



## 3D numerical investigation of effects of density and surface tension on mixing time in bottom-blown gas-stirred ladles

Matin GHADIMI REZAEI<sup>1</sup>, Pooyan HASHEMI TARI<sup>1</sup>, Mohammad EMAMZADEH<sup>1</sup>, Leili TAFAGHODI KHAJAVI<sup>2</sup>

1. Mechanical Engineering Department, Shahid Beheshti University, Tehran, 16589-53571, Iran;

2. Material Science and Engineering Department, McMaster University, Hamilton L8S 4L7, Canada

Received 12 October 2020; accepted 18 June 2021

**Abstract:** In molten phase metallurgical processes, mixing via gas injection has a vital role in obtaining a homogeneous product. The efficiency of mixing depends on operational variables such as gas flow rate and slag height as well as physical properties of the molten phases. A numerical simulation is conducted to study the above parameters in the flow behavior of a bottom-blown bath. The molten metal and the slag are modeled by water and oil, respectively. The numerical results, particularly the mixing time, are validated against experimental data. The results show that mixing time increases as the slag height increases and decreases as the density of the slag material increases. The mixing time decreases with an increase in the density of the primary phase; however, it increases as the surface tension between air and water increases. A case with properties close to a real molten metal is also modeled. The performance of the system is influenced by the momentum rather than the dissipative forces. Thus, the effect of the density of the molten phase on the mixing process is more pronounced compared to the effect of the surface tension between the air and the molten phase.

**Key words:** gas-stirred ladle; mixing time; density; surface tension; tracer concentration; numerical simulation

### 1 Introduction

Extraction and refining at molten state is a common approach for producing various metals and alloys. Within this process, mixing of the molten bath is a routine practice to promote reactions or to homogenize the bath. This will in turn result in producing high quality homogeneous metals and alloys. In addition, mixing enhances the reaction rate between the slag and metal by increasing the interfacial area and mass transfer rate within each phase and between the two phases [1,2]. Mixing is typically conducted using gas injection through a nozzle.

Numerous investigations including theoretical and experimental studies as well as numerical simulations have been conducted to examine the

hydrodynamics of gas-stirred ladles [3–9]. Gas injection, in metallurgical operations, can be done via bottom, top or lateral nozzles [9–13]. Special attention has been paid to the mixing of bottom-blown baths, because of their widespread applications. Rising gas bubbles induces a re-circulatory liquid flow that agitates the liquid. The droplet generation and emulsification mechanisms have been investigated through numerical simulations [14–16], low temperature water modeling [17–20], as well as high temperature experiments [18,21].

The previous studies were mostly focused on two phenomena namely the mixing process within the molten metal and interphase mixing between the slag and the molten metal phase. Mixing time is a commonly used parameter to evaluate the efficiency of mixing in the metal phase. Mixing time is defined

**Corresponding author:** Pooyan HASHEMI TARI, E-mail: [p\\_hashemi@sbu.ac.ir](mailto:p_hashemi@sbu.ac.ir)

DOI: 10.1016/S1003-6326(21)65722-9

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as the time required for the metal phase to reach nearly the fully homogenized chemical and/or thermal state [22]. For cold modeling of metallurgical and chemical processes, mixing time is typically defined as the time required for the concentration of an additive (dye or tracer) to reach the nearly fully homogenized concentration [23]. Several investigations have been performed to measure the mixing time in different experimental set-ups. Mixing time is typically considered as the time needed to reach 95% [3,24,25] or 99% [26] of the fully homogenized value. In a comprehensive study by ASAI et al [26], mixing time was measured in three different cylindrical vessels. MAZUMDAR and GUTHRIE [22] performed experimental investigation to measure mixing time in water baths. KHAJAVI and BARATI [25] examined the effect of the slag layer and the specific gas flow rate on mixing time. All the above-mentioned studies show that at a constant water height, the mixing time decreases with the increase of the specific gas flow rate. In a fixed specific gas flow rate, the mixing time decreases as the water height increases.

In the past two decades, numerical modeling has been proven to be a powerful technique to study the mixing phenomena in molten metal/slag bath. It also provides an appropriate method to overcome the limitations associated with experimental investigations. Accordingly, the main differences between various molten/slag bath simulations are the geometrical and physical specifications of the system as well as mathematical modeling methods. For the latter, the difference is mainly associated with the modeling of the gas injection. The injection can be modeled using the Eulerian or Lagrangian approach. The metal and slag phases in multiphase systems are simulated using Eulerian approach and taken as interpenetrating continua. However, the gas phase can be modeled with both Eulerian and Lagrangian approaches. In Lagrangian approach, the discrete phase model (DPM) is commonly used. In this approach, the gas phase, which is taken as a discrete phase, is modeled as a large number of particles inside the flow field [27]. CLOETE et al [28,29] used a DPM approach for gas injection phenomena coupled with volume of fluid (VOF) multiphase model in order to simulate bubble plumes in ladle. Many researchers employed VOF method to simulate the gas injection

phenomena. SINGH et al [30] simulated a three-phase steel–slag–argon system to study desulfurization process in three-dimensional model of a steel ladle, and also to investigate “slag eye” formation. LLANOS et al [31] used VOF method to create a three-dimensional bottom-blown model in which argon was injected into a steel ladle. CAO et al [32] provided a fully transient model of a gas stirred ladle for desulphurization kinetic analysis using Euler–Euler approach and VOF coupled with corresponding sub-models. CHU et al [6] also used the VOF multiphase model to simulate bottom-blown converters in different gas distribution configurations.

Although direct numerical simulation (DNS) and large eddy simulation (LES) methods may offer more accurate turbulence characteristics, many researchers have chosen to use URANS models for simulating bottom-blown gas stirred ladles [29,31–33]. This is due to the applicability and simplicity of this method. In the present study, URANS method is used since the assessment and comparisons mainly lie on the average turbulence characteristics. The validation against the empirical equations [1,11,12], in which average values are taken into account, is an evidence of the applicability of the current turbulence model. Another reason to choose the URANS approach rather than the LES method lies on the fact that, as PIRKER [34] pointed out, the detailed modeling of the phenomena like slag eye formation is not considered in this research.

In order to estimate the mixing process in computational analysis, a tracing method is employed. This technique is often known as residence time distribution (RTD) in chemical and metallurgical engineering [23]. RTD is generally investigated via continuous fluid tracing and discrete phase technique [35]. In discrete phase method, the mixing time is computed based on the concentration of the discrete particles, which gives a reasonable and quick estimation of mixing time on several points such as fluid exits [35,36]. Unlike the discrete phase approach, continuous methods, which are categorized by two general groups namely tracer species and scalar transport models, treat the tracer as a continuous media and provide a complete set of mixing time curves over time [35]. Continuous methods are widely used in predicting mixing time in gas stirred metallurgical ladles. Both

species [10,29,37–39] and scalar transport [40,41] are used to simulate the tracer dispersion into flow domain.

Despite numerous experimental studies [29,30] on the effect of the physical properties of the fluids on mixing time, the mixing time correlations are not explicitly examined using numerical models, through which detailed flow structures associated with the fluid parameters can be studied. In the present study, CFD simulations are performed to analyze the flow structure as well as the mixing process of a bottom-blown metallurgical bath. The geometry of the system and the operational variables are chosen based on the experimental model of KHAJAVI and BARATI [25]. Mixing time is estimated for molten baths without a slag phase and for systems including a slag layer with different heights. For this purpose, a VOF formulation is adapted to model the interface between different continuum phases. Mixing time is predicted using the species transport method. The results are validated against the experimental data presented in Ref. [25]. The correlation between mixing time and different fluids' properties is also examined. In particular, the effect of liquid density and surface tension is investigated. The quantitative assessment of the mixing time, qualitative and quantitative studies of the flow structure associated with different cases are also presented.

