Note

Model Experiments on the Mixing Time in a Bottom Blown Bath Covered with Top Slag

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1. Introduction

Many efforts have been devoted to understand the mixing in a bath agitated by bottom gas injection.^{1–3)} Information on the effect of the top slag layer on the mixing time, however, is very limited.⁴⁾ In this study water model experiments were carried out to clarify the effect of the top oil layer on the mixing time in a bottom blown bath. Particular attention was paid to the relation between the mixing time and the reverse emulsification, *i.e.*, entrapment of oil droplets in the lower water layer.⁵⁾

2. Experimental Apparatus

Figure 1 shows a schematic of the experimental apparatus. The diameter of the cylindrical vessel, D , was 0.200 m, 0.300 m, and 0.500 m. The vessel was made of transparent acrylic resin. As ladle refining operations were mentioned in this study, water was filled in each vessel to a depth, H_L , of 1.5 vessel diameters. The aspect ratio, H_L/D , therefore was fixed to be 1.5. A bubbling jet formed above the nozzle rose straight in the bath. The inner diameter of the nozzle, d_{ni} , was 2.0×10^{-3} m. Three kinds of silicone oils with different kinematic viscosities ($\nu_s = 2.0, 5.0, 10 \text{ mm}^2/\text{s}$) and n-pentane ($\nu_s = 0.37 \text{ mm}^2/\text{s}$) were used as models for top slag. The physical properties of these liquids are listed in **Table 1**.⁶⁾ The thickness of the top slag layer was denoted by h_o .

and varied from $0.067H_L$ to $0.200H_L$. Air was injected through the single-hole nozzle with a compressor. The gas flow rate, Q_g , was adjusted so that the specific input energy rate, ϵ_m , became the same in every vessel. The specific input energy rate denotes the input energy per unit time and mass of liquid. The range of ϵ_m extended from $31.2 \times 10^{-4} \text{ m}^2/\text{s}^3$ to $129 \times 10^{-4} \text{ m}^2/\text{s}^3$.

Mixing time measurements were carried out with an electric conductivity sensor.⁷⁾ The sensor was placed near the bottom wall of the vessel: 25 mm from the bottom and 10 mm from the side wall of the vessel. The mixing time was determined based on the 95% criterion.

3. Experimental Results and Discussion

3.1. Mixing Time

Figure 2 shows photographs of the reverse emulsification in the bath for $D = 0.200 \text{ m}$ and $Q_g = 41.4 \times 10^{-6} \text{ m}^3/\text{s}$. The numerical value attached to the tail of each silicone oil indicates the kinematic viscosity. The reverse emulsification became significant, as the density difference between

Fig. 1. Experimental apparatus for mixing time measurement.

Table 1. Physical properties of liquids at 298 K.

Liquid	Kinematic viscosity (mm ² /s)	Density (kg/m ³)	Interfacial tension (mN/m)
Water	0.857	996	52.7
Silicone oil2	2.0	873	
Silicone oil5	5.0	915	
Silicone oil10	10	935	
N-pentane	0.37	630

Fig. 2. Photographs of bath ($D = 0.200 \text{ m}$, $Q_g = 41.4 \times 10^{-6} \text{ m}^3/\text{s}$, $h_o/H_L = 0.067$).

Fig. 3. Relationship between specific input energy rate and mixing time ($v_o = 5.0 \times 10^{-6} \text{ m}^2/\text{s}$, $h_o/H_L = 0.200$).

the two liquids decreased. The buoyancy force acting on oil droplets therefore governs the downward motion of them under the present experimental conditions. The position at which oil droplets can arrive in the lower layer is named the entrapment depth and expressed by H_d . The entrapment depth, H_d , is a function of Q_g and the density difference between the two liquids.

The mixing in the bath is mainly governed by the existence of a large scale recirculating flow caused by the buoyancy force acting on bubbles generated above the nozzle exit. When the reverse emulsification takes place, the formation of the recirculating flow is highly suppressed because the most energy introduced into the bath by the bubbles is consumed to keep the oil droplets in the lower layer against the buoyancy force acting on them. This is the main reason why the mixing time becomes longer as the reverse emulsification becomes significant.

