Mixing characteristics of additives in viscous liquid BOF slag

Yannan Wang, Lingling Cao, Zhongfu Cheng, Bart Blanpain, Muxing Guo

Department of Materials Engineering, KU Leuven, 3000 Leuven, Belgium.

Abstract

In order to understand better the mixing behavior of compositional modifiers of BOF slag in the hot stage slag engineering process, the Volume of Fluid (VOF) method coupled with the Large Eddy Simulation (LES) is adopted to simulate the gas-liquid slag two-phase turbulent flow. The Discrete Phase Model (DPM) is used to track the migration of the solid additive particle during the mixing. Area fraction of the particle migration zone is calculated to quantify the mixing process. The results show that increasing gas flow rate and/or submerged lance depth can reduce the relatively quiescent region at the bottom of the slag pot, shortening the mixing process. Influence of the submerged lance depth is more significant than other process parameters on the particle mixing process. The input energy flux can be used as a measure to quantitatively evaluate the mixing behavior. Besides, increasing the slag viscosity prolongs the mixing process. Particle size has little influence on the particle migration. This work provides references for the industrial operators to optimize the hot stage slag engineering process by properly selecting the operational conditions.

Keywords: hot stage engineering, mixing behavior, VOF-LES-DPM, operational parameters, input energy flux.

Nomenclature

a_1, a_2, a_3	constants in drag coefficient for spherical particle.
A	cross-section area of lance, m^2 .
A_p	area of the particle migration zone, m^2 .
A_s	area of the slag phase in the slag pot, m^2 .
C_d	drag coefficient.
C_s	model constant in LES-DSL model.
C_{VM}	virtual mass factor, 0.5.
d_{ij}, d_{kl}, d_{lk}	deformation tensor, s^{-1} .
d_p	particle diameter, mm.
E_{In}	input energy flux accompanied with the gas phase, $\text{kJ}/(\text{m}^2 \cdot \text{s})$.
E_{ke}	power input from gas kinetic energy, W.
F_{int}	interphase force, N.
F_D	drag force, N.
F_L	lift force, N.
F_{VM}	virtual mass force, N.
g	gravitational acceleration, m/s^2 .
k	constant coefficient in lift force, 2.594.

K	curvature, 1/m.
l	submerged lance depth, m.
l_s	characteristics length of the system, m.
m	particle mass, kg.
$\dot{n}$	molar flowrate, mol/s.
p	pressure, Pa.
p_a	atmosphere pressure, Pa.
Q_a	gas flowrate at P_a and slag temperature, m ³ /s.
Q_g	injected gas flow rate, Nm ³ /s.
R	gas constant, 8.314 J/(mol·K).
Re	Reynolds number.
S	source term in the momentum equation.
St	Stokes number.
t	time, s.
T	particle migration time, s.
T_{in}	temperature of the gas phase entering the slag pot, K.
T_s	slag temperature, K.
u	velocity, m/s.
v	particle velocity, m/s.
v_s	characteristic velocity of the system, m/s.
V_p	particle volume, mm ³ .
Greek symbols	
α	phase volume fraction.
β	particle loading ratio.
η_1	conversion efficiency of the gas kinetic power.
η_2	conversion efficiency of the gas buoyancy power due to heating.
μ	dynamic viscosity of the fluid, Pa·s.
ν	kinematic viscosity of the fluid, m ² /s.
ρ	density, kg/m ³ .
σ	surface tension coefficient.
$\bar{\tau}$	stress tensor, N/m ² .
Φ	area fraction of the particle migration zone, %.

Subscripts

g	gas phase.
l	liquid slag phase.
p	solid particle phase.

1 Introduction

The BOF slag is conventionally disposed through landfill/dumping, leading to land occupation, environmental impact and a waste of material resource [1, 2]. In order to solve these problems, considerable efforts to reuse BOF slag have been made in the last decades [2-4]. However, the application of BOF slag is restricted by its volume expansion during natural aging due to the presence of free lime [5, 6].

