Relationship between Mixing Time and the Number of Holes of a Top Blowing Immersion Nozzle in a Cylindrical Bath

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(Received on April 12, 2011; accepted on May 27, 2011)
KEY WORDS: refining; mixing time; water model; immersion nozzle.

1. Introduction

In a previous study1) water model experiments were carried out to enhance the mixing efficiency of the refining processes such as the desulfurization process. A top nozzle having four holes on its side wall was vertically immersed in a cylindrical water bath, as schematically shown in Fig. 1. The nozzle was placed on the centerline of the bath. Air was injected into the bath from the four holes at the same flow rate, \( Q_{gi} \). The total gas flow rate was denoted by \( Q_g (= 4Q_{gi}) \). Mixing time, \( T_m \), was measured with an electrical conductivity sensor, and the following empirical equation was derived by referring to information on mixing time for bottom gas injection.2)

\[
T_m(H_L/D)(g/D)^{1/2}Re^{0.47} = 3.00 \times 10^3(H_{in}/H_L)^{-0.38} \ldots (1)
\]

\[
Re = D\nu_p/\nu_L\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)
\]

\[
\nu_p = 4Q_g/(\pi D^2)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)
\]

where \( H_L \) is the bath depth, \( D \) is the vessel diameter, \( g \) is the acceleration due to gravity, \( Re \) is the Reynolds number, \( H_{in} \) is the immersion depth of the nozzle, \( \nu_p \) is the superficial velocity of gas in the bath, and \( \nu_L \) is the kinematic viscosity of liquid. The vessel diameter, \( D \), the aspect ratio of the bath, \( H_L/D \), and the number of holes, \( N_n \), were fixed as: \( D = 0.300 \) m, \( H_L/D = 0.5 \), and \( N_n = 4 \). Equation (1) could approximate the measured values within a scatter of ±40%.

The number of holes, \( N_n \), was varied in this study as \( N_n = 2, 3, \) and 4 to reveal its effect on mixing time.

2. Experimental Apparatus and Procedure

In Fig. 1 the test vessel made of transparent acrylic resin had an inner diameter, \( D \), of 0.300 m and a height, \( H_l \), of 0.680 m, just as in the previous study.1) De-ionized water was filled in the vessel to a prescribed depth, \( H_L \). A top nozzle made of acrylic resin had multi-holes on its side wall. The holes were drilled at \( 2.0 \times 10^{-2} \) m above the nozzle tip. The holes were located on the same perimeter at equal intervals, as shown in Fig. 2. The inner diameters of the holes, \( d_{ni} \), were the same: \( d_{ni} = 1.0 \times 10^{-3} \) m. The inner and outer diameters of the nozzle, \( D_{ni} \) and \( D_{no} \), were \( 1.0 \times 10^{-2} \) m and \( 1.6 \times 10^{-2} \) m, respectively. The aspect ratio of the bath, \( H_L/D \), was varied as: \( H_L/D = 0.3, 0.4, 0.5, \) and 0.8. The nozzle was immersed vertically into the bath. The distance from the holes to the bath surface was denoted by \( H_{in} \). The dimensionless immersion depth of the nozzle, \( H_{in}/H_L \), was varied from 0.07 to 0.81. The total flow rate of air, \( Q_g (= N_nQ_{gi}) \), was adjusted with a mass flow controller and then the air was injected horizontally into the bath under the bubbling regime (\( M < 1 \)), where \( M \) is the Mach number. In this study the modified Froude number, \( Fr_m = \rho_gQ_{gi}^2/\rho_LgH_Ld_{ni}^5 \), was varied from 600 to 9500, where \( \rho_g \) is the density of gas and \( \rho_L \) is the density of liquid.