Figure 3 shows the relationship between the specific input energy rate, ϵ_m , and mixing time, T_m , for the silicone oil of $v_o = 5.0 \times 10^{-6} \text{ m}^2/\text{s}$ and a thickness ratio, h_o/H_L , of 0.200. The mixing time measured in the bath with a top oil layer became longer than that in the absence of it. The solid line denotes the value calculated from an empirical equation proposed previously by one of the authors for a bottom blown bath without a top layer.⁸⁾

$$T_{m(\text{cal},w)} = 1200 Q_g^{-0.47} D^{1.97} H_L^{-1} v_w^{0.47} \quad \text{.....(1)}$$

where ρ_w is the kinematic viscosity of water. The specific input energy rate, ϵ_m , is expressed by

$$\epsilon_m = (\rho_w - \rho_g) g Q_g H_L / [(\pi/4) \rho_w D^2 H_L] \quad \text{.....(2)}$$

where ρ_w is the density of water (kg/m^3), ρ_g is the density of gas (kg/m^3), and g is the acceleration due to gravity (m/s^2). In every bath with a top oil layer the measured value of the mixing time decreased monotonically with an increase in the specific input energy rate, ϵ_m , for $\epsilon_m = (31.2-93.6) \times 10^{-4} \text{ m}^2/\text{s}^3$. It increased suddenly at $\epsilon_m = 129.1 \times 10^{-4} \text{ m}^2/\text{s}^3$. Under this condition oil droplets dispersed in the whole bath and arrived at the bottom wall. Such a case ($H_d/H_L = 1$) will be excluded in the following analysis and discussion will be given only on the relation between T_m and ϵ_m for $\epsilon_m = (31.2-93.6) \times 10^{-4} \text{ m}^2/\text{s}^3$. The thickness of the top oil layer hardly affected the mixing

Fig. 4. Top layer entrapment in the water ($D=0.200 \text{ m}$).

time. This is probably because under the present experimental conditions the amount of top oil entrapped in the lower layer is independent of the thickness of the top oil layer.

3.2. Entrapment Depth of Oil Droplets, H_d

The mixing time in the presence of the top oil layer is closely associated with the reverse emulsification. Accordingly, an empirical equation for the entrapment depth of oil droplets, H_d , will be derived in the following. The entrapment depth, H_d , was determined based on the motions of oil droplets whose diameters were greater than 0.01 m. Figure 4 shows the measured values of H_d/H_L against the following Reynolds number, Re .

$$Re = v_{sp} D / v_w \quad \text{.....(3)}$$

$$v_{sp} = 4 Q_g / (\pi D^2) \quad \text{.....(4)}$$

where v_{sp} is the superficial velocity of gas. This Reynolds number is introduced because the entrapment depth is dependent on the intensity of the recirculating flow and the intensity is characterized by the superficial velocity and the bath diameter. The measured values of H_d/H_L increased with an increase in the Reynolds number and with a decrease in the density ratio, $(\rho_w - \rho_o)/\rho_w$, between the two liquids. It became evident that H_d/H_L decreases as the bath diameter, D , increases.

3.3. Derivation of Empirical Equation for Entrapment Depth

The entrapment of oil droplets is considered to be closely associated with the oscillation of the bath surface inherent in the bath diameter. The free surface of the bottom blown bath is highly oscillated by bubbles escaping from the bath, and, as a result, the bath oscillations are very similar to those caused by external forced oscillation. The periods of the oscillations are given by the following equation regardless of the oscillation modes (radial and tangential modes).⁹⁾

$$T_s = k(D/g)^{1/2} \quad \text{.....(5)}$$

where k is a function of the aspect ratio, H_L/D . The radial modes were dominant under the present experimental conditions.