For the purpose of BOF slag valorisation, different hot stage engineering processes have been proposed [7-11]. Jingye Engineering in China developed the pyrolytic self-slaking process [7], where molten BOF slag is poured into a tank with a cover, followed by spraying water into the tank. Water stream is generated and then reacts with the free lime in the BOF slag. After this treatment, the free lime is fully slaked [8] and more than 60% of the slag grains are smaller than 10 mm, which is easy to be separated or grounded further and the steel entrapped in the slag can be recovered with a high yield. Apart from this process, the drum-granulation process [7, 8] and the Baosteel's Slag Short Flow (BSSF) [7, 8] process can also effectively stabilize the free lime by water or water steam. After metal recovery, the stabilized BOF slag is applied as building materials. Most of the industrial processes stabilize the slag only through cooling control (water and/or air granulation) and the processes only aim at the free lime stabilization. No one is available for the high-added value applications (*e.g.*, hydraulic and cementitious binders) through slag chemistry modification. To this end, the FEhS institute developed and implemented a process, where silica-rich additives are injected into the liquid BOF slag with nitrogen or oxygen as a carrier gas through a top submerged lance for the free lime stabilization and the microstructure/mineralogy control towards high-added value products [9-11]. In this hot stage slag engineering process, fast mixing of the additives is desired for their rapid dissolution into slag, allowing sufficient time for the modifiers to react with the other components in the slag, for instance with free CaO and MgO. Understanding the mixing behavior of the slag modifiers/additives is critically important to optimize the hot stage slag engineering process.

Due to difficulties of high temperature experiments (*e.g.*, opacity of a slag pot, hazardous operating environment, lack of velocity measuring techniques at high temperature) and the complex gas-liquid-solid multiphase flow, physical modelling [12-14] and numerical simulation [13-15] have been performed to understand the mixing behavior in high temperature processes such as ladle metallurgy. The mixing time is measured through the electrical conductivity of the aqueous solution by injecting conductive tracers (*e.g.*, NaCl/KCl solution or acid solution) in the physical modelling, or calculated by solving the species transport equation for a numerical tracer in numerical simulation. The mixing behavior obtained by the two methods is represented in the stage after the additive dissolution. The additive mixing behavior in the stage before the dissolution has not been studied. In the present work, the Discrete Phase Model (DPM) is used to account for the additive migration behavior thanks to the successes achieved by DPM in the gas-liquid and solid-gas/liquid systems [16-18]. The Volume of Fluids (VOF) model is used for the gas-liquid two-phase flow simulation because of its robustness in capturing the transient interfaces of large gas bubbles or a gas jet formed during the top lance injection [19]. According to the results of previous model validations [20, 21], the Large Eddy Simulation with Dynamic Smagorinsky-Lilly subgrid-scale model (LES-DSL) is adopted for the turbulence simulation.

The objective of this paper is to develop a numerical approach with VOF-DPM-LES to study the migration of solid additives without considering the additive dissolution, which can help industrial

operators to understand the effect of the operational factors, *e.g.*, lance depth and gas flow rate, on the mixing behavior of the additives, and therefore to optimize the hot stage engineering process.

2 Numerical model

VOF

In the VOF model, the gas volume fraction α_g is introduced, where α_g is unity when the cell is full of the gas phase; α_g is zero when the cell is entirely occupied by the liquid phase; α_g is between zero and unity when the cell contains the gas-liquid interface. The interface position is tracked by solving the α_g continuity equation (see Equation (1)). The geometric reconstruction scheme developed by Youngs [22] is adopted for this calculation. This scheme assumes that the interface has a linear slope within each cell, and the linear slope is used to calculate the face fluxes. The volume fraction in each cell is obtained by calculating the consequent face fluxes. The scheme is considered to be accurate due to small numerical diffusion [23, 24]. The volume fraction of the liquid slag phase is computed under the constraint given in Equation (2). In the VOF model variables are shared by all phases, only one set of momentum equations is solved in Equation (3). Since the bubble behavior and the liquid surface distortion are affected by surface tension of the liquid, the surface tension force is simulated based on the Continuum Surface Force (CSF) model developed by Brackbill *et al.* [25]. The surface tension force is expressed in Equation (4). The interphase forces between the dispersed solid particle and the continuous phase, *i.e.*, the drag force, lift force and virtual mass force, are described in the following section.

