Comment on “Effect of Swirl Motion on Mixing Time in Water Bath Agitated by Upward Gas Injection”, ISIJ Int., 41 (2001), 124–127, by Y. Takatsuka and M. Iguchi

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1. Introduction

Takatsuka and Iguchi\(^1\) have recently published a paper on effect of swirl motion on mixing time \(t_{\text{mix}}\) in water bath agitated by upward gas injection. According to them, no information on the effect of swirl motion on mixing time had been available in literature before their work. I wish to point out that this is not correct. We had extensively investigated it several years back.\(^2\) In this communication, a very brief report on our earlier studies is being presented so that researchers and others interested in this area can make better appraisal of the status of the subject, since Takatsuka et al.\(^3\) have not referred to this in their paper.

We, first of all, carried out experimental measurements of mixing time in a water bath, stirred by gas injection from an axial nozzle at the bottom.\(^2\) The effect of swirling of the plume was presented in this paper. We also extensively characterized the two-phase axisymmetric plume by photographic techniques.\(^3\) Experimental data were correlated as dimensionless plume cone angle as function of modified Froude No., \(H/D\) ratio and \(d_n/D\) ratio, where \(H\) is bath height, \(D\) is vessel diameter, and \(d_n\) is nozzle diameter. Finally, we formulated a macroscopic, steady state energy balance model. This, along with experimental data, was utilized to make some predictions as well as formulation of dimensionless empirical correlation of mixing time with physical variables.\(^4\)

The experimental set up employed a cylindrical perspex vessel of diameter 0.48 m and height 0.65 m, which contained distilled water at room temperature. The water bath was stirred by injecting air through a straight circular nozzle fitted axially at the bottom of the vessel. Mixing times were measured by pulse-tracer technique with electrical conductivity probe using KCl solution as tracer. Degree of mixing was 99.5%.

Reproducibility of measurements was tested by a large number of repeat measurements. Further, in order to check that the measured mixing time can be employed as a parameter characterizing the mixing in the entire bath, influence of probe location, probe size, location of tracer injection point etc. were studied. It was found that, for a certain experimental condition (i.e., bath height, gas flow rate and nozzle diameter), \(t_{\text{mix}}\) was independent of the above.\(^5\) Figure 1 illustrates this point. Thus, measured \(t_{\text{mix}}\) was taken as the parameter characterizing mixing in the entire bath.

Four different nozzle diameters were employed. Air flow rate varied from \(2.2 \times 10^{-4}\) to \(36.0 \times 10^{-4}\) \(\text{Nm}^3/\text{s}\). Height of water bath was varied from 0.1 m to 0.45 m (i.e., \(H/D\) ratio from 0.21 to 0.94).

2. Swirling of Plume and Mixing\(^3\)

Mixing time was found to decrease with increasing gas flow rate as usual. When a gas is injected into a liquid bath, it provides energy for bath stirring. In this context, a more fundamental parameter is rate of energy dissipation per unit volume of liquid (\(\dot{\varepsilon}_b\)). Although kinetic energy of gas may have some contributions, buoyancy energy input has been considered to be the principal source of energy input by investigators in this area. Hence, it was assumed that \(\dot{\varepsilon}_b = \dot{\varepsilon}_b^p\), where \(\dot{\varepsilon}_b\) is rate of buoyancy energy input per unit volume of the liquid bath. As per derivation of Bhavaraju et al.,\(^6\)

\[
\dot{\varepsilon}_b = \frac{4QP_{T_{\text{a}}}}{298.2\pi D^3H} \ln \left(1 + \frac{\rho_g gH}{P_{T_{\text{a}}}}\right) \quad \text{..............(1)}
\]

where \(\dot{\varepsilon}_b\) is in \(\text{kg/m}^2\text{s}\), \(Q\) is gas flow rate in \(\text{Nm}^3/\text{s}\), \(P_{T_{\text{a}}}\) is atmospheric pressure in \(\text{N/m}^2\), \(T_{\text{a}}\) is liquid temperature in Kelvin, \(\rho_g\) is liquid density in \(\text{kg/m}^3\), \(g\) is acceleration due to gravity in \(\text{m/s}^2\).

