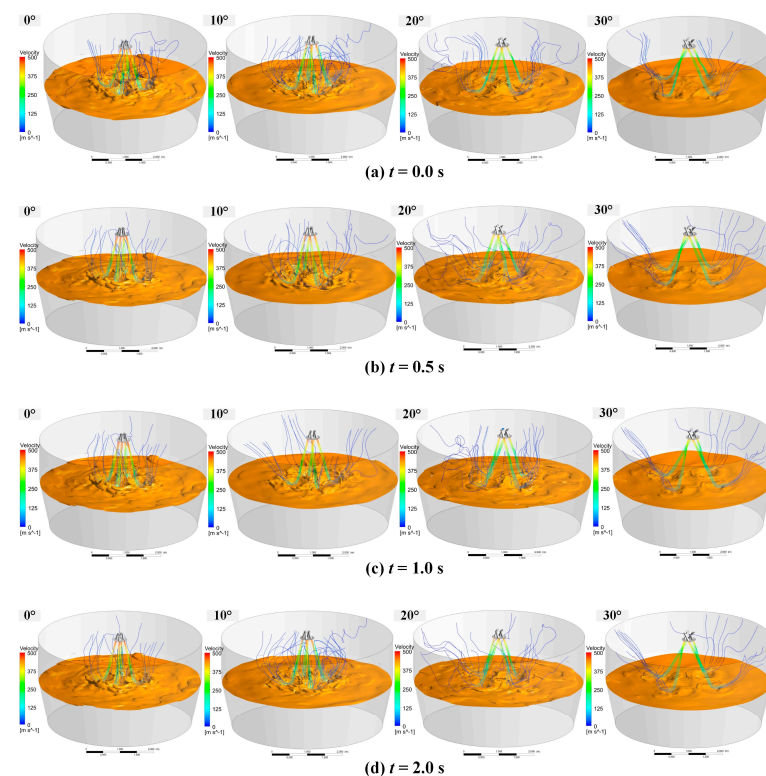


Figure 2. Molten bath surface profile created by swirling oxygen-powder mixture jets at the different nozzle twist angles and at the moments of (a) 0 s, (b) 0.5 s, (c) 1.0 s, and (d) 2.0 s.

