Dispersion Characteristics of Small Buoyant Particles in a Gas-agitated Vessel

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Model experiments were made of the floating and dispersing characteristics of buoyant particles in a gas-agitated water vessel to learn the behavior of inclusion particles in a turbulent flow field of liquid steel. Hollow glass particles were put into the vessel, nitrogen gas was blown from the bottom of the vessel, and the particle concentration was measured by a silicon photodiode. It was found that the concentration of particles in the bulk water increased abruptly at a certain gas-flow rate and saturated at higher rates. This critical gas-flow rate was correlated well with the terminal velocity and vessel geometries. Numerical simulation of the particle dispersion was also carried out using the k - ϵ model and the effect of turbulence on the particle behavior was discussed.

KEY WORDS: gas injection; inclusion removal; model experiment; numerical analysis; k - ϵ model; turbulence; clean steel.

1. Introduction

The removal of nonmetallic inclusions from liquid steel depends mainly on flotation in current steelmaking processes. Since inclusion particles are dispersed by the turbulent diffusion during flotation, the spatial distribution of buoyant particles in steelmaking vessels must be affected by the intensity of liquid turbulence as well as the terminal velocity of the particles. The purpose of the present study was to investigate the dispersion characteristics of small buoyant particles in water-model vessels under gas injection.

A number of experimental studies have been made of inclusion behaviors in liquid steel in relation to the deoxidation kinetics.^{1–4)} Model experiments have also been made of particle dispersion and the removal rate of particles⁵⁾ and collision between bubbles and particles.⁶⁾ An increasing number of computer simulations has been made on fluid flow and particle transport in the past few years.^{7–13)}

In the present study, characteristics of dispersion and flotation of buoyant particles in a turbulent flow field were investigated experimentally and theoretically. The distribution of buoyant particles in a gas-injected vessel was measured in the experiment at various terminal velocities of particle and gas-flow rates. The results of experiments have been discussed by numerical simulation on the particle transport in turbulent flow using a mathematical model composed of our bubble-dispersion model^{14–18)} and the k - ϵ -turbulence model.¹⁹⁾

2. Experiment

2.1. Experimental Method

Two kinds of buoyant particles were used in the experiment. Both are hollow glass, one is called a glass microballoon and has a density of 460 kg/m³ and the other is a silica balloon with a density of 580 kg/m³. Particles were classified by sieves into different sizes ranging from 54.5 to 102 μ m for the glass microballoon and from 241 to 325 μ m for the silica balloon. Measured terminal velocities of sized particles in still water ranged from 0.76 to 16.1 mm/s.

Figure 1 shows a schematic diagram of the experimental apparatus. Nitrogen was injected into the water through a nozzle with a 2-mm diameter located at the center bottom of the tank. As seen in Fig. 1(b), a vertical plane including the axis of the tank was lit through 4-mm slits placed on either side of the tank to observe particles suspended in water. The intensity of light scattered by the particles was detected from the front side of the tank by a silicon photodiode. For the experiment, a suitable quantity of buoyant particles was put into the tank and nitrogen was injected. Several minutes later, the signal from the photodiode was recorded for a period of 2 to 4 min and the average light intensity was obtained. The light intensity was measured at two positions, point A and point B, as shown in Fig. 1(a).

The experimental conditions were as follows: particle amount $V_p = (1-12) \times 10^{-6}$ m³; height of water $z_1 = 0.1-0.3$ m; radius of vessel $r_1 = 0.095, 0.145$ m; gas-flow rate $q_G = (3.3-150) \times 10^{-6}$ m³ s⁻¹.

Fig. 1. Schematic diagram of experimental apparatus.

2.2. Results and Discussions

In Fig. 2 the scattered light intensity, E , is plotted against the gas-flow rate at points, A and B. As seen, the value of E increases abruptly at low gas-flow rate and saturates in the larger gas-flow-rate region. The value of E at point A is always larger than that at point B, because the former is near the free surface. For the characterization of these curves, the critical gas-flow rate, q_L , was adopted to represent the limiting gas-flow rate beyond which particles at the free surface start to disperse into liquid. For convenient sake, the critical gas-flow rate was defined as the rate corresponding to the half value of the saturation of E as shown in Eq. (1).

$$q_L = q_G (E = 0.5E_{\text{sat}}) \quad (1)$$

To determine q_L accurately, Eq. (2) was applied to approximate the E -curve, and the critical gas-flow rate was calculated from this equation.