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \vec{u}) = 0 \quad (1)$$

$$\alpha_l = 1 - \alpha_g \quad (2)$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \bar{\tau} + \rho \vec{g} + \vec{F}_{csf} + \vec{F}_{int} + S \quad (3)$$

$$\vec{F}_{csf} = \sigma K \nabla \alpha \quad (4)$$

DPM

Dissolution of the solid particle is not considered in this work due to difficulties/complexities to build a fully realistic model, which can simultaneously involve the velocity field, temperature field, particle movement and the dissolution of all the injected particles. The latter is approximately 4×10^6 - 2.4×10^7 per minute with the particle diameter of 2 mm and mass flow rate of 50-300 kg/min. The global particle loading defined in Equation (5) ranges from 0.02 to 0.1. However, the local value can be considerably increased especially at the lance inlet region when the particles are injected into the slag pot at the beginning. Two-way coupling method is adopted in the present calculations as shown in Figure 1: 1) Governing equations of the continuous phase is solved to obtain field variables such as the flow velocity; 2) Particle trajectory is calculated based on the obtained flow variables; 3) The continuous phase is recalculated by using the interphase exchange during the previous particle calculation; 4) The particle trajectory is updated in the modified continuous phase flow field; 5) The above-mentioned two steps are repeated until a converged solution is achieved in which both the continuous phase flow field and the discrete phase particle trajectory are unchanged.. Due to computationally unaffordable to track the motion of all the particles even at a very low particle loading, only a representative set of particles are considered in this work. It is postulated that each simulated particle represents a large number of identical particles at the same location as the tracked particle [26]. In this way, the number of the simulated particles is reduced to a few hundred thousand in a 2D simulation and a few million in a 3D simulation. The disadvantage of this method is that the effect of the discrete phase on the continuous phase is reduced. This disadvantage can be alleviated by incorporating the momentum of particles injected at real mass flowrate (*i.e.*, 50-300 kg/min) into the source term S (see Equation (3)). The

particle Stokes number St , which is defined as the ratio of particle response time to system response time (see Equation (6)), ranges from 0.003 to 0.28 in this work. $St < 1$ indicates that the particles closely follow the slag flow. The drag force, lift force and virtual mass force are considered in the Newton's second law for simulating the particle migration. The mathematical expressions are given in Equations (7)-(13).

Figure 1 Flow chart of the two-way coupling method.

$$\beta = \frac{\alpha_p \rho_p}{\alpha_l \rho_l} \quad (5)$$

$$St = \frac{\rho_p d_p^2 v_s}{18 \mu_l l_s} \quad (6)$$

$$m \frac{d\vec{v}}{dt} = \vec{F}_D + \vec{F}_{VM} + \vec{F}_L \quad (7)$$

$$\vec{F}_D = \frac{3C_d \mu_l Re V_p (\vec{u} - \vec{v})}{4d_p^2} \quad (8)$$

where

$$Re = \frac{\rho_l d_p |\vec{u} - \vec{v}|}{\mu_l} \quad (9)$$

$$C_d = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \quad (10)$$

$$\vec{F}_{VM} = C_{VM} V_p \left(\vec{v} \nabla \vec{u} - \frac{d\vec{v}}{dt} \right) \quad (11)$$

$$\vec{F}_L = \frac{2k\nu^{0.5} V_p \rho_l d_{ij} (\vec{u} - \vec{v})}{d_p (d_{lk} d_{kl})^{0.25}} \quad (12)$$

$$\frac{dx}{dt} = \vec{v} \quad (13)$$

LES-DSL

Unlike the Reynolds Averaged Navier-Stokes (RANS) model, the instantaneous Navier-Stokes equations are subjected to a filtered operation in the LES model, where grid scale and subgrid scale components are obtained. The grid scale component is resolved directly, and the subgrid scale component is modelled by the established subgrid-scale model. In this work, the DSL subgrid-scale

model proposed by Germano *et al.* [27] and Lilly [28] is adopted, where the model constant C_s is dynamically calculated by using a second filter to avoid specifying C_s in advance.