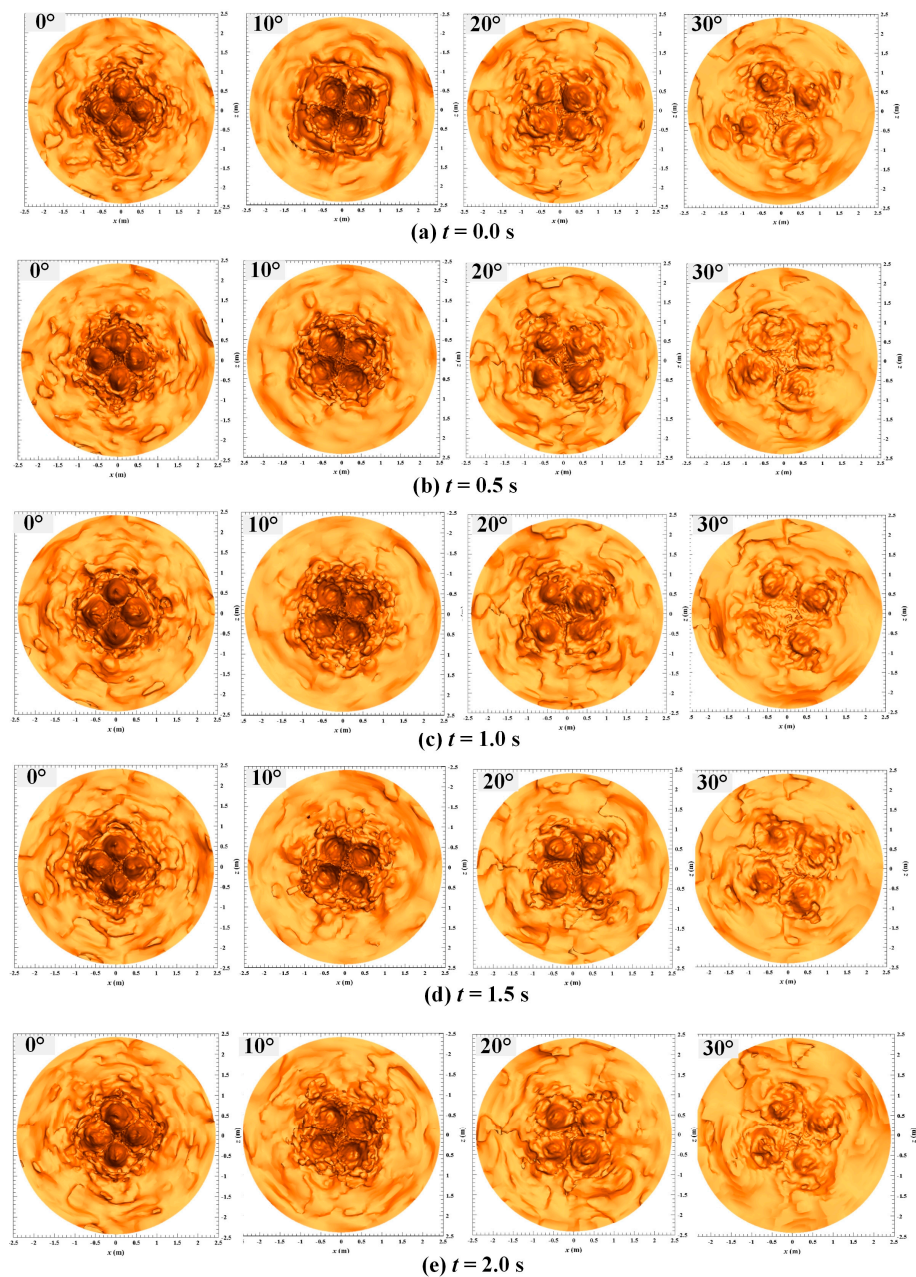


Figure 3. Cavity profile impinged by swirling oxygen-powder mixture jets at the different nozzle twist angles and at the moments of (a) 0 s, (b) 0.5 s, (c) 1.0 s, (d) 1.5 s, and (e) 2.0 s.

3.2. Penetration of Oxygen-Powder Mixture Jets

The penetration into the molten bath of the oxygen-powder mixture jets was investigated. Figure 4 shows the snapshots of the cavity depth profile created by the oxygen-powder mixture jets of the oxygen lance with different nozzle twist angles. It can be seen that regardless of the limestone powder injection or not, the nozzles-twisted oxygen lance jets create shallower cavities than those of the conventional oxygen lance jets. This phenomenon becomes increasingly obvious when gradually increasing the nozzle twist angle. This can be explained by the fact that the nozzles-twisted oxygen lance jets have a smaller impacting force normal to the molten bath surface than that of the conventional ones. It can be also found that the limestone powder top blowing in BOF influences the cavity depth to some extent. Specifically, a sharp cusp is created at the bottom of the cavity by the oxygen-powder mixture jets, whereas no distinct cusp is found for the oxygen jets without limestone injection. This case is especially true for the conventional oxygen lance, but it be-

comes less obvious for the nozzles-twisted oxygen lance. The reason for this phenomenon may be explained as follows. For the conventional oxygen lance, the axial velocity of the oxygen stream is relatively high, and therefore the powder particles are carried by the high velocity oxygen stream to mainly gather around the center of the oxygen stream. Abundant powder particles are wrapped in the center of the oxygen stream and result in the formation of a cusp at the bottom of the cavity when the oxygen-powder mixture jets penetrate into the molten bath. For the nozzles-twisted oxygen lance, however, a swirling oxygen stream is generated, and the stream has higher tangential velocity and smaller axial velocity than that of the stream from a conventional oxygen lance. The tangential velocity increases with the increase of the nozzle twist angle. As a result, the powder particles are easily driven to move and spread towards the radial direction of the furnace by the high tangential velocity. Thus, the distribution of the powder particles in the oxygen stream is dispersive, and the concentration of the powder particles in the oxygen stream center decreases, which leads to the vanishing of the cusp.