$$E = \{1 - \exp(-\alpha q_G^{\beta})\} E_{\text{sat}} \quad (2)$$

The dependence of q_L on the terminal velocity of particles obtained at point A is shown in Fig. 3, and the value is proportional to $v_{\text{pt}}^{0.18}$, where v_{pt} is the terminal velocity of particles. The effects of z_1 and r_1 on q_L were also investigated and the following empirical equation was derived.

$$q_L = 3.5 \times 10^{-4} v_{\text{pt}}^{0.18} z_1^{-0.76} r_1^{1.6} \quad (3)$$

3. Numerical Analysis

3.1. Fundamental Equations and Method of Calculation

The assumptions used in this study were as follows:

- (1) Flow is axisymmetrical and in steady state.

 Fig. 2. Scattered light intensities as a function of gas-flow rate. ($r_1 = 0.145$ m, $z_1 = 0.2$ m, $d_p = 102$ μ m, $V_p = 3 \times 10^{-6}$ m³)

 Fig. 3. Values of q_L as a function of v_{pt} . ($r_1 = 0.145$ m, $z_1 = 0.2$ m)

- (2) Free surface is flat.
 - (3) Fluid is a continuum having density, $\rho = (1 - \sigma)\rho_L$.
 - (4) Bubble diameter is uniform and slip velocity is the same as terminal velocity.
 - (5) Bubbles and particles are moved by liquid motion and dispersed by turbulent diffusion.
 - (6) Effective diffusivity of bubbles and particles is the same as the effective kinematic viscosity of fluid.
- Based on these assumptions, the following equations of fluid flow and bubble transport are given:

$$\frac{1}{r} \frac{\partial}{\partial r} (\rho r u) + \frac{\partial}{\partial z} (\rho v) = 0 \quad (4)$$

$$\begin{aligned} & \rho \left(u \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial z} \right) \\ &= -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left\{ \rho v_e r \left(2 \frac{\partial u}{\partial r} - \frac{2}{3} \nabla \cdot \mathbf{v} \right) \right\} \\ &+ \frac{\partial}{\partial z} \left\{ \rho v_e \left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z} \right) \right\} - \frac{\rho v_e}{r} \left(\frac{2}{r} u - \frac{2}{3} \nabla \cdot \mathbf{v} \right) \quad (5) \end{aligned}$$

$$\begin{aligned} & \rho \left(u \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \left\{ \rho v_e r \left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z} \right) \right\} \\ &+ \frac{\partial}{\partial z} \left\{ \rho v_e \left(2 \frac{\partial v}{\partial z} - \frac{2}{3} \nabla \cdot \mathbf{v} \right) \right\} - \rho g \quad (6) \end{aligned}$$

$$u \frac{\partial \sigma}{\partial r} + (v + v_B) \frac{\partial \sigma}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_e \frac{\partial \sigma}{\partial r} \right) + \frac{\partial}{\partial z} \left(D_e \frac{\partial \sigma}{\partial z} \right) \quad (7)$$

$$\frac{1}{r} \frac{\partial}{\partial r} (\rho r u k) + \frac{\partial}{\partial z} (\rho v k) = \frac{1}{r} \frac{\partial}{\partial r} \left(\rho r \frac{v_e}{\sigma_k} \frac{\partial k}{\partial r} \right) + \frac{\partial}{\partial z} \left(\rho \frac{v_e}{\sigma_k} \frac{\partial k}{\partial z} \right) + G + G_B - \rho \varepsilon \quad (8)$$

$$\begin{aligned} \frac{1}{r} \frac{\partial}{\partial r} (\rho r u \varepsilon) + \frac{\partial}{\partial z} (\rho v \varepsilon) &= \frac{1}{r} \frac{\partial}{\partial r} \left(\rho r \frac{v_e}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial r} \right) + \frac{\partial}{\partial z} \left(\rho \frac{v_e}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial z} \right) \\ &+ \frac{c_1}{k} \varepsilon (G + G_B) - \frac{c_2}{k} \rho \varepsilon^2 \quad (9) \end{aligned}$$

where u and v are the velocities in the radial and axial directions. v_e and D_e are the effective kinematic viscosity and effective bubble diffusivity given by the following equations:

$$v_e = \mu_e / \rho, \quad \mu_e = \mu + \mu_t, \quad \mu_t = \rho C_D k^2 / \varepsilon$$

$$D_e = v_e$$

The constants included in fundamental equations are the same as those of the standard k - ε model.