Numerical setup

The simulation is performed by using the commercial software package ANSYS FLUENT 16.2. The geometrical dimensions, operational parameters and materials properties used in the numerical calculations are listed in Table 1. The injected silica-rich additive has a close density to the molten BOF slag (*i.e.*, 3000 kg/m³). In order to simplify the simulation, the density of 3000 kg/m³, which is the same as the density of the BOF slag, is adopted for the additive particle in this work. Geometry of the slag pot is depicted in Figure 2. The whole domain is patched by two zones, *i.e.*, the gas zone and the liquid zone. The boundary between the two zones is set as an interface. The remaining boundary conditions, *i.e.*, velocity inlet, pressure outlet and wall, are also indicated in Figure 2. Structured meshes are established by ICEM software in the computational domain. Approximately 32500 quadrilateral cells are structured with a grid size from 2.5 mm to 20 mm in the 2D simulation, and approximately 481000 hexahedral cells are structured with the grid size from 3 mm to 80 mm in the 3D simulation (see Figure 3). The particles are injected from the inlet at the same initial velocity with the carrier gas phase. It is assumed that the particle can escape from the outlet of the computational domain, which is reflected by the lance wall and trapped at the side and bottom walls of the slag pot.

Table 1 Geometrical dimensions, operational parameters and material properties used in the simulations.

Top diameter of the slag pot, m	3.36
Bottom diameter of the slag pot, m	2.39
Height of the slag pot, m	3.558
Lance diameter of the slag pot, m	0.04
Height of slag level, m	3.0
Submerged lance depth, m	0.3, 0.65, 1.0
Gas flow rate, Nm ³ /s	0.025-0.05
Pressure, kPa	300
Density of slag, kg/m ³	3000
Viscosity of slag, Pa·s	0.1, 1.0
Gas density, kg/m ³	0.574 [♦]
Gas viscosity, Pa·s	5.87×10^{-5} [*]
Interfacial tension of slag/air, N/m	0.55
Particle diameter, mm	0.3, 1.0, 2.0
Density of the additive particle, kg/m ³	3000

“♦” and “*” indicate the values calculated by the ideal gas law and Sutherland’s law [29], respectively.

Figure 2 Geometry of the slag pot and the boundary conditions in the simulation.

Figure 3 3D mesh (left) and 2D mesh (right) of the computational domain.

The Semi-Implicit Method for Pressure-Linked Equations - Consistent (SIMPLEC) scheme [30] is adopted to solve the velocity-pressure coupling equation. The pressure and momentum equations are spatially discretized by the PREssure STaggering Option (PRESTO!) and the bounded central differencing schemes, respectively. Convergence of the continuous phase is determined by monitoring the unscaled residual of the continuity equation. It is considered that a sufficient accuracy is achieved when the residual of the continuity equation drops at least 3 orders of magnitude. The convergence criterion is 1×10^{-7} . The time step is 1×10^{-5} s, and the global Courant number is 0.65.

3 Results and discussion

Calculation of the particle migration zone

Area fraction of the particle migration zone Φ (see Equation (14)) is used to measure the particle mixing behavior in this work. In order to quantify this value, a boundary of the particle migration zone needs to be determined firstly (see Figure 4). By selecting an appropriate range of the particle concentration, the boundary of the particle migration zone can be clearly figured out. For a reliable determination of the boundary, the boundary profile must be steady and cannot be changed with further reducing the particle concentration. In this work, a particle concentration of 1×10^{-7} kg/m³ is chosen to determine the boundary profile. The obtained boundary profile (see the green line in Figure 4) matches the boundary of the particle migration zone filled by the red-colored particles. Based on the profile, coordinates of n points on the determined boundary are measured by using Image Pro Plus software. n ranges from 10 to 15 in this work, depending on the smoothness and clearness of the boundary profile. A polynomial equation is then obtained by fitting the coordinates. By integrating this equation area value of the indicated region A_{abde} in Figure 4 can be determined. The area value of the particle migration zone is then calculated by Equation (15). Finally, the area fraction value is obtained based on Equation (14). The flow chart of calculating the particle migration zone are shown in Figure 5. For a 3D simulation, the area fractions of particle migration zone in the given vertical cross-sections are calculated by the aforementioned steps in Figure 5. The number of the vertical cross-section used in the calculation ranges from 8 to 12. The average value of the obtained area fractions is used to measure the mixing behavior.