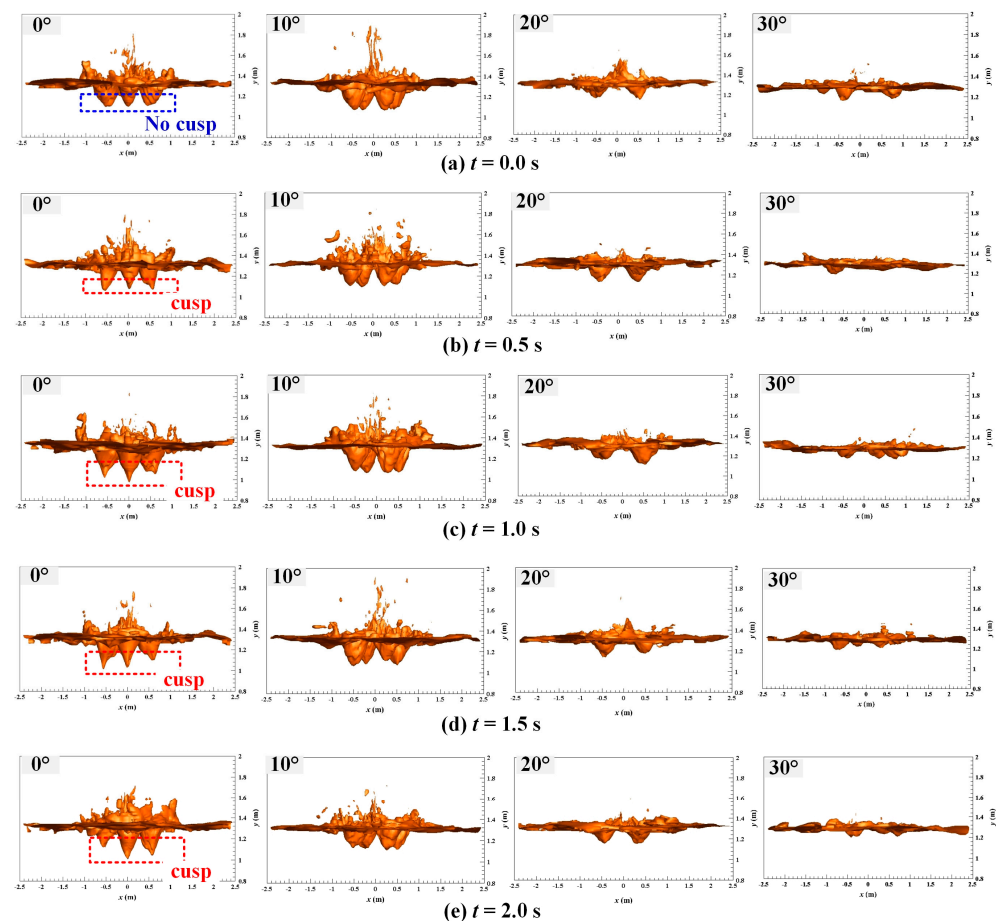


Figure 4. Cavity depth created by oxygen-powder mixture jets at the different nozzle twist angles and at the moments of (a) 0 s, (b) 0.5 s, (c) 1.0 s, (d) 1.5 s, and (e) 2.0 s.

Further, the cavity depth and the cavity width created by the oxygen-powder mixture jets of the oxygen lance with the different nozzle twist angles are quantified in Figures 5 and 6. Notably, since the cavity profile is unsteady, as mentioned earlier, the cavity depth and the cavity width are determined based on the time-averaged values at the different blowing moments. It can be seen from Figure 5 that the cavity depth decreases when increasing the nozzle twist angle. For the conventional oxygen lance, the cavity of the oxygen-powder mixture jets is deeper than that of the oxygen jets without the limestone powder injection. This is because that the powder particles create a sharp cusp at the

cavity bottom, as demonstrated in Figure 4. However, for the nozzles-twisted oxygen lance, the cavity depth seems to be affected little by the powder injection. The reason could be that the high tangential velocity of the swirling oxygen stream drives the powder particles to move towards the periphery of the oxygen stream, which thus decreases the penetration of the oxygen-powder mixture jets. As for the cavity width, it can be seen from Figure 6 that the cavity width of the oxygen-powder mixture jets is smaller than that of the oxygen jets without the limestone powder injection. This means that the powder particles limit the radial expansion of the oxygen stream. Nevertheless, the cavity width of the oxygen-powder mixture jets can be increased by increasing the nozzle twist angle.