## 2 Model formulation

### 2.1 Physical assumptions

The present numerical process is based on a cold physical model in which water is used to model the metal phase, while kerosene and silicone represent the slag phase. The physical properties of these liquids are presented in Table 1.

**Table 1** Physical properties of slag materials

| Slag material | Density/<br>( $\text{kg}\cdot\text{m}^{-3}$ ) | Viscosity/<br>( $10^{-6}\text{m}^2\cdot\text{s}^{-1}$ ) | Interfacial tension<br>with water/( $\text{N}\cdot\text{m}^{-1}$ ) |
|---------------|-----------------------------------------------|---------------------------------------------------------|--------------------------------------------------------------------|
| Water         | 998                                           | 1                                                       | N/A                                                                |
| Kerosene      | 790                                           | 1.14                                                    | 0.0582                                                             |
| Silicone oil  | 960                                           | 50                                                      | 0.0639                                                             |

Bubbles created and propagated into the metallurgical bath are treated using Eulerian

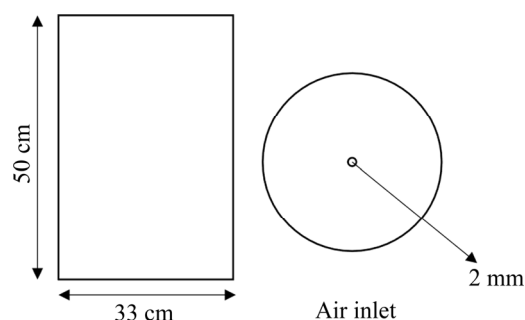
method of bubbly flow. Water and oil are considered as continuum media. The density and other physical properties of continuous phases are considered to be constant.

### 2.2 CFD simulation

The numerical procedure including the geometry generation, mesh generation and solution description are presented as follows.

#### 2.2.1 Geometry setup

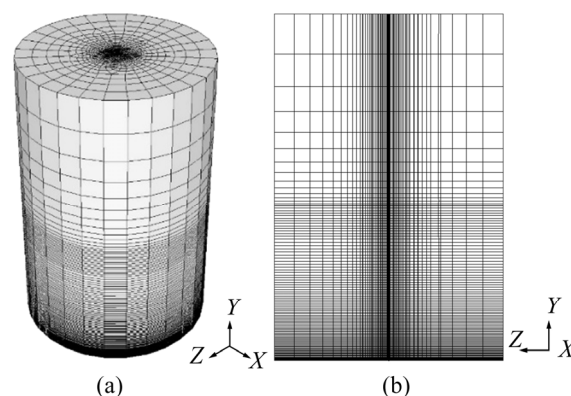
The vessel is a cylindrical container with a bottom injection nozzle, located at the center of the base. Corresponding dimensions are presented in Fig. 1. The water height varies from 0.198 to 0.366 m.



**Fig. 1** Geometry of system

#### 2.2.2 3D grid setup

3D geometry model and the corresponding mesh have been created using Gambit 2.4.6. Figure 2 shows the mesh of the fluid zone.



**Fig. 2** Fluid 3D zone (Mesh 2) (a) and 2D cross-section of cylindrical vessel (b)

#### 2.2.3 Mesh independency

In order to analyze the mesh independency, three different mesh specifications are taken into account. The details of the meshes are represented in Table 2.

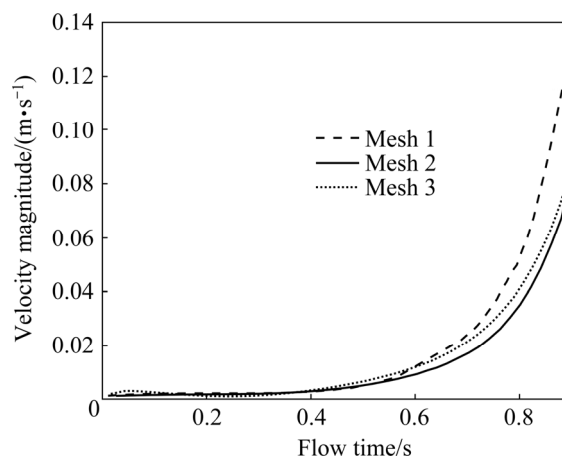
**Table 2** Mesh specifications

| Mesh No. | Number of cells | Minimum orthogonal quality | Maximum orthogonal skew |
|----------|-----------------|----------------------------|-------------------------|
| 1        | 73200           | 0.614                      | 0.386                   |
| 2        | 133215          | 0.774                      | 0.226                   |
| 3        | 602784          | 0.754                      | 0.246                   |

To perform a mesh independency analysis, a velocity profile at a point in the centerline with the height of 0.15 m is considered.

As shown in Fig. 3, the results are obtained using Mesh 3 with maximum number of grid cells, i.e. the results using Mesh 3 are close to those of found by employing Mesh 2. Thus, in order to reduce the computational time, Mesh 2 is considered for further computations.

The height of the lower liquid phase, oil thickness and gas flow rate for the cases modeled using numerical simulations, as well as the values of particular properties of the lower liquid phase, namely its density and surface tension, are listed in Table 3. The letters N, O, D, S and C, denoted in case indexes, represent without slag layer, with oil

**Fig. 3** Velocity magnitude versus flow time

as the slag layer, density analysis, surface tension analysis and combined effect, respectively.

#### 2.2.4 Governing equations

The governing equations by which the fluid flow is solved are presented as follows. These equations can be categorized into three groups: multiphase equations, turbulence modeling and mixing time prediction.

**Table 3** Specifications of systems simulated via CFD modeling (“k” stands for kerosene and “s” stands for silicone oil)

| Case index | Water height/m | Oil thickness/m | Gas flow rate/<br>( $10^{-5} \text{ m}^3 \cdot \text{s}^{-1}$ ) | Surface tension of<br>water/( $\text{N} \cdot \text{m}^{-1}$ ) | Density/<br>( $\text{kg} \cdot \text{m}^{-3}$ ) |
|------------|----------------|-----------------|-----------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------|
| N1         | 0.198          | 0               | 3.55                                                            | 0.072                                                          | 998                                             |
| N2         | 0.198          | 0               | 7.85                                                            | 0.072                                                          | 998                                             |
| N3         | 0.198          | 0               | 21.87                                                           | 0.072                                                          | 998                                             |
| N4         | 0.231          | 0               | 3.55                                                            | 0.072                                                          | 998                                             |
| N5         | 0.231          | 0               | 7.85                                                            | 0.072                                                          | 998                                             |
| N6         | 0.231          | 0               | 21.87                                                           | 0.072                                                          | 998                                             |
| O1         | 0.198          | 0.033 (k)       | 3.55                                                            | 0.072                                                          | 998                                             |
| O2         | 0.198          | 0.066 (k)       | 3.55                                                            | 0.072                                                          | 998                                             |
| O3         | 0.198          | 0.033 (s)       | 3.55                                                            | 0.072                                                          | 998                                             |
| O4         | 0.198          | 0.066 (s)       | 3.55                                                            | 0.072                                                          | 998                                             |
| D1         | 0.198          | 0               | 7.85                                                            | 0.072                                                          | 1500                                            |
| D2         | 0.198          | 0               | 7.85                                                            | 0.072                                                          | 3000                                            |
| D3         | 0.198          | 0               | 7.85                                                            | 0.072                                                          | 6000                                            |
| D4         | 0.198          | 0               | 7.85                                                            | 0.072                                                          | 7200                                            |
| S1         | 0.198          | 0               | 7.85                                                            | 0.14                                                           | 998                                             |
| S2         | 0.198          | 0               | 7.85                                                            | 0.35                                                           | 998                                             |
| S3         | 0.198          | 0               | 7.85                                                            | 0.72                                                           | 998                                             |
| S4         | 0.198          | 0               | 7.85                                                            | 1.4                                                            | 998                                             |
| C1         | 0.198          | 0               | 7.85                                                            | 1.4                                                            | 7200                                            |

Mass conservation equation (VOF equation):

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{V}_k) = S_{\alpha_k} + \sum_{p=1}^n (\dot{m}_{pk} - \dot{m}_{kp}) \quad (1)$$

where  $\dot{m}_{pk}$  is the mass transfer rate from phase  $p$  to phase  $k$ ,  $t$  is the time,  $\alpha_k$  is the volume fraction of phase  $k$ ,  $S_{\alpha_k}$  is the source term of volume fraction equation,  $\rho_k$  is the density of phase  $k$ , and  $\mathbf{V}$  is the velocity vector.