$$\Phi = \frac{A_p}{A_s} \times 100\% \quad (14)$$

$$A_p = A_s - (A_{abde} - A_{cde}) \quad (15)$$

Figure 4 Determination of the boundary of particle migration zone ($l = 1.0$ m, $Q_g = 0.027$ Nm³/s (inlet velocity 50.0 m/s), $d_p = 2.0$ mm, $\mu_l = 1.0$ Pa·s, $t = 75$ s).

Figure 5 Flow chart for the calculation of particle migration zone.

2D vs 3D simulation

Figure 6 shows area fraction of particle migration zone Φ as a function of the time T after injecting silica-rich particles (*i.e.* particle migration time) in a 2D and a 3D simulation with the same operational conditions. Φ increases with T for both the 2D and 3D simulation. The area fraction Φ in the 3D simulation is around 3.7% to 6.2% larger than that in 2D simulation under current operational conditions. This is probably attributed to 1) the numerical error in tracking particle migration caused by the slightly different mesh densities in 2D and 3D simulation; 2) the calculation error in determining particle migration zone. Since difference of the calculated Φ between 2D and 3D simulation is relatively small and the 2D simulation is approximately 4 times faster than the 3D simulation by using computing power (Intel(R) Xeon(R) Gold 5120 CPU@2.20GHz with 16 cores), the 2D simulation is adopted to evaluate the particle migration behavior in this work.

Figure 6 Area fraction of the particle migration zone vs particle migration time in 2D and 3D simulation ($l = 1.0$ m, $Q_g = 0.034$ Nm³/s (inlet velocity 62.5 m/s), $d_p = 2$ mm, $\mu_l = 0.1$ Pa·s).

Gas flow rate

Figure 7 shows the effect of gas flow rate on the area fraction of particle migration zone Φ . For each carrier gas flow rate, the area fraction increases rapidly at the early stage of the mixing process, however the extent/speed of this increase gradually slows down with the particle migration time, and the area fraction levels off at certain value (95-98%) at the late stage. The particle mixing process becomes longer with decreasing the gas flow rate from 0.046 Nm³/s to 0.027 Nm³/s. These can be explained through the velocity gradient caused by a top gas injection into the slag pot. As seen in Figure 8, the fluid velocity gradually decreases from the top to the bottom of the slag pot, which is attributed to the fact that the fluid flow is mainly driven by the buoyancy force of the rising gas phase and the gas phase cannot directly agitate the slag phase at the bottom region [21]. Accordingly, the liquid slag is intensively agitated in the top region, while a relatively quiescent area exists at the bottom region of the slag pot. The particles in the liquid slag flow move very fast in the well-agitated region and migrate slowly in the relatively quiescent area, which limits the mixing process in the bottom region of the slag pot. Increasing the gas flow rate can decrease the relatively quiescent area (see the region with velocity less than 0.01 m/s in Figure 8(a), (b) and (c)), therefore shortening the mixing process. In order to quantify the particle mixing behavior, a parameter $t_{0.95}$, *i.e.*, the time required for 95% of the area fraction of particle migration zone is employed in this work. As seen in Figure 9, $t_{0.95}$ decreases from 195 s to 20 s when the gas flow rate increases from 0.027 Nm³/s to 0.046 Nm³/s. Since the liquid slag flow is related to the input energy into the system, the input energy flux is calculated by Equation (16) [31] at three different gas flow rates (see Figure 9). In the present calculation, the energy efficiencies, *i.e.*, both η_1 and η_2 in Equation (16) are adopted as 0.06 [32, 33]. Increasing the input energy flux facilitates the agitation of the liquid slag, therefore the mixing process.