The length scale over which the momentum is transferred by the oscillations to the liquid in the bath in the period, T_s ,

is introduced by referring to the Stokes second problem.¹⁰⁾

$$L = (\nu_w T_s)^{1/2} \dots\dots\dots(6)$$

Substitution of Eq. (6) into Eq. (5) yields

$$L = [k \nu_w (D/g)^{1/2}]^{1/2} \dots\dots\dots(7)$$

We assume that this relation holds in the presence of the top oil layer because the thickness of the top layer is very small compared with the depth of the lower liquid ($h_o/H_L \ll 1$).

The aspect ratio, H_L/D , is kept constant in this study ($H_L/D=1.5$), and, hence, k is regarded as a constant. Accordingly, the following length scale is newly chosen.

$$L = [\nu_w (D/g)^{1/2}]^{1/2} \dots\dots\dots(8)$$

The following relationship can be derived from Fig. 4.

$$H_d/H_L = m_1 \text{Re} \dots\dots\dots(9)$$

where m_1 is a function of the density ratio, $(\rho_w - \rho_o)/\rho_w$, and bath diameter, D . The following equation was derived.

$$m_1 = m_2 [(\rho_w - \rho_o)/\rho_w]^{-0.96} \dots\dots\dots(10)$$

$$m_2 = 0.137 [D/L]^{-1.22} \dots\dots\dots(11)$$

Combination of Eqs. (9) through (11) gives

$$H_d = 0.137 \text{Re} [(\rho_w - \rho_o)/\rho_w]^{-0.96} (D/L)^{-1.22} H_L \dots\dots(12)$$

All the measured values of the entrapment depth, H_d , could be approximated by Eq. (12) within a scatter of $\pm 45\%$, as shown in Fig. 5.

3.4. Derivation of Empirical Equation for Mixing Time

The mixing time, T_m , is assumed as follows:

$$\begin{aligned} T_m/T_{m(\text{cal.w})} &= m_3 (H_d/H_L)^{m_4} \\ (93.5 \times 10^{-4} \text{ m}^2/\text{s}^3 \geq \varepsilon_m &\geq 31.2 \times 10^{-4} \text{ m}^2/\text{s}^3, H_d/H_L < 1) \end{aligned} \dots\dots\dots(13)$$

where m_3 and m_4 are constants, and $T_{m(\text{cal.w})}$ and H_d/H_L are expressed by Eqs. (1) and (12), respectively.

The measured value of mixing time, $T_{m(\text{mea})}$, was non-dimensionalized by $T_{m(\text{cal.w})}$ and plotted against H_d/H_L in Fig. 6. The measured values are satisfactorily correlated by this arrangement method. Equation (13) reduces to

$$\begin{aligned} T_m/T_{m(\text{cal.w})} &= 2.94 (H_d/H_L)^{0.25} \quad (0.0134 < H_d/H_L < 0.5) \\ &= 1 \quad (0.0134 \geq H_d/H_L) \dots\dots\dots(14) \end{aligned}$$

Substitution of Eqs. (1) and (12) into Eq. (14) yields

$$\begin{aligned} T_m &= 1.910 Q_g^{-0.217} D^{1.49} H_L^{-1} \nu_w^{0.37} [(\rho_w - \rho_o)/\rho_w]^{-0.243} \\ &\quad (0.0134 < H_d/H_L < 0.5) \dots\dots\dots(15) \end{aligned}$$

Equation (15) can approximate the measured values of the mixing time within a scatter of $\pm 60\%$. The kinematic viscosity of the top oil had a negligible effect on the mixing time under the experimental conditions considered. The interfacial tension was not mentioned in this study because it was nearly constant. Further investigations are required for the effect of the interfacial tension on the mixing time.

Fig. 5. Comparison of measured H_d values with Eq. (12).

Fig. 6. Relationship between H_d/H_L and $T_{m(\text{mea})}/T_{m(\text{cal.w})}$.

4. Conclusions

(1) The mixing time became longer in the presence of the top oil layer than in the absence of it. The entrapment of many oil droplets in the water layer weakened the large scale recirculating flow in the bath, and, hence prolonged the mixing time.

(2) The entrapment depth, H_d , was closely associated with the mixing time in the bath. Equation (12) was derived for the entrapment depth, H_d .

(3) Equation (15) was proposed for the mixing time in the presence of the top oil layer.

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