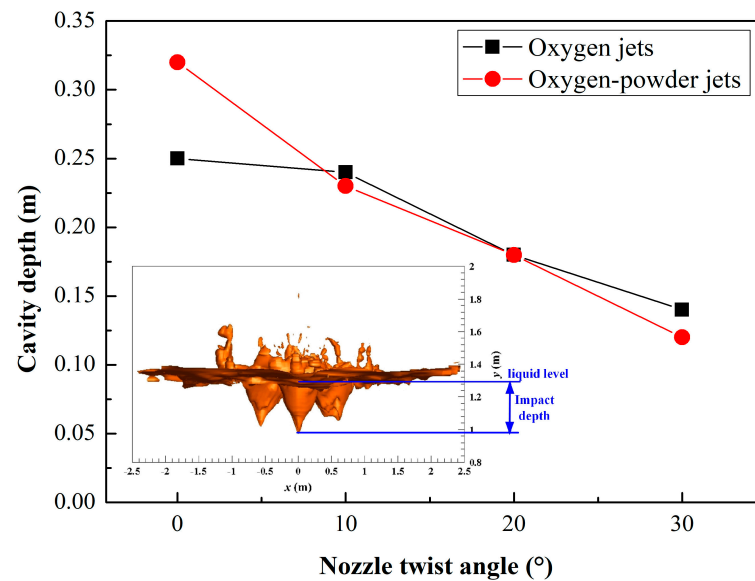


Figure 5. Cavity depth created by oxygen-powder mixture jets at the different nozzle twist angles.

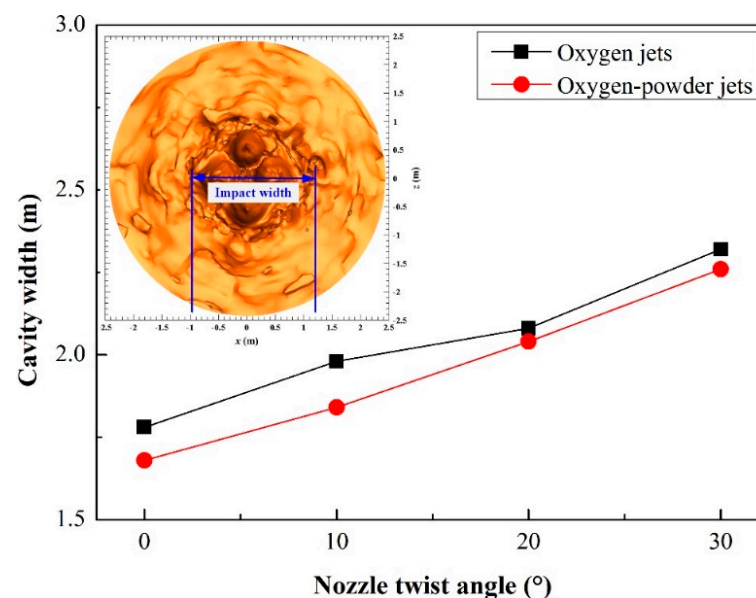


Figure 6. Cavity width created by oxygen-powder mixture jets at the different nozzle twist angles.

3.3. Motion Behavior of Powder Particles in Converter

Figure 7 shows the motion behavior of the powder particles in the converter after they are released from the oxygen lance with the different nozzle twist angles. It can be seen from the figure that at the blowing moment of $t = 0.1$ s, the powder particles are delivered

to the molten bath by the oxygen stream. Most of the particles concentrate on the cavity, while the rest are taken out of the furnace by the reflecting stream or penetrate into the molten bath. Then the concentration of the powder particles gathering around the cavity increases gradually with the continuous blowing of the powder. This case is also true for the powder particles taken out by the reflecting stream, which leads to the loss of the powder. However, during a practical BOF steelmaking process, the foaming slag fills in the upper space of the furnace, and can prevent the powder particles from being taken out from the furnace by the reflective stream and thus reduce the loss of the powder. Furthermore, it is also observed that compared with the limestone powder injection using the conventional oxygen lance, the distribution range of the powder particles on the molten bath surface is larger than that using the nozzles-twisted lance. The reason could be explained as follows. For the nozzles-twisted oxygen lance, the axial velocity of the oxygen-powder mixture jets is smaller and the cavity created by the jets is shallower. As a result, the velocities of the reflecting stream as well as the reflection angle between the reflecting stream and the horizontal plane are smaller, which causes the decrease of the powder loss caused by the reflecting stream. Moreover, the large tangential velocity of the nozzles-twisted oxygen lance jets can drive the powder particles to disperse easily and lead to large distribution range of the powder particles inside the molten bath.

