Occurrence Condition of a Swirling Bubbling Jet in a Water Bath Covered with an Oil Layer

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(Received on June 28, 2005; accepted on July 29, 2005)

1. Introduction

In a previous study1) water model experiments were carried out to examine a possibility of treating wastewater with oil using a swirl motion of an ozone-air mixture. Air was used as a model gas for the mixture. Water and silicone oil were used as model liquids for wastewater and oil, respectively. Air was injected through a centered single-hole bottom nozzle into a cylindrical water bath covered with a silicone oil layer (see Fig. 1). A bubbling jet thus formed above the nozzle rotated around the vertical vessel axis under specific conditions. Two types of swirl motions appeared; shallow-water wave type and deep-water wave type. The latter swirl motion is useful for wastewater treatment because it has excellent mixing ability. Unfortunately, the occurrence condition of the swirl motion is not fully understood yet. A prediction method is proposed in this study for the occurrence condition.

2. Prediction of Occurrence Condition of Swirl Motion

2.1. Previous Result for Water Bath without Oil Layer

According to previous experiments2–8) on a swirl motion of a bubbling jet generated in a single liquid bath, i.e., a bath without an oil layer, the occurrence region of the swirl motion of the deep-water wave type can be schematically shown in Fig. 2. The boundary of the occurrence region is divided into four sub-boundaries (1), (2), (3), and (4).

In this study particular attention will be paid to the sub-boundary (2) because information on this sub-boundary is important in practical applications. This sub-boundary is expressed by the following empirical equation in the absence of a top oil layer.6)

\[
\log \left( \frac{H_{L2}}{D} \right) \approx 0.05 - 1.35(X + 6)/\exp(5) \quad (-4 < X < 0) \tag{1}
\]

\[
X = \log \frac{W_e}{r_w} \tag{2}
\]

\[
W_e = \rho_w Q_g^2 / (\sigma_w D^4) \tag{3}
\]

where \(H_{L2}\) is the bath depth, \(D\) is the vessel diameter, \(W_e\) is the modified Weber number, \(\rho_w\) is the density of water, \(Q_g\) is the gas flow rate, and \(\sigma_w\) is the surface tension of water.

Equation (1) is very complicated. Accordingly, it was modified as follows9):

\[
H_{L2}/D = (1 + 0.3X)^{1/2} \tag{4}
\]

The minimum gas flow rate for the occurrence of the swirl motion appears at around \(H_{L2}/D = 0.5\). An equation for the minimum gas flow rate is derived from Eq. (4) to give

\[
Q_{g,critical} = 0.0562(\sigma_w D^3/\rho_w)^{1/2} \tag{5}
\]

2.2. Occurrence Condition of Swirl Motion in Water Bath Covered with Oil Layer

In the previous study,1) the kinematic viscosity of silicone oil was varied over a wide range to cover the kinematic viscosity values encountered in the real wastewater treatment. The swirl motion of the deep-water wave type is the most likely to occur when the aspect ratio of the water
layer, \(H_{L2}/D\), is around 0.5 even if a top oil layer is present. The aspect ratio of the water bath, \(H_{L1}/D\), therefore was kept at 0.5, and the thickness of the top oil layer was increased over a wide range.

Figure 3 shows some examples of the occurrence region of a swirl motion of the deep-water wave type in the presence of a top silicone oil layer. As the aspect ratio of the lower water layer was kept at 0.5, the swirl motion occurred in the region enclosed with the thick solid line \((H_{L2}/D=0.5)\) and the open symbols representing the sub-boundary (2) for three kinds of silicone oils. The solid circles (●) represent the sub-boundary (2) for a single water bath.

As the thickness of the top layer decreases, the gas flow rate on the sub-boundary (2) should approach Eq. (5). The sub-boundary (2) therefore is further divided into two parts depending on the aspect ratio of the whole bath, \(H_{L}/D\). According to Fig. 3, a reflection point appears at around \(H_{L}/D=0.7\), where

\[
H_L = H_{L1} + H_{L2} \tag{6}
\]

We express the two parts as follows:

1. **Part 1**

\[
H_{L}/D = (1+0.3X_{wo})^{1/2} \quad (H_{L}/D>0.7) \tag{7}
\]

\[
X_{wo} = \log \frac{W_{wo}}{r_{m}} \tag{8}
\]

\[
W_{wo} = \frac{\rho_w}{\left(\sigma_{wo}D^2\right)}\left(\frac{Q_g - Q_{g,wo,cr}}{Q_{g,wo}}\right)^2 \tag{9}
\]

\[
\rho_m = \rho_o + (1-\phi)\rho_w \tag{10}
\]

\[
Q_{g,wo,cr} = 0.0562\sigma_{wo}D^2\rho_m^{1/2}\left(V_{g} / V_w\right)^{0.4} \tag{11}
\]

2. **Part 2**

\[
H_{L}/D = 0.2\left[\left(Q_{g} - Q_{g,wo}\right)\left(Q_{g,wo} - Q_{g,wo,cr}\right)\right]^2 + 0.5 \quad (0.7<H_{L}/D<0.5) \tag{12}
\]

\[
Q_{g,wo} = Q_{g,wo,cr} + 0.1413\sigma_{wo}D^2\rho_m^{1/2} \tag{13}
\]

where \(\rho_m\) is the mean density, \(\phi\) is the volume fraction of oil, \(\rho_o\) is the density of oil, and \(\sigma_{wo}\) is the interfacial tension between oil and water. Equation (7) was assumed by referring to Eq. (4), while Eq. (12) was assumed to pass the reflection point and \(H_{L}/D=0.5\) at \(Q_g = Q_{g,wo}\). The index of \(V\) in Eq. (11), 0.4, was determined by fitting Eqs. (7) and (12) to the presently measured values of the aspect ratio for the sub-boundary (2).

### 3. Comparison between Predicted and Measured Aspect Ratio Values for Sub-boundary (2)

Figures 4 through 6 compare the predicted and measured values of the aspect ratio for the sub-boundary (2). The three thin solid lines represent the predictions based on Eqs. (7) and (12). It is evident that the empirical Eqs. (7) and
can approximate the measured values with sufficient accuracy.

4. Conclusions

Two empirical equations (7) and (12) were proposed for predicting the sub-boundary (2) of the occurrence region of a swirl motion of a bubbling jet generated in a water bath covered with a silicone oil layer. The kinematic viscosity of silicone oil was varied to cover the kinematic viscosity values encountered in the real wastewater treatment. The measured aspect ratio for the sub-boundary (2) was satisfactorily approximated by these equations.

Nomenclature

- \( D \): Vessel diameter (m)
- \( d_{ni} \): Inner diameter of nozzle (m)
- \( H_l \): Bath depth \((=H_{L1}+H_{L2})\) (m)
- \( H_{L1} \): Thickness of silicone oil layer (m)
- \( H_{L2} \): Thickness of water layer (m)
- \( Q_g \): Gas flow rate \((m^3/s)\)
- \( \phi \): Volume fraction of oil \((-)\)
- \( \nu_s \): Kinematic viscosity of silicone oil \((m^2/s)\)
- \( \nu_w \): Kinematic viscosity of water \((m^2/s)\)

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