$$C_D = 0.09, \quad C_1 = 1.44, \quad C_2 = 1.92, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3$$

G and G_B in Eqs. (8) and (9) are the generation rate of turbulence energy due to the time-averaged velocity gradient and the relative motion of bubbles, respectively. They are described by the following equations.

$$G = \mu_t \left[2 \left\{ \left(\frac{\partial u}{\partial r} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 + \left(\frac{u}{r} \right)^2 \right\} + \left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z} \right)^2 \right] - \frac{2}{3} \mu_t (\nabla \cdot v)^2 \quad (10)$$

$$G_B = \rho_L \sigma g v_B \quad (11)$$

Equation (11) was originally proposed by Johansen *et al.*²⁰⁾

The boundary conditions and the method for solving equations are the same as the previous study.¹⁸⁾

The equation of particle transport is shown by Eq. (12) which is the same as Eq. (7).

$$u \frac{\partial c}{\partial r} + (v + v_{pt}) \frac{\partial c}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_e \frac{\partial c}{\partial r} \right) + \frac{\partial}{\partial z} \left(D_e \frac{\partial c}{\partial z} \right) \quad (12)$$

The boundary conditions are given by the following equations:

$$r = 0 \text{ or } r_1, \quad 0 < z < z_1: \quad \frac{\partial c}{\partial r} = 0 \quad (13)$$

$$z = z_1, \quad 0 < r < r_1: \quad -\eta D_e \frac{\partial c}{\partial z} + v_{pt} c = 0 \quad (14)$$

$$z = 0, \quad 0 < r < r_1: \quad -D_e \frac{\partial c}{\partial z} + v_{pt} c = 0 \quad (15)$$

At the free surface and the bottom of the vessel the particle flux by turbulent diffusion was balanced with the flux by terminal velocity. To fit the computed result with the observation, parameter η was multiplied by the effective diffusivity. The above equations were solved in a manner similar to the flow equations.

3.2. Results and Discussion

Figure 4 shows the computed flow pattern, local gas holdup distribution and particle-concentration profile together with the observation obtained for $d_p = 102 \mu\text{m}$. The computed particle concentrations in the figure are normalized by the concentration at uniform dispersion. The features of flow and bubble dispersion are similar to those observed. The computed particle concentration is nearly uniform in the upper region, but is small near the bottom, which is similar to the observation.

Figures 5(a) and 5(b) show the comparisons between calculated and observed particle concentrations. For the sake of quantitative comparison, the observed light intensities were normalized by the average of the saturation values at point A and point B. Figure 5(a) shows the case for $\eta = 1$, namely, without modification for the particle diffusivity at the free surface. The

Fig. 4. Computed flow pattern, local gas holdup distribution and particle concentration profile compared with observation.
 $(r_1 = 0.145 \text{ m}, z_1 = 0.2 \text{ m}, q_G = 50 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}, d_p = 102 \mu\text{m})$

Fig. 5. Comparison between observed and calculated particle concentration.
($d_p = 102 \mu\text{m}$, $V_p = 3 \times 10^{-6} \text{ m}^3$)

estimation is clearly inadequate to reproduce the observed results, especially at point A. If the value 0.29 for η is chosen, a good agreement between observed and calculated results can be obtained as seen in Fig. 5(b).

There may be at least two explanations of the necessity for η to adjust the model with the experiment. In general, the $k-\varepsilon$ model is applicable to fully developed turbulence, however, the particle entrainment occurs at low gas-flow rates. Therefore, the estimate of turbulence intensity might be larger than real values; that is one explanation. The second explanation is as follows. Some other factors in addition to v_{pt} , z_1 and r_1 should be introduced into the empirical equation of q_L to obtain a completely dimensionless equation, e.g., surface tension or wettability. These factors possibly retard the entrainment of particles from the free surface. These theories should, however, be confirmed in further studies.

4. Conclusions

Behaviors of inclusion particles in molten steel such as flotation and turbulent dispersion were studied here by a water-model experiment and a numerical calculation. The following results were obtained:

- (1) Buoyant particles were trapped at the free surface

below a critical gas-flow rate, q_L , and entrained into bulk water beyond q_L .

- (2) The value of q_L was correlated with terminal velocity of particle, v_{pt} , height of water, z_1 , and radius of vessel, r_1 . An empirical equation, Eq. (3), was derived.

- (3) Turbulent flow and particle dispersion were investigated by numerical simulations. Calculated concentration profiles agreed well with observed results when a correction factor of particle diffusivity was introduced at the free surface.

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