A NOTE ON THE RELATIONSHIP BETWEEN GAS ENTRAINMENT CURVE AND ITS STARTING VELOCITY

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Introduction

The gas entrainment rate and the gas entrainment phenomena of an impinging jet were reported in our previous papers. Accurate information on the jet velocity at the lower limit of the gas entrainment curve is also needed to develop the general trend of the curve, particularly in the initial entrainment region.

The present study is concerned with the relationship between the gas entrainment curve and the jet velocity at the lower limit of that curve. The minimum jet length on the occurrence of gas entrainment was determined with regard to vertically impinging liquid jets.

1. Experimental

The experimental apparatus used in this work was presented diagrammatically in our previous paper. The kinematic viscosity (\( \nu \)) of the liquid (aqueous solution) was in the range from 1.01 x 10^{-6} to 6.04 x 10^{-6} m²/s. The nozzle inner diameters (D) were 2.00 x 10^{-3} m and 3.02 x 10^{-3} m.

The jet length at the threshold of gas entrainment, i.e. the minimum jet length, was measured when the liquid jet impinged vertically on the liquid surface. The minimum jet lengths, from the nozzle exit to the liquid surface, were determined by shifting the nozzle vertically at constant jet velocity.

2. Results and Discussion

Figure 1 shows an example of the threshold curve on gas entrainment. The ratios (L_/D) of minimum jet length to nozzle inner diameter are plotted against jet velocities. The minimum jet length (L_) indicates the lower limit of the jet length when gas entrainment occurs. The data of Pedro Lara are also shown in Fig. 1.

Gas entrainment occurs when the value of the ratio (L_/D) of jet length to nozzle inner diameter is greater than that corresponding to the threshold curve, while it does not occur when the value of the L_/D ratio is less than that curve. It can be seen from Fig. 1 that the threshold curve shifts in the direction of high jet velocity with an increase of kinematic viscosity (\( \nu \)) of the liquid or with a decrease of nozzle inner diameter (D).

Gas entrainment occurred by the disturbed liquid jet like a train of drops below the jet velocity corresponding to the maximum value of the threshold curve. Such jets could be observed when the liquid jet disintegrated into drops. A cavity was created at the impacting point of such a jet. When no gas entrainment could be observed, the liquid surface in contact with the impinging smooth jet was elevated. The same behavior was reported by Ohyama et al. and Lin and Donnelly.

Near the nozzle exit no disturbances could be observed on the jet surface, and the surface was smooth. As the distance from the nozzle exit increased, disturbances appeared on the jet surface. The disturbances developed gradually with increasing jet length, and the liquid jet eventually disintegrated into drops. This jet length is the breakup length of the liquid jet.

The minimum jet length (L_) must be somewhat shorter than the breakup length, because gas entrainment necessarily occurs when a drop collides with the liquid surface. Gas entrainment resulting from the collision of a drop with the liquid surface has been
discussed in detail by other authors.\textsuperscript{1,2,9)}

The breakup length of the liquid jet decreases with liquid flow rate. Therefore, the $L_d/D$ ratio decreases with jet velocity.

When the liquid jet velocity is greater than that corresponding to the maximum value of the threshold curve, gas entrainment occurred with small bubbles by the liquid jet, on whose surface irregular disturbances could be observed. Gas entrainment could be observed when irregular disturbances on the jet surface developed to some extent.

Although no irregular disturbances could be observed near the nozzle exit at low jet velocity, those appeared with increasing distance from the nozzle exit. This distance from the nozzle exit to the point at which disturbances appeared on the jet surface decreased as jet velocity increased. Irregular disturbances could ultimately be observed on the jet surface at the nozzle exit. It is evident from the above-mentioned reasons that the value of the $L_d/D$ ratio decreases and would become about zero with increasing jet velocity.

Consequently, in the former range gas entrainment occurred by the jet like a train of drops, and in the latter range it depended upon the irregular disturbances on the jet surface. It can be considered that the maximum value of the $L_d/D$ ratio would correspond to the jet velocity at which the disturbances on the jet surface began to change.

Figure 2 shows the general trend of the variation of the gas entrainment curve with increasing kinematic viscosity of the liquid. Measurements of the gas entrainment rate could be made beyond somewhat greater jet velocity than that corresponding to the threshold curve. From this figure the gas entrainment curve tends to shift in the direction of high jet velocity with increasing kinematic viscosity.

To elucidate this trend, it is necessary to determine the starting velocity of the gas entrainment curve. The starting velocity can be defined as the jet velocity at the lower limit of the gas entrainment curve. Thus, such a velocity can be considered to fall on the extended line of the gas entrainment curve in the direction of low jet velocity. As soon as the liquid jet velocity is greater than the starting velocity, gas entrainment of an impinging liquid jet occurs intermittently. On the other hand, it does not occur below the starting velocity. Hence, the starting velocity of the gas entrainment curve is predictable from the threshold curve obtained under the same experimental conditions.

It can be seen from Fig. 1 that for vertically impinging jets the threshold curve shifts in the direction of high jet velocity with increasing kinematic viscosity. For example, the values of the starting velocities at an $L_d/D$ ratio of 50 increase with the kinematic viscosity. That is to say, the occurrence of gas entrainment becomes lower with increasing kinematic viscosity. Consequently, the gas entrainment curve tends to shift in the direction of high jet velocity as the kinematic viscosity of the liquid increases. This is because the starting velocities increase.

\textbf{Nomenclature}

\begin{itemize}
  \item $D$ \hspace{1cm} \text{nozzle inner diameter} \hspace{1cm} [m]
  \item $G$ \hspace{1cm} \text{gas entrainment rate} \hspace{1cm} [m^3/s]
  \item $L_e$ \hspace{1cm} \text{minimum jet length on the occurrence} \hspace{1cm} \text{of gas entrainment} \hspace{1cm} [m]
  \item $L_j$ \hspace{1cm} \text{length of liquid jet} \hspace{1cm} [m]
  \item $P_1$, $P_2$, $P_3$ \hspace{1cm} \text{transition points of gas entrainment curve}
  \item $V$ \hspace{1cm} \text{liquid jet velocity at nozzle exit} \hspace{1cm} [m/s]
  \item $\alpha$ \hspace{1cm} \text{angle between liquid jet discharge and} \hspace{1cm} \text{bath surface} \hspace{1cm} [°]
  \item $\nu_l$ \hspace{1cm} \text{kinematic viscosity of liquid} \hspace{1cm} [m^2/s]
\end{itemize}

\textbf{Literature Cited}