Aqueous KCl solution was chosen as tracer and an electrical conductivity sensor was used to measure the history of the electrical conductivity of the mixture of de-ionized water and the aqueous KCl solution (see Fig. 3). The sensor was placed near the bottom wall of the vessel. The sensor and
tracer charge positions are shown in Fig. 2. Further details of the mixing time measurement should be referred to the previous paper.1)

3. Experimental Results and Discussion

3.1. Data on Mixing Time

Figures 4 through 8 collectively show the measured values of mixing time, $T_m$, against the total gas flow rate, $Q_g$. The dimensionless immersion depth, $H_{in}/H_L$, was chosen as a parameter. It should be noted that the measured values shown in Fig. 6 were re-plotted from the previous paper.1) In the remaining figures $T_m$ decreased with $Q_g$ and $H_{in}/H_L$ in similar manners to those shown in Fig. 6.

3.2. Derivation of Empirical Equation for Mixing Time

The above-mentioned facts suggest that the mixing time for $N_n = 2$ and 3 can be correlated by the same functional relationship as Eq. (1). Figures 9 through 11 plot the dimensionless values of the mixing time against $(H_{in}/H_L)^{0.38}Re^{0.47}$ for $N_n = 2$, 3, and 4, respectively. Although Eq. (1) was originally derived for $D = 0.300$ m, $H_L/D = 0.5$, $H_{in}/H_L = 0.07–0.81$, and $N_n = 4$, it can approximate the measured values of $T_m$ for $H_L/D = 0.3$ and 0.8, too, as seen in Fig. 11. The measured values shown in Figs. 9 and 10 also can be satisfactorily correlated by this arrangement method. The following empirical equations therefore were proposed.

$$T_m(H_L/D)(g/D)^{1/2}Re^{0.47} = 1.60 \times 10^3(H_{in}/H_L)^{0.38} ... (4)$$

Fig. 4. Mixing time against gas flow rate for $N_n = 2$ and $H_L/D = 0.5$.

Fig. 5. Mixing time against gas flow rate for $N_n = 3$ and $H_L/D = 0.5$.

Fig. 6. Mixing time against gas flow rate for $N_n = 4$ and $H_L/D = 0.5$.

Fig. 7. Mixing time against gas flow rate for $N_n = 4$ and $H_L/D = 0.3$.

Fig. 8. Mixing time against gas flow rate for $N_n = 4$ and $H_L/D = 0.8$.

Fig. 9. Comparison of measured mixing time value with Eq. (4).
These empirical equations can be combined into the following equation as a function of the number of holes, $N_n$.

$$T_m\left(\frac{H_L}{D}\right)^{\frac{1}{2}}\left(\frac{g}{D}\right)^{\frac{1}{2}}Re^{0.47} = 762N_n\left(\frac{H_{in}}{H_L}\right)^{-0.38}$$

Equation (6) was derived based on the following empirical equation proposed previously\(^1\) for the bottom gas injection.

$$T_m\left(\frac{H_L}{D}\right)^{\frac{1}{2}}\left(\frac{g}{D}\right)^{\frac{1}{2}}Re^{0.47} = 4.21 \times 10^3 \left(\frac{H_{in}}{H_L}\right)^{0.38}$$

Comparison of Eqs. (6) and (8) implies that the multi-hole immersion nozzle injection is more effective than bottom gas injection when the following relationship is satisfied.

$$762N_n\left(\frac{H_{in}}{H_L}\right)^{0.38} \leq 4.21 \times 10^3 \quad \text{.................} \quad (9)$$

Rearrangement of Eq. (9) yields Eq. (7). The solid and broken lines indicate

$$N_n \leq 5.52\left(\frac{H_{in}}{H_L}\right)^{0.38} \quad \text{.................} \quad (10)$$

although the broken line is drawn beyond the present experimental conditions.

In the real processes however the erosion and oscillation of the immersion nozzle would be serious. Further investigations on these phenomena should be carried out for detailed discussion of the applicability of a multi-hole immersion nozzle to the real processes.

4. Conclusion

An empirical equation, Eq. (6), was proposed for the mixing time in a bath agitated by gas injection with a multi-hole immersion nozzle. This equation implies the possibility that the multi-hole immersion nozzle gas injection gives shorter mixing time than the conventional single-hole bottom nozzle gas injection.

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