In VOF method, the sum of all volume fractions is equal to unity. Thus, we have

$$\sum_{k=1}^N \alpha_k = 1 \quad (2)$$

The conservation of momentum is presented in Eq. (3):

$$\frac{\partial}{\partial t}(\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla p + \nabla \cdot [\mu (\nabla \mathbf{V} + \nabla \mathbf{V}^T)] + \rho \mathbf{g} + \mathbf{F} \quad (3)$$

where  $\mu$  and  $\rho$  are viscosity and density of the fluid, respectively, which are calculated from Eqs. (4) and (5).  $\mathbf{g}$  stands for gravitational acceleration and  $\mathbf{F}$  is the source term of the momentum equation.

$$\mu = \alpha_a \mu_a + \mu_w + \alpha_o \mu_o \quad (4)$$

$$\rho = \alpha_a \rho_a + \rho_w + \alpha_o \rho_o \quad (5)$$

Indices a, w and o represent air, water and oil, respectively.

Species conservation equation is:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \mathbf{V} Y_i) = -\nabla \cdot \mathbf{J}_i + R_i + S_i \quad (6)$$

where  $\mathbf{J}_i$ ,  $Y_i$ ,  $R_i$ , and  $S_i$  are the diffusion flux vector, mass fraction, net production rate and source term of species  $i$ , respectively. The  $\mathbf{J}_i$  is calculated using Eq. (7):

$$\mathbf{J}_i = -(\rho D_{i,m} + \frac{\mu_t}{Sc_t}) \nabla Y_i \quad (7)$$

where  $Sc_t$  is the turbulent Schmidt number,  $D_{i,m}$  is the mass diffusivity of species  $i$ , and  $\mu_t$  is the turbulent viscosity.

## 2.2.5 Turbulence model

The standard  $k-\varepsilon$  model consisting of Eqs. (8) and (9) is used to solve the turbulent kinetic energy,  $k$ , and its dissipation rate,  $\varepsilon$ .

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho \mathbf{V} k) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_b - \rho \varepsilon + S_k \quad (8)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \mathbf{V} \varepsilon) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (9)$$

The  $C_{1\varepsilon}$ ,  $C_{2\varepsilon}$  and  $C_{3\varepsilon}$  in Eq. (9) are constants.  $\sigma_k$  and  $\sigma_\varepsilon$  are the turbulent Prandtl numbers for  $k$  and  $\varepsilon$ , respectively. Their values are as follows:  $C_{1\varepsilon}=1.44$ ,  $C_{2\varepsilon}=1.92$ ,  $C_{3\varepsilon}=0.09$ ,  $\sigma_k=1.0$ ,  $\sigma_\varepsilon=1.3$ . The  $G_k$  and  $G_b$  terms represent the generation of turbulence kinetic energy due to the mean velocity gradients and buoyancy, respectively. They are calculated using Eqs. (10) and (11):

$$G_k = -\rho \bar{u}_i' \bar{u}_j' \frac{\partial u_j'}{\partial x_i} \quad (10)$$

$$G_b = -g_i \left( \frac{\mu_t}{\rho Pr_t} \right) \frac{\partial \rho}{\partial x_i} \quad (11)$$

where  $u_i'$  and  $u_j'$  are velocity fluctuations and  $Pr_t$  is turbulent Prandtl number.

$S_k$  and  $S_\varepsilon$  are the source terms for turbulence kinetic energy and its dissipation rate, respectively. Turbulent viscosity  $\mu_t$  in Eq. (9) is calculated using Eq. (12):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (12)$$

Surface tension,  $\sigma$ , is modeled by continuum surface force (CSF) method which is presented in Eq. (13) [42]:

$$\mathbf{F}_{CSF} = \sigma k_1 \nabla \alpha \quad (13)$$

The  $\mathbf{F}_{CSF}$  is considered as a non-conservative force field. In Eq. (13),  $k_1$  is the interface curvature and  $\alpha$  is the volume fraction.

## 2.2.6 Bubble injection

A transient pressure-based solver of ANSYS Fluent 16.0<sup>®</sup> is employed to perform the simulations. “Coupled” scheme is used among applicable velocity–pressure coupling algorithms. The second order upwind and compressive schemes are used to discretize momentum and volume fraction equations, respectively. A plane that is aligned with the centerline of the cylinder is regarded as the cross-section view to obtain the gas volume fraction

contours from 3D simulations.

### 2.2.7 Presence of slag layer

The slag layer is introduced as a third continuum phase in VOF multiphase model. The key factor in interfacial interaction of the slag layer with the gas and the metal phase is the slag surface tension.

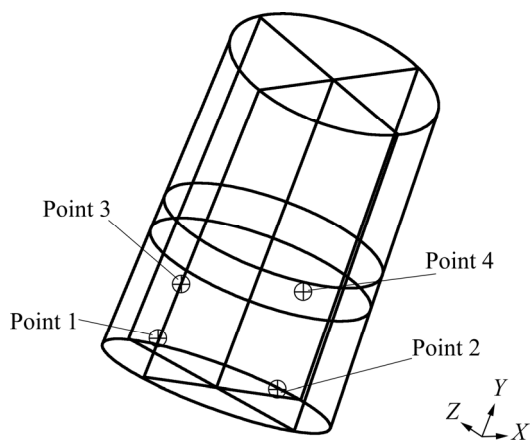
### 2.2.8 Mixing time

Mixing time is predicted using species transport model where a small volume is adapted near the interface [33]. This volume represents a dye used as a tracer. The frozen flow field technique is employed where the fluid flow needs to reach a nearly steady state condition. The time in which the ladle reaches the 95% concentration criteria, is considered as the mixing time. The mixing time results obtained from numerical modeling are provided in the next section. The predicted mixing time is compared with that obtained from the experiments in order to validate the model.