Most investigators had reported a linear relation between \(\ln(t_{\text{mix}})\) and \(\ln(\dot{\varepsilon}_b)\) as

\[
\ln(t_{\text{mix}}) = a - n \ln(\dot{\varepsilon}_b) \quad \text{..............(2)}
\]

where, \(a, n\) are empirical constants.

Figure 2 presents \(\ln(t_{\text{mix}})\) vs. \(\ln(\dot{\varepsilon}_b)\) at \(d_n = 10\) mm, and for various bath heights. An interesting feature of all such
curves was two intersecting straight lines. The values of \( n \) were larger at higher \( \dot{\varepsilon}_b \) (i.e., higher gas flow rates). Values of \( \dot{\varepsilon}_b \) corresponding to these transitions were designated as \( \dot{\varepsilon}_{bc} \). Various possible explanations for this behavior were considered, but it appeared that this transition was most likely due to the onset of swirling motion (i.e., rotation) of the plume. It was, therefore, decided to investigate this aspect further in detail.

As the gas flow rate increased, the plume of the top surface of the bath became larger and larger. At a certain stage it started oscillating, leading to vigorous wave motion at the bath surface which, in turn, caused the plume to rotate. Through careful visual observations, the gas flow rates corresponding to onsets of swirling motion were recorded.\(^3\) The onset was quite clear at low bath height. At large bath, it was not that clear. Therefore, the onsets were taken as occurring within a small range of gas flow rate. \( \dot{\varepsilon}_b \) corresponding to these values were designated as \( \dot{\varepsilon}_{bs} \) (i.e., \( \dot{\varepsilon}_b \) for onset of swirling).

After this, \( \dot{\varepsilon}_{bc} \) for critical transition in \( \ln(t_{mix}) \) vs \( \dot{\varepsilon}_b \) curves (as in Fig. 2), were compared with \( \dot{\varepsilon}_{bs} \), obtained by visual observations of swirling. Figure 3 shows the comparison for various values of \( H \) and \( d_w \). The shaded regions are for \( \dot{\varepsilon}_{bs} \). Circles are values of \( \dot{\varepsilon}_{bc} \). Excellent agreements between these confirmed our initial guess that the transitions in slope were due to onset of swirling motion.

3. Conclusions

Takatsuka et al.\(^{11} \) have made measurements only in the swirling region. Their empirical equations have been formulated in a different way. Moreover, they made measurements at degree of mixing of 0.95, whereas we did it at 0.995. Hence, comparisons are difficult. However, both have found that swirling decreases mixing time. Their empirical data fitting has yielded \( t_{mix} \propto Q^{-0.47} \). This is equivalent to \( n=0.47 \) in Eq. (1). This is in general agreement with our finding that \( n \) varied from 0.28 to 0.51 in presence of swirling.

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Reply

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The paper by Murthy et al. is regarded as one of pioneering papers concerning mixing time in a bath agitated by bottom gas injection. Murthy et al. have pointed out that the mixing is enhanced by the onset of swirl motion in the bath. Unfortunately, an empirical equation proposed by Murthy et al. for the mixing time is dimensional. The authors cited that paper in their first paper in a series of investigations on the swirl motion [Iguchi et al., ISIJ Int., 33 (1993), 1037] and in a book published recently [Ilegbusi, Iguchi and Wahnrieder, Mathematical and Physical Modeling of Materials Processing Operations, Chapman & Hall/CRC, Boca Raton, (1999)]. The authors are sorry to miss to cite the paper by Murthy et al. this time. The reason is that the 99.5% criterion is used by Murthy et al. to determine the mixing time instead of 95% criterion used by the authors, and, hence, it is difficult to compare the two results quantitatively.