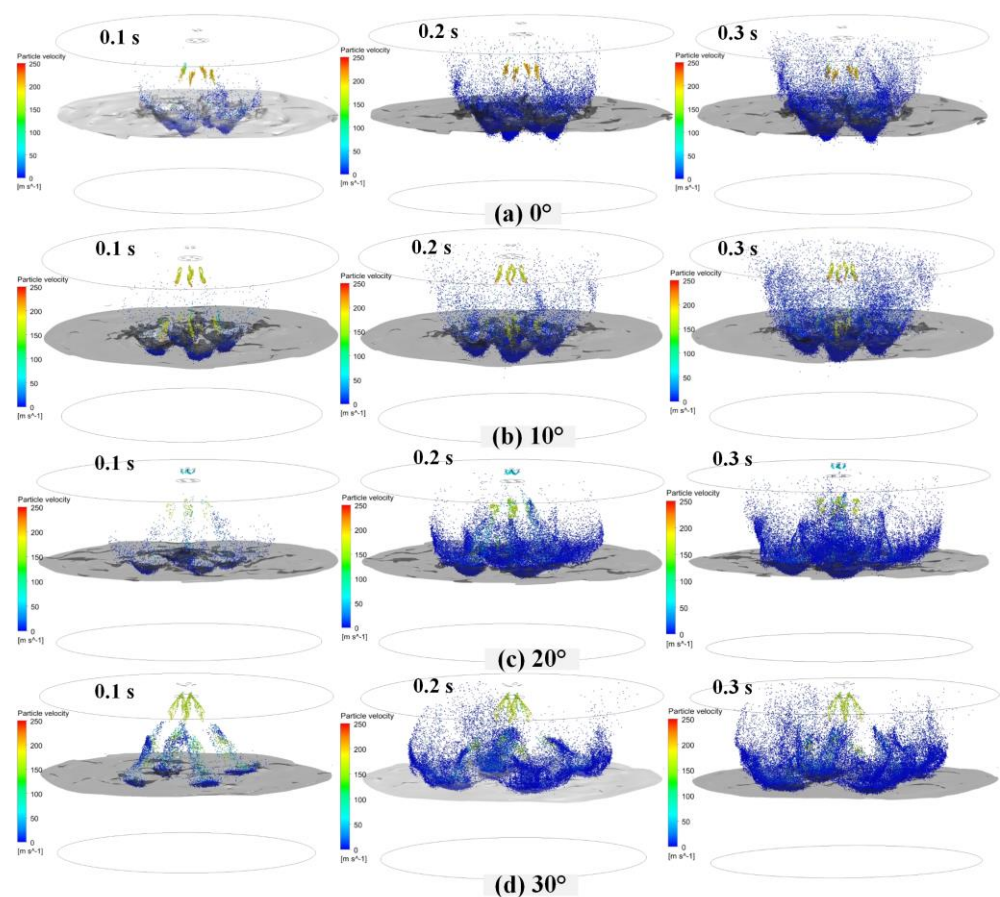


Figure 7. Motion of the powder particles in BOF at the different moments and at the nozzle twist angles of (a) 0° , (b) 10° , (c) 20° , and (d) 30° .