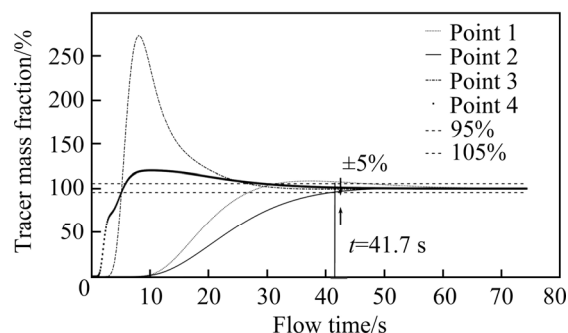
## 3 Results

### 3.1 Mixing time

Considering the anisotropic nature of the system and the presence of the dead zones [43,44], mixing time is determined at four different points to make sure various regions of the bath reach homogeneity. The dye concentration distribution at four distinct points (Fig. 4), is plotted with respect to the flow time (Fig. 5). The vertical axis represents tracer mass fraction normalized by the final concentration value ( $=0.0042$ ). The results are



**Fig. 4** Probe locations for determining concentration distribution: Point 1 ( $x=0, y=0.02, z=0.12$ ); Point 2 ( $x=0.12, y=0.01, z=0$ ); Point 3 ( $x=0, y=0.10, z=0.12$ ); Point 4 ( $x=0.10, y=0.15, z=0$ )



**Fig. 5** Mass fraction of tracer at probe locations for Case N3

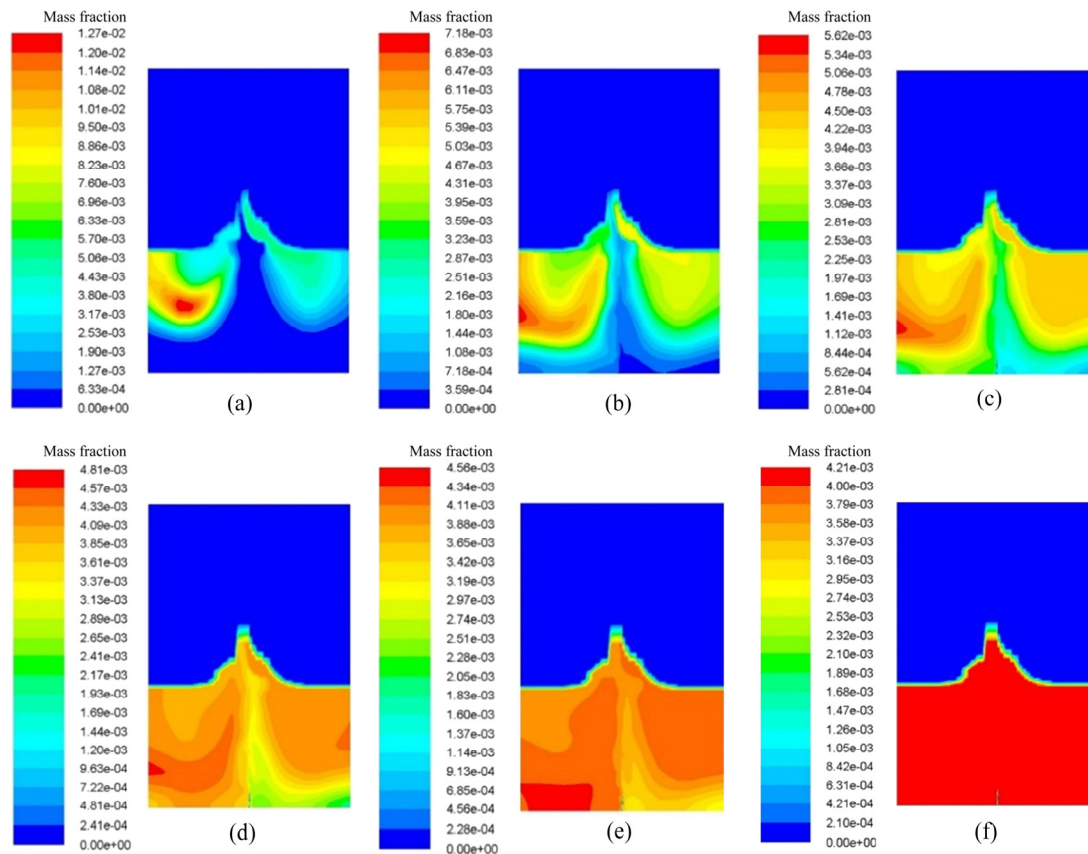
associated with Case N3 with the maximum air flow rate and the minimum water height. The mixing time is predicted to be 41.7 s. This value is in a good agreement with the time obtained from the experimental measurement, i.e. 40.3 s [25].

Contours of the tracer mass fraction for Case N3 are plotted in Fig. 6 in order to present a better visualisation of the mixing process. The variation of the tracer mass fraction distribution with time confirms the presence of dead zones at the bottom of the reactor (see Figs. 6(c, d)).

Similarly, all the cases are simulated numerically and validated against the experimental data. The mixing time obtained from the numerical simulations as well as the experiment data is presented in Table 4. The findings of the numerical simulation are in a very good agreement with the experimental results.

### 3.2 Effect of slag layer

As illustrated in Table 4, the mixing time predicted for Case O2 is higher than that for Case O1. The difference is associated with the height of the kerosene layer, i.e. 0.033 m for Case O1 and 0.066 m for Case O2. Similar behavior is observed for Cases O3 and O4 with the silicone heights of 3.3 and 0.066 m, respectively. To have a more qualitative understanding, the simulated contours of the slag volume fraction for different cases at the flow time equal to 2 s are displayed in Fig. 7. The numerical simulations show a slower uprising motion of bubble plumes in cases with kerosene slag layer i.e. Figs. 7(a, c) compared to the cases with silicone oil slag layer i.e. Figs. 7(b, d). Thus, one can infer that the mixing process would be more difficult in cases with kerosene in contrast to the silicone oil, which is in consistent with the values presented in Table 4. Figure 7 also displays



**Fig. 6** Tracer mass fraction contours for Case N3 at flow time of 8 s (a), 16 s (b), 24 s (c), 32 s (d), 40 s (e) and 64 s (f)

**Table 4** Comparison of experimental and predicted mixing time

| Case No. | Experimental mixing time/s [25] | Predicted mixing time/s | Relative error/% |
|----------|---------------------------------|-------------------------|------------------|
| N1       | 87.5                            | 79                      | 9.7              |
| N2       | 76                              | 70                      | 7.8              |
| N3       | 40.3                            | 41.7                    | 3.5              |
| N4       | 32.5                            | 33                      | 1.5              |
| N5       | 42.2                            | 43                      | 1.8              |
| N6       | 62.5                            | 68                      | 8.8              |
| O1       | 70                              | 72.5                    | 3.5              |
| O2       | 83                              | 87                      | 4.8              |
| O3       | 66                              | 63.5                    | 3.8              |
| O4       | 71.5                            | 66                      | 7.6              |

the effect of the slag height on the mixing of the ladle. Comparison of Fig. 7(a) with Fig. 7(c) and Fig. 7(b) with Fig. 7(d), reveals that by increasing the slag height, at a certain flow time, the bubbles take longer time to reach the interface, and thus the mixing process becomes slower.