$$E_{In} = \left\{ Q_a p_a \left[2 \ln \left(1 + \frac{\rho_l g l}{p_a} \right) - \frac{\rho_l g l}{p_a + \rho_l g l} \right] + \eta_1 E_{ke} + \eta_2 \dot{n} R (T_s - T_{in}) \frac{\rho_l g l}{p_a + \rho_l g l} \right\} / A \quad (16)$$

$$E_{ke} = \frac{1}{2} Q_a \rho_g u_g^2 \quad (17)$$

Figure 7 Area fraction of the particle migration zone vs particle migration time at different gas flowrates ($l = 1.0$ m, $d_p = 2$ mm, $\mu_l = 0.1$ Pa·s).

Figure 8 Velocity field with isovalue lines at different gas flowrates ($l = 1.0$ m, $\mu_l = 0.1$ Pa·s).

Figure 9 $t_{0.95}$ vs gas flowrate and input energy flux vs gas flowrate ($l = 1.0$ m, $d_p = 2$ mm, $\mu_l = 0.1$ Pa·s).

Submerged lance depth

Figure 10 shows effect of the submerged lance depth on the area fraction of particle migration zone Φ . Clearly, increasing the submerged lance depth significantly increases area fraction of the particle migration zone at a given particle migration time, facilitating the mixing process. As explained in the previous section, the particle migration speed is restrained in the relatively quiescent area. Increasing the submerged lance depth reduces the quiescent area (see the region with velocity less than 0.01 m/s in Figure 11(a), (b) and (c)), leading to a rapid mixing. Figure 12 shows the relationship between $t_{0.95}$ and the submerged lance depth. $t_{0.95}$ decreases from 1008 s to 20 s when the submerged lance depth increases from 0.3 m to 1.0 m. It is worth mentioning that $t_{0.95}$ dramatically decreases from 1008 s to 276 s when the submerged lance depth is changed from 0.3 m to 0.65 m. The input energy flux is also calculated as seen in Figure 12. $t_{0.95}$ decreases as the input energy flux increases. The input energy flux is dependent on both the gas flow rate and the submerged lance depth. However, The input energy flux can only be used to compare $t_{0.95}$ when one of the two factors is fixed. As shown in Table 2, when case I with a larger submerged lance depth and a smaller gas flow rate compared to case II, the input energy flux and $t_{0.95}$ of case I are respectively smaller than those in case II, implying that the submerged lance depth more significantly affects the mixing process. Obviously, a fast mixing can be effectively achieved by a combination of increasing the gas flow rate and the submerged lance depth. On the other hand, increasing the gas flow rate leads to strong shear stresses near the lance exit region [21], which can enhance the wear of the lance and reduce its service life. A large submerged lance depth can generate a severe splashing, causing metal losses during the slag engineering process [21]. In this context, the process conditions, such as the submerged lance depth and gas flow rate, should be optimized in a whole picture of the hot stage slag engineering process, *i.e.* taking into account not only the mixing efficiency, but also the lance service life and metal recovery.

Table 2 two cases with different gas flow rates and submerged lance depths.

Case	Gas flow rate/Nm ³ ·s ⁻¹	Submerged lance depth/m	Input energy flux/kJ·m ⁻² ·s	$t_{0.95}$ /s
I	0.027	1	4443	195
II	0.046	0.65	4958	276

Figure 10 Area fraction of the particle migration zone vs particle migration time at different submerged lance depths ($Q_g = 0.046 \text{ Nm}^3/\text{s}$ (inlet velocity 84.5 m/s), $d_p = 2 \text{ mm}$, $\mu_l = 0.1 \text{ Pa}\cdot\text{s}$).

Figure 11 Velocity field with isovalue lines at different submerged lance depths ($Q_g = 0.046 \text{ Nm}^3/\text{s}$ (inlet velocity 84.5 m/s), $\mu_l = 0.1 \text{ Pa}\cdot\text{s}$).