3.4. Distribution of Powder Particles in Converter

In order to further evaluate the concentration distribution of the powder particles inside the molten bath, Figure 8 shows the concentration distribution of the powder particles at the different molten bath depth levels when the nozzle twist angle is varied. The molten bath depth here is defined as the distance to the molten bath surface. The cavity depths of

the oxygen-powder mixture jets at the nozzle twist angle of 0° , 10° , 20° , and 30° are 0.32 m, 0.23 m, 0.18 m, and 0.12 m, respectively, as shown in Figure 5. It can be seen that with the powder injection using the conventional oxygen lance, the powder particles go into the molten bath to a depth of 0.52 m, while a smaller penetration depth of the powder particles is observed for the nozzles-twisted oxygen lance. Further, Figure 9 plots the variation of the average concentration of the powder particles with the molten bath depth. As can be seen, the powder concentration at the cavity for the nozzles-twisted oxygen lance is higher than that of the conventional oxygen lance, and the maximum powder concentration is obtained at the nozzle twist angle of 10° . Since there are high temperature and FeO concentration at the cavity, the limestone particles there are well placed for forming FeO-CaO melt for dephosphorization. In view of this, the preferred nozzle twist angle is 10° for limestone powder top blowing by the nozzles-twist oxygen lance in BOF steelmaking.