### 3.3 Effect of density

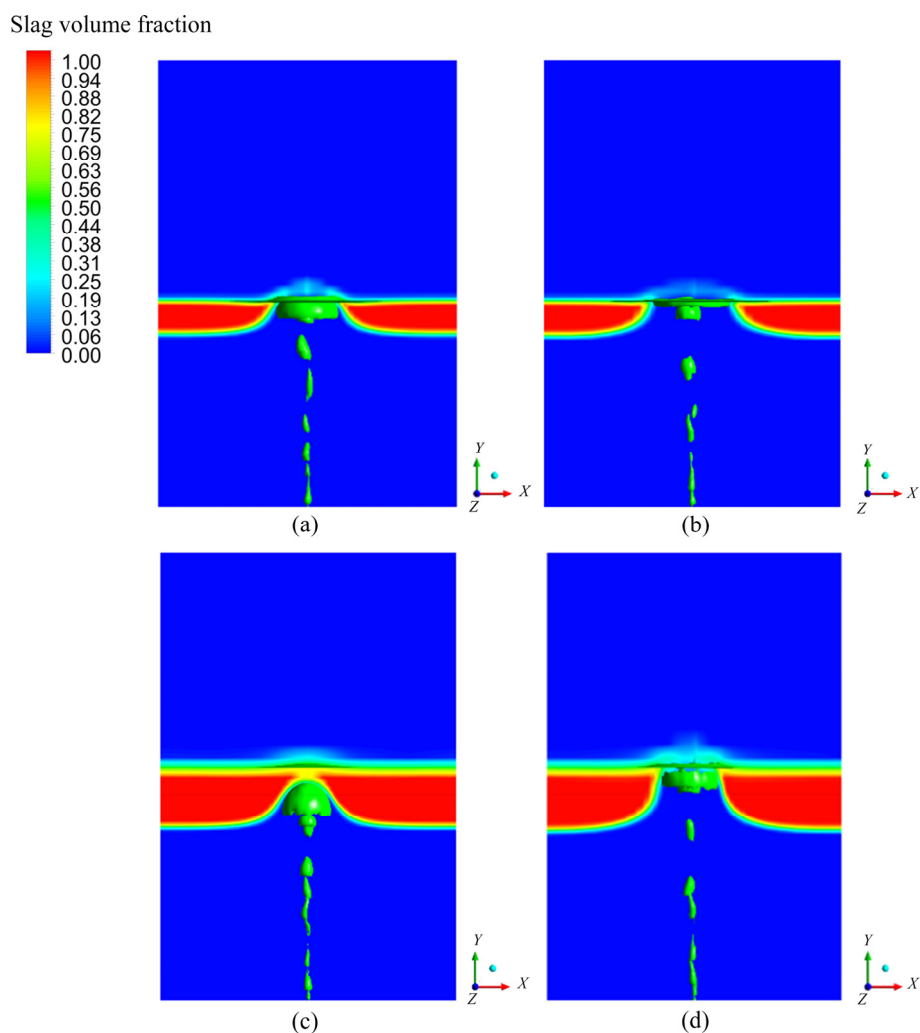
The choice of water as the representative of the

molten metal in bottom-blown metallurgical baths, is partially based on the similarity of viscosity. However, water has a lower density in comparison with any molten metal. In order to investigate the effect of the density of the lower phase on the flow structure and finally on mixing phenomenon, 5 different values for density are chosen, while the other parameters are considered to be constant. These cases are numbered as D1–D4 in Table 3. Case N2, with water representing the lower molten phase, belongs to this series of simulations as well. Aside from the density of the lower fluid, all other variables are the same as those of Case N2.

Turbulent viscosity and momentum, as two influential parameters, are employed to assess the mixing time and the flow behavior for different cases. As shown in Eq. (14), turbulent viscosity is proportional to density [45]:

$$\mu_{t,av} = C_v \rho_L L (gQ/D)^{1/3} \quad (14)$$

where  $C_v$  is the proportionality constant,  $\rho_L$  stands for the fluid density,  $L$  is the liquid depth,  $g$  is the gravitational acceleration magnitude,  $Q$  is the volumetric input rate, and  $D$  is the diameter of the ladle. Equation (14) shows an empirical relation



**Fig. 7** Slag volume fraction contours at flow time of 2 s for different cases: (a) Case O1; (b) Case O3; (c) Case O2; (d) Case O4

which is observed from the experimental studies of the bubble injection through a gas-stirred ladle. Contours of turbulent viscosity are presented in Fig. 8 for Cases N2 and D1–D4. As the density increases, turbulent viscosity increases in magnitude, in particular within the regions adjacent to the air plume, representing a vertical flow structure. The size of the regions with high turbulent viscosity increases as the density increases and the maximum value of turbulent viscosity occurs at the midway distance between the central air plume and the wall (see Fig. 8). In addition, considering Eqs. (6) and (7), the increase in turbulent viscosity leads to an increase in diffusive terms and acts as an obstacle for the mixing process.

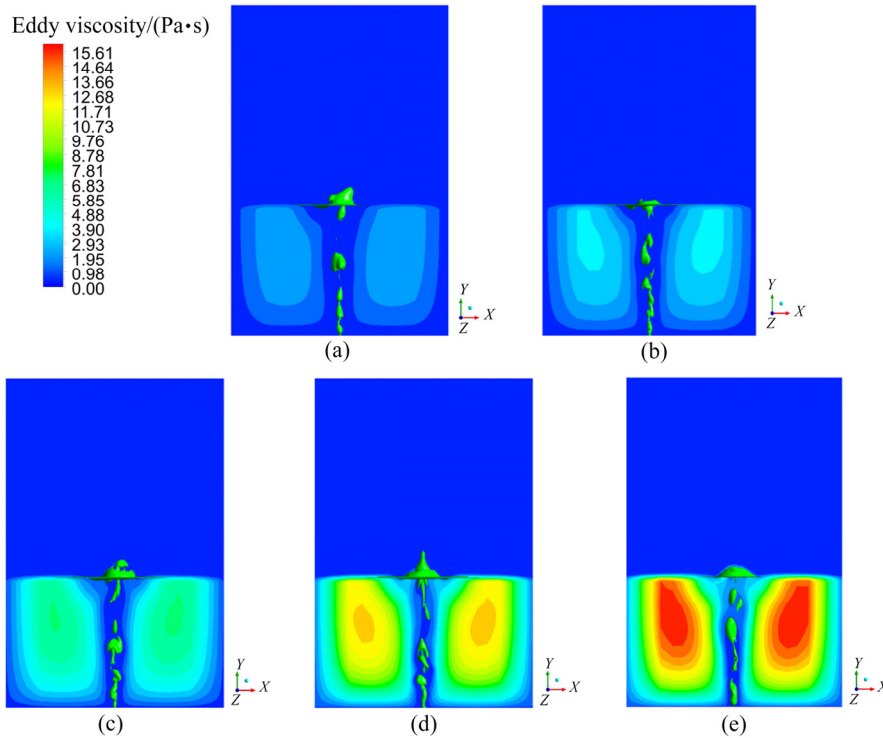
Momentum is defined based on the multiplication of density and velocity of the lower phase.

Contours of momentum are presented in Fig. 9 for Cases N2 and D4. The forces resulted by fluid momentum become more significant as the density increases. Similarly, within the regions with vertical flow structures, the momentum increases with the increases of density; particularly, there is a significant rise of the momentum magnitude in the region of the air plume due to the higher fluid velocity (see Fig. 9). Considering the effect of the momentum as well as the experimental correlation presented in Eq. (15) [45], we expect that the mixing time ( $\tau_{\text{mix}}$ ) decreases as the density increases.

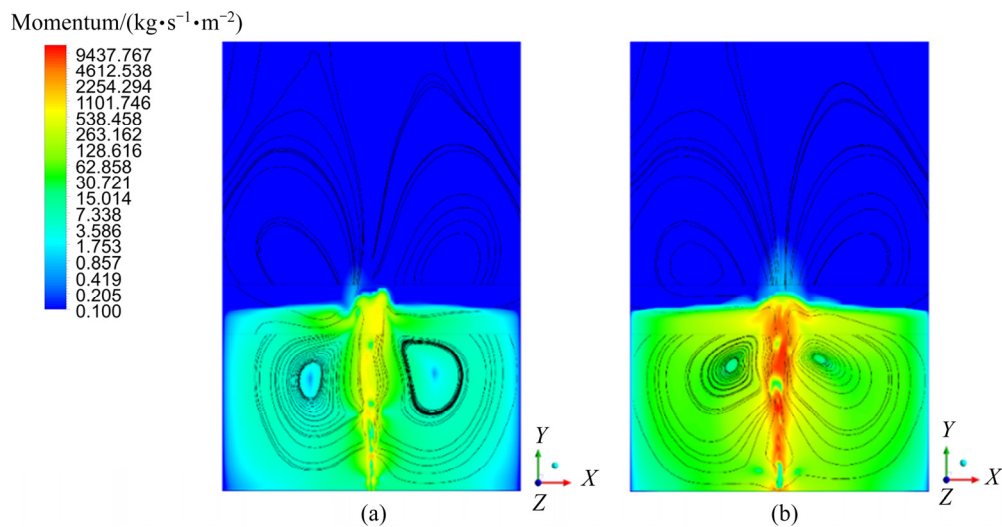
$$\tau_{\text{mix}} \sim (\rho_L Q)^{-0.33} L^{-1.0} R^{2.0} \quad (15)$$

where  $R$  is the radius of the ladle. Figure 10 displays the variation of the mixing time and the maximum value of turbulent viscosity. According