Figure 12 $t_{0.95}$ vs submerged lance depth and input energy flux vs submerged lance depth ($Q_g = 0.046 \text{ Nm}^3/\text{s}$ (inlet velocity 84.5 m/s), $d_p = 2 \text{ mm}$, $\mu_l = 0.1 \text{ Pa}\cdot\text{s}$).

Slag viscosity

Figure 13 shows influence of the slag viscosity on the calculated Φ value. Increasing the slag viscosity remarkably reduces area fraction of the particle migration zone for a given particle migration time. The effect of slag viscosity further enhanced with increasing the particle migration time. This can be interpreted by the domination of the inertial force over the viscous force in the top region of the slag pot. Since the particle is mainly driven by the inertial force, particles move fast in the top region of the slag pot. Hence, the difference of the particle migration zone is small in this region. The viscous force becomes dominant in the bottom region of the slag pot, resulting in a large resistance for the particle migration. In addition, $t_{0.95}$ is increased by approximately 14 times when the slag viscosity is increased from 0.1 Pa·s to 1.0 Pa·s. The particle migration behavior is believed to be much more complex in the slag engineering process, since the slag viscosity is significantly affected by the slag temperature, which is heterogeneous in the process due to 1) cool materials injected near the lance region; 2) large heat transfer near the wall and the surface; 3) heat generation by the oxidation of metallic iron. In order to simulate the real particle migration behavior in the process, it is needed to dynamically calculate the slag viscosity. This is beyond the scope of this paper and further work is needed in future.

Figure 13 Area fraction of the particle migration zone vs particle migration time at slag viscosities ($l = 1.0 \text{ m}$, $Q_g = 0.034 \text{ Nm}^3/\text{s}$ (inlet velocity 62.5 m/s), $d_p = 2 \text{ mm}$).

Particle size

The particle size of the slag modifiers is in a range from 0.06 mm to 2 mm in the hot stage slag engineering process. Figure 14 shows the effect of the particle size on the mixing behavior. The particle size has little influence on the area fraction of the particle migration zone when other process parameters (such as lance depth, carrier gas flow rate, slag viscosity) are fixed. The calculated St number ranges from 0.003 to 0.28, suggesting that the additive particles closely follow the liquid slag flow and the additive particle migration is mainly affected by the liquid slag flow during the process. Changing the particle size is not likely to alter the liquid slag flow as the gas flowrate and the submerged lance depth are fixed. Nevertheless, the particle size is still an important parameter in the hot stage slag engineering process, since it significantly affects the particle dissolution [34, 35]. The smaller the particle size is, the faster dissolution of the particle will be achieved.

Figure 14 Area fraction of particle migration zone vs particle migration time at different particle sizes ($l = 1.0$ m, $Q_g = 0.027$ Nm³/s (inlet velocity 50.0 m/s), $\mu_l = 0.1$ Pa·s).

Conclusions

A numerical approach, *i.e.*, VOF-DPM-LES has been developed to study the mixing behavior of the injected additives in a hot stage slag engineering process without considering the additive dissolution. The main conclusions are summarized as follows:

- 1) The area fraction of the particle migration zone is calculated to quantify the additive mixing in the hot stage slag engineering process. Based on the calculated results, this area fraction can well characterize the mixing behavior
- 2) Increasing the gas flow rate and/or the submerged lance depth shorten the mixing process. Compared to the gas flow rate, the submerged lance depth more significantly affects mixing of the additive. The operational conditions should be optimized by considering not only the mixing efficiency but also the lance service life and metal recovery. To certain extent, the input energy flux can be used to evaluate the additive mixing behavior during the process.
- 3) Increasing the slag viscosity considerably prolongs the mixing process. In order to simulate the real particle migration behavior in the process, dynamically calculating of the slag viscosity is necessary.
- 4) The particle size has little influence on the particle migration behavior.
- 5) The present findings form basic guidelines for industrial operators to optimize the slag engineering process by properly selecting the operational conditions.

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