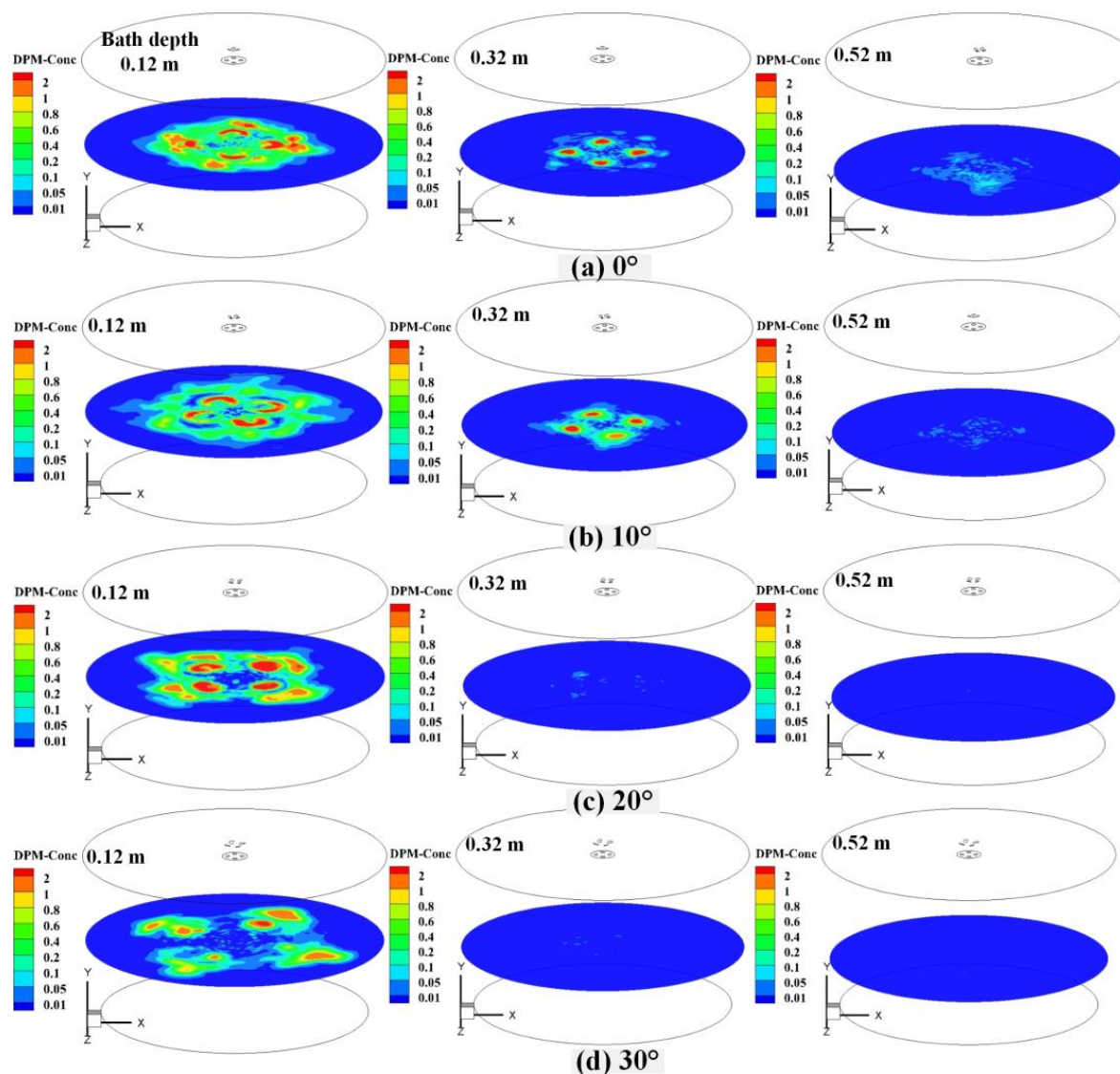


Figure 8. Particles concentration distribution on the different molten bath depth levels at the different moments and at the nozzle twist angles of (a) 0° , (b) 10° , (c) 20° , and (d) 30° .

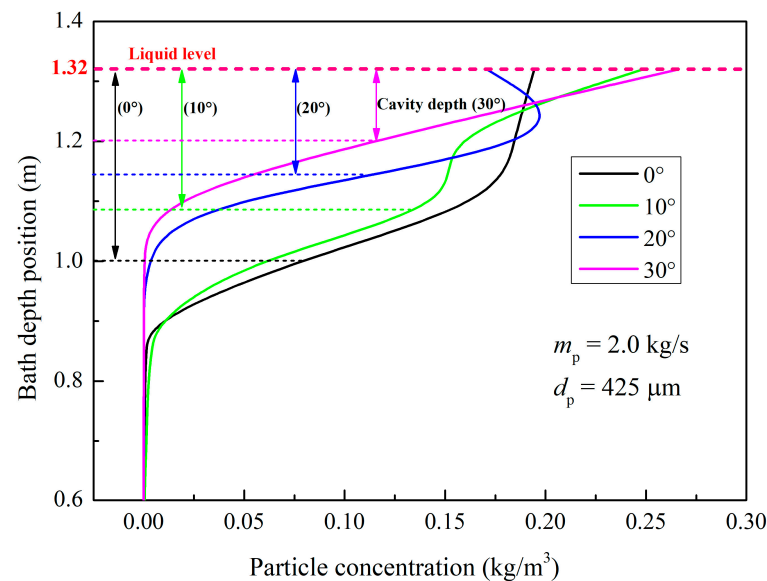


Figure 9. Particles concentration at the different molten bath depth levels for the different nozzle twist angles.

4. Remarks and Outlook

In this study, a VOF-DPM model accounting for the coupled flow of gas, liquid and solid phases was established to evaluate the limestone powder injection by a novel nozzles-twisted oxygen lance in BOF steelmaking. The penetration into the molten bath of the oxygen-powder mixture jets and the motion and distribution of the powder particles at the varied lance design were discussed. The conclusions can be summarized as follows.

- (1) Limestone powder injection by the conventional oxygen lance creates a sharp cusp at the cavity bottom and thus deepens the cavity, whereas no distinct cusp is created for the case without limestone injection. The cavity depth is affected little by the powder injection through the nozzles-twisted oxygen lance. The cavity width is reduced due to the powder injection. Increasing the nozzle twist angle decreases the cavity depth but increases the cavity width.
- (2) Most of the powder particles gather around the cavity while the rest are taken out of the furnace by the reflecting stream or penetrate into the molten bath. The swirling flow generated by the nozzles-twisted oxygen lance decreases the concentration of the powder particles taken by the reflecting stream and increases penetration into the molten bath by changing the motion paths of the powder particles.
- (3) Limestone powder injection through the nozzles-twist oxygen lance enables an increase in the concentration of the powder particles around the cavity, which favors the formation of FeO-CaO melt and thus dephosphorization. The preferred nozzle twist angle of the oxygen lance for this process could be 10°.

This work represents our effort to explore the process of efficient dephosphorization by proposing the limestone powder injection using a novel nozzles-twisted oxygen lance during a BOF steelmaking process. The present study is the first step to understand such a new process, and much more work is necessary, such as to determine the suitable powder feeding rate and powder particle size. In addition, industrial test or small-scale trials are needed to further evaluate the effectiveness of the process by understanding the fundamentals of the thermodynamics and kinetics of limestone slagging and dephosphorization. These are expected to be reported soon.

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