**Fig. 8** Turbulent viscosity contours for Cases N2 (a), D1 (b), D2 (c), D3 (d) and D4 (e)



**Fig. 9** Fluid momentum contours for Cases N2 (a) and D4 (b) at flow time of 2 s (The color bar scale is set to be logarithmic to achieve a clear comparison)

to Fig. 10(a), as the density increases, the mixing time decreases. Figure 10(b) shows that the maximum value of turbulent viscosity increases as the density increases. These observations imply that the mixing process in this specific gas-stirred ladle is dominated by the momentum term rather than the turbulent viscous forces.

### 3.4 Effect of surface tension

In order to investigate the effect of the surface

tension of the lower liquid phase, i.e. the interfacial tension between the lower liquid phase and the air, on mixing efficiency of gas-stirred ladles, the simulation is performed for 5 different values of surface tension, i.e. Samples S1 to S4 in Table 3. Case N2 with the lowest surface tension is considered as the fifth case in this series of experiments. Similar to the previous section, the effect of surface tension is assessed using the momentum and turbulent viscosity.

Figure 11 shows the contours of turbulent viscosity (eddy viscosity) for Cases N2 and S1–S4 at 2 s. The effect of the surface tension on turbulent viscosity is less pronounced in comparison with the effect of density. However, one can still observe the increase of turbulent viscosity as the surface tension increases. This indicates that mixing becomes harder as the surface tension increases. One can also observe that the increases within the regions with vertical flow structures; however, the higher values of turbulent viscosity in these regions

are closer to those at the interface. As the surface tension increases, the regions with higher values of turbulent viscosity move downward to the bottom of the vessel.

Figure 12 displays contours of the fluid momentum for Cases N2 and S4. The comparison of the momentum contours of the two cases provides an understanding of the physics of the mixing process of the tracer. The change in the momentum in these two cases appears to be small. Consequently, one can conclude that the momentum

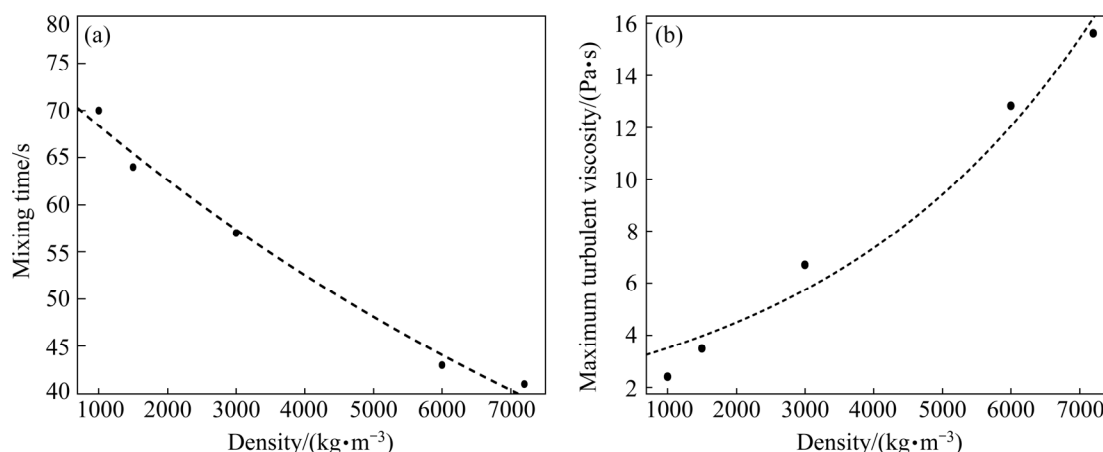


Fig. 10 Mixing time (a) and maximum turbulent viscosity (b) with respect to density of lower phase at flow time of 2 s

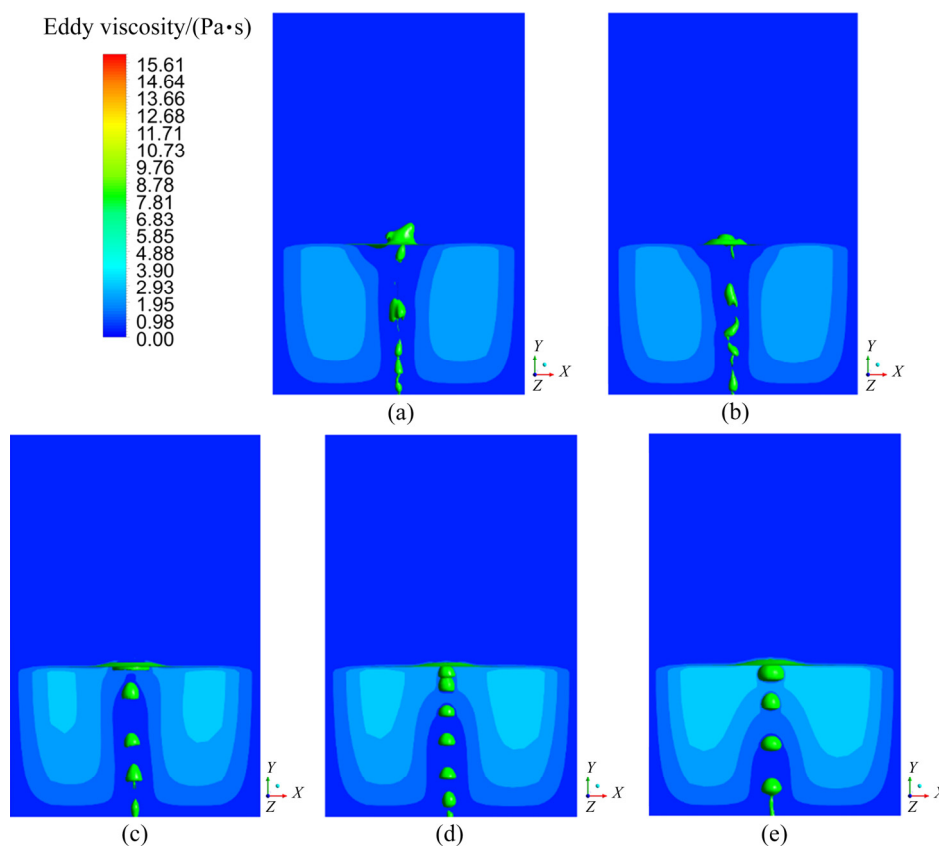


Fig. 11 Turbulent viscosity contours for Cases N2 (a), S1 (b), S2 (c), S3 (d) and S4 (e) at flow time of 2 s

remains constant while the turbulent viscosity has a small increase, and this in turn leads to an increase in mixing time.

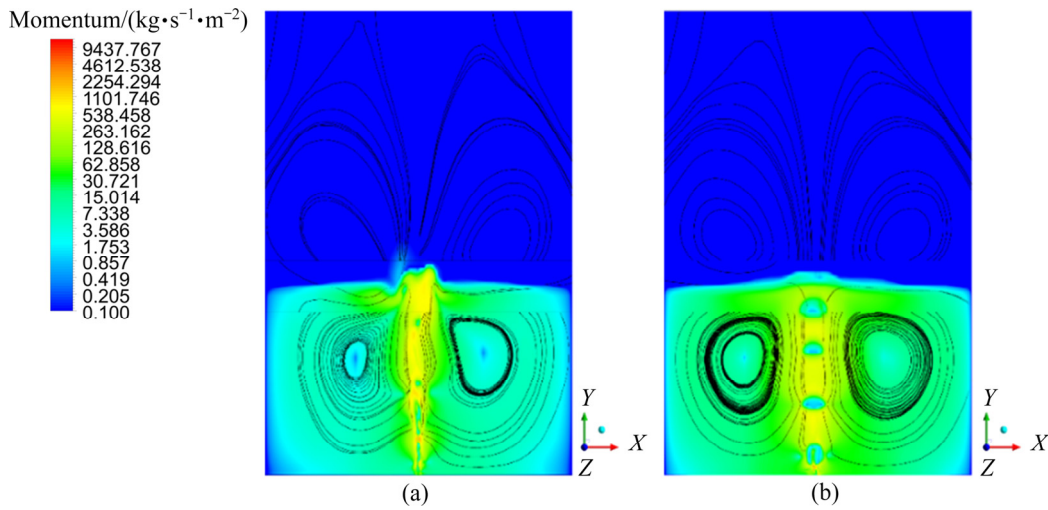
Considering these observations, one can expect that the effect of the surface tension on the mixing time would be less significant in comparison to the density. The mixing time results are also presented in Fig. 13(a), which proves the aforementioned observation. The maximum values of turbulent viscosity for cases with varied surface tensions are presented in Fig. 13(b). Accordingly, it can be concluded that, as surface tension increases, the variation of the maximum value of turbulent viscosity is rather small.

To have a clearer understanding of the effect of surface tension, the process of bubble formation for two cases (i.e. N2 and S4) with respect to flow time is displayed in Fig. 14. Two distinguished forces play significant role in the process of air bubble uprising: drag force and buoyancy force, which are

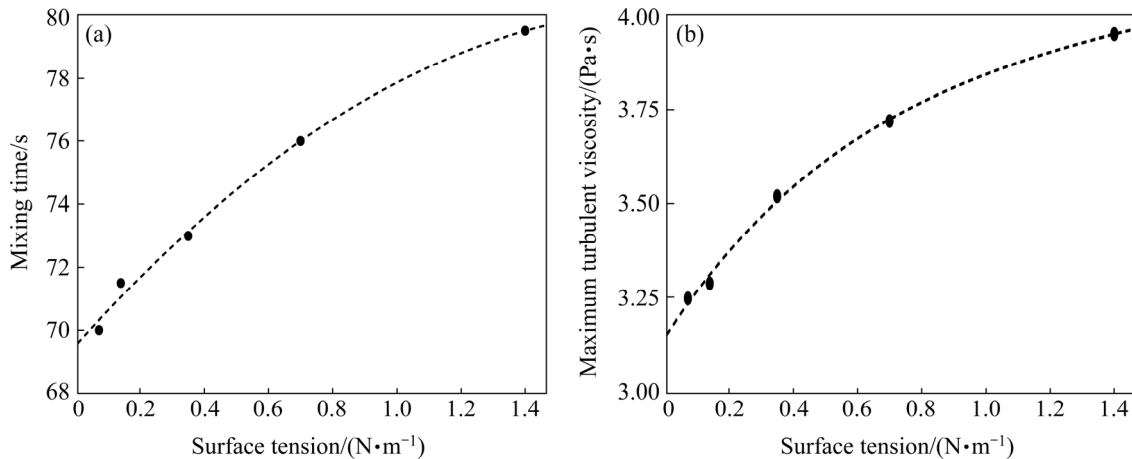
proportional with the shape and the volume of the bubbles, respectively. According to Fig. 14, it can be observed that by increasing the surface tension of the lower phase, the mushroom-like front wave of air jet inside the liquid phase disappears and discrete spherical air bubbles start to form. The spherical shape of the bubbles results in higher drag force and consequently slows down the air bubble uprising. However, there is a slight difference in time required for the bubbles to reach the interfaces for Case N2 compared to Case S4. The reason can be explained as follows: while the maximum bubble size, which remains stable through rising, is proportional with surface tension, it has a reverse proportion with density of the molten metal which is presented in Eq. (16) [46]:

$$d_{\max} \propto \left( \frac{\sigma}{\rho_L} \right)^{0.5} \quad (16)$$

where  $d_{\max}$  is the maximum bubble size. The density



**Fig. 12** Fluid momentum contours of Cases N2 (a) and S4 (b) at flow time of 2 s (The color bar scale is set to be logarithmic to give a better viewpoint)



**Fig. 13** Mixing time (a) and maximum turbulent viscosity (b) versus surface tension

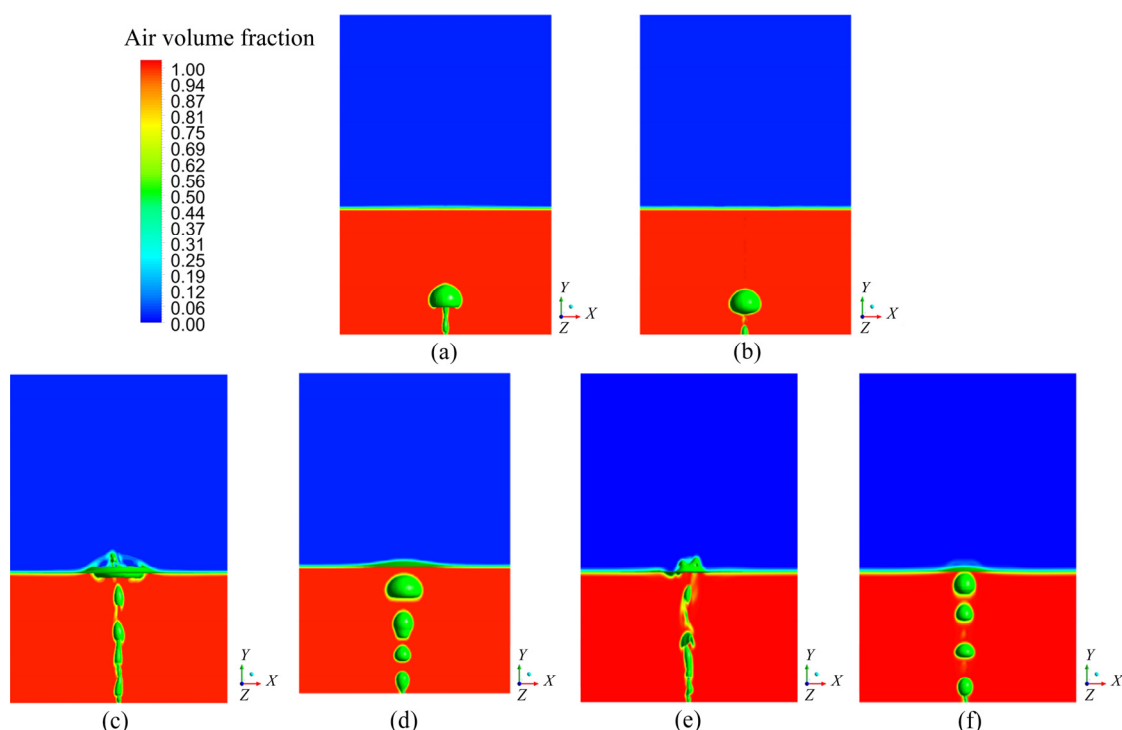
shows its effect on the buoyancy force. Since the density of air is significantly smaller than that of water, there will be a small change in the volume of the bubbles. Thus, it is expected that the buoyancy force remains almost constant and since it has a dominant role (due to the high density of water) in the uprising process, the effect of surface tension on the speed of uprising will be negligible.

### 3.5 Combined effect of density and surface tension

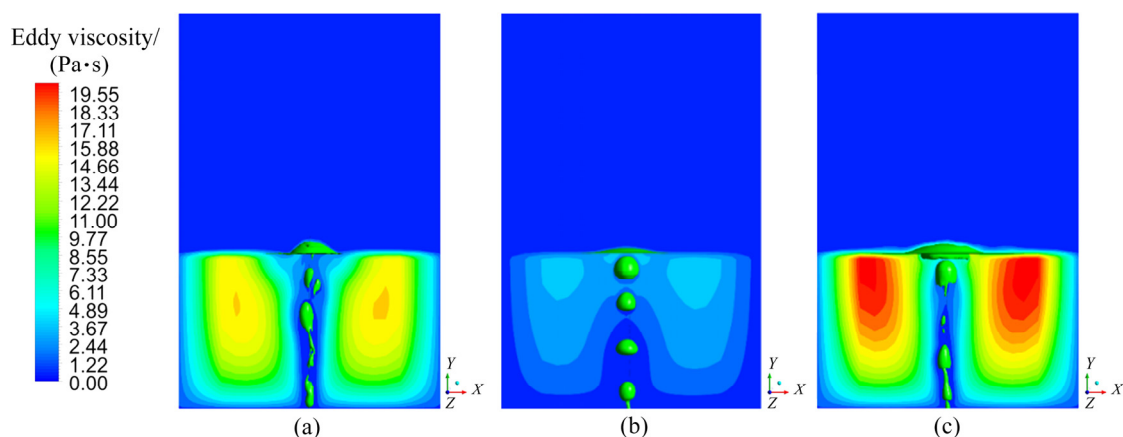
The change of mixing time of the system with the density of Case D4 and surface tension of Case S4 is calculated using the same methodology

presented in Section 2. This predictive case named C1 represents the slag-free form of the molten metal at the initial gas flow rate of  $7.85 \times 10^{-5} \text{ m}^3/\text{s}$  and liquid height of 0.198 m. Turbulent viscosity and the momentum associated with Case C1 are compared with those of Cases D4 and S4. Figure 15 illustrates the turbulent viscosity contours for these cases.

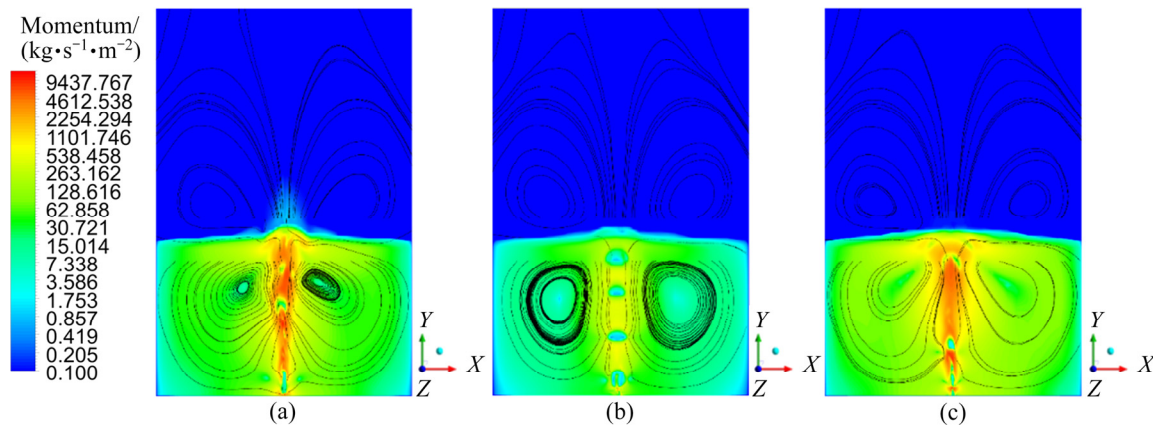
Figure 15 shows that Case C1 has the maximum value of turbulent viscosity. This observation is associated with the increase in density and the form of the plume is mostly influenced by the increase in the surface tension of the liquid. Figure 16 illustrates the momentum for



**Fig. 14** Air volume fraction contours for Cases N2 (a, c, e) and S4 (b, d, f) at different flow time: (a, b) 0.5 s; (c, d) 1.2 s; (e, f) 2 s



**Fig. 15** Turbulent viscosity contours for Cases D4 (a), S4 (b) and C1 (c) at flow time of 2 s



**Fig. 16** Fluid momentum contours for Cases D4 (a), S4 (b) and C1 (c) at flow time of 2 s (The color bar scale is set to be logarithmic to give a better viewpoint)

Cases D4, S4 and C1. The momentum of Case C1 is slightly smaller than that of Case D4. This is mostly due to the shape of the bubbles which increases the drag force.

Hence, it is expected that the mixing time for Case C1 would be slightly higher than that for Case D4. Mixing time for Case C1 is estimated to be 46.5 s, which is lower than that of Case D4, i.e. 41.0 s.

## 4 Conclusions

(1) The presence of slag layer influences the mixing of the gas-stirred ladle. The mixing time increases as the slag height increases and it decreases with increasing the density of the slag material.

(2) The assessment of density effect revealed that the mixing time decreases with the density of the primary phase, due to an increase in the fluid momentum.

(3) The results obtained from the assessment of surface tension effect showed that the mixing time increases as the surface tension between two phases (air and water) increases. However, the effect of surface tension is less pronounced compared with the effect of density. The reason for this slight increase of mixing time is that by increasing the surface tension, the size of the corresponding bubbles increases and they become more spherical in shape and result in higher values of turbulent viscosity coefficients and drag forces.

(4) When the density of the liquid remains constant, the variation in momentum is insignificant

and the buoyancy which is mainly influenced by density and size of the bubbles, remains constant. Consequently, as the surface tension increases, although the drag force increases, the reduction of the bubble plumes uprising speed is negligible. Therefore, it can be concluded that the performance of the system is more dependent on momentum rather than the unfavorable diffusive forces caused by turbulent viscosity.

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## 密度和表面张力对底吹气体搅拌钢包中混合时间影响的 3D 数值研究

Matin GHADIMI REZAEI<sup>1</sup>, Pooyan HASHEMI TARI<sup>1</sup>,  
Mohammad EMAMZADEH<sup>1</sup>, Leili TAFAGHODI KHAJAVI<sup>2</sup>

1. Mechanical Engineering Department, Shahid Beheshti University, Tehran, 16589-53571, Iran;

2. Material Science and Engineering Department, McMaster University, Hamilton L8S 4L7, Canada

**摘 要:** 在熔融相冶金过程中, 注入气体进行混合对于获得均质产物至关重要。混合效率取决于气体流速、渣层高度以及熔融相物理性质等工艺参数。本文通过数值模拟研究底吹浴槽中流体行为的上述参数。用水和油分别模拟熔融金属和熔渣, 根据实验数据对数值模拟结果、特别是混合时间进行验证。结果表明, 混合时间随渣层高度增大而增加, 随炉渣材料密度增加而减小。混合时间随主相密度的增加而减小, 随着空气和水间表面张力的增大而增加。还模拟一种性质接近真实熔融金属的情形。系统的行为主要受动量的影响, 而不是受耗散力的影响。因此, 与空气和熔融相间表面张力的影响相比, 熔融相密度对混合过程的影响更为显著。

**关键词:** 气体搅拌钢包; 混合时间; 密度; 表面张力; 示踪剂浓度; 数值模拟

(Edited by Wei-ping CHEN)