GAS ENTRAINMENT AND DEPTH OF PENETRATION IN A CO-CURRENT GAS-LIQUID DOWNFLOW BUBBLE COLUMN

GAUTAM KUNDU, DIBYENDU MUKHERJEE AND ARUN K. MITRA
Chemical Engineering Department,
Indian Institute of Technology, Kharagpur - 721302, India

Key words: Two Phase Downflow, Jet Penetration, Secondary Air, Gas Entrainment Ratio, Bubble Column

Performance of a two phase downflow bubble column fitted with an ejector has been evaluated with respect to depth of penetration of the jet in the liquid column and entrainment of secondary air. Experiments were carried out with a column of 51.6 mm i. d. and five different nozzles. Three systems, namely air-water, air-kerosene and air-paraffin were used. Correlations have been developed for predicting the gas entrainment ratio and the jet coefficient for momentum transfer during penetration as functions of the physical and dynamic variables of the system.

Introduction

In recent years some studies with two phase downflow system have appeared in the literature. In these studies the dispersion of gas has been carried out either with a plunging jet or with a sparger type system. In the plunging jet system, a jet of liquid plunging in to a pool of the same liquid carries along with it some ambient gas which breaks into bubbles due to momentum transfer of the jet. The liquid and the bubbles move downwards into the liquid pool and then the gas bubbles move up. In a sparger-type system, the gas sparger is fixed at the top of the column. Liquid with high velocity is forced through the column and as it moves it shears the gas from the sparger in the form of bubbles that move downwards to form a downflow bubble column.

Examples of relevant work published on plunging jet systems are; water aeration, gas liquid mixing in hazardous and fouling environments, mixing and reaction of gas-liquid in biochemical industries, and absorption potential of gas in liquid. These studies are highly encouraging and are said to be energetically attractive. No quantification of energy utilization, however, has been reported. The major drawbacks of the plunging jet system are i) Co-current downflow of gas and liquid is limited to a short distance depending upon the jet momentum and ii) the time of contact of the gas and liquid is very short.

In the sparger-type system, it is very difficult to get a stable flow and according to Bando et al. and Kulkarni and Shah, the range of meaningful operation is quite narrow. Apart from the above reported studies, other two phase downflow systems of interest are reported by Herbrechtmansmeier et al., Rao et al., Okhawa et al., Velan and Ramanujam, Ben Brahim et al., Stein and Schafer, Bhutado and Pangarkar etc.

A review on the design and development of fluid co-current contacting equipment shows that contactors belonging to the jet mixing category such as ejectors have gained importance due to the high interfacial area generation and high transfer coefficients. Since the use of liquid jet ejectors has been reported to be an efficient technique for gas-liquid mixing in two-phase flow, it has been thought that a column fitted with an ejector will be an appropriate gas liquid downflow system.

In the present work, a downflow bubble column fitted with an ejector has been developed from a novel gas/liquid contacting concept. It consists of a column fitted with an ejector on top wherein the liquid (continuous phase) is introduced through the nozzle as primary fluid and the gas (dispersed phase) is aspirated as the secondary fluid. Part of the kinetic energy of the primary fluid is used in the dispersion of the gas and in the formation of fine bubbles. The system not only incorporates the effect of a plunging jet but also gives the effect of a sparger-type of systems used as gas-liquid downflow bubble columns. This paper presents a detailed analysis on the length of mixing zone and the gas entrainment ratio.

1. Length of the Mixing Zone

It is well known that when a liquid jet of uniform initial velocity is discharged from a nozzle into a fluid, a tangential separation surface is created between the jet and the surrounding medium. The instability of this surface creates eddies which move both in the main direction of flow and in the direction across it. This causes exchange of momentum with the surrounding medium. As a result, a region of finite thickness with a downward velocity is formed between the border of the jet and the surrounding fluid. When the jet impinges on the liquid surface, it entrains the surrounding gas along with it. This mechanism of entrainment of gas by the jet has been well described by McKeogh & Eevine.
In the present downflow gas-liquid system, the liquid jet and the aspirated secondary gas move coaxially in the ejector and gas-liquid mixing occurs in the extended contactor. It is observed that three distinct zones are prevalent; the coaxial zone, the intense mixing zone and the uniform bubble flow zone (Fig. 2d). The length of the intense mixing zone has been termed as the jet penetration depth.

It is well known that when a free liquid jet is expelled from a nozzle, the magnitude of the axial velocity component of the jet is much greater compared to the magnitude of the radial velocity component. Therefore, for all practical purposes in any analytical treatment, the radial velocity component can be neglected. Further, since the magnitude of axial point velocity of the jet changes along the radius of the jet, it can be said that,

\[ V_1 / V_r = f(r) \]

(1)

As the pressure along the length of a jet remains practically constant and is equal to the pressure in the surrounding fluid, the momentum with which the jet is emerging from the nozzle also remains constant. Therefore,

\[ \rho_1 V_0 \pi r_n^2 \int_0^r \rho_1 V_1^2 r dr = \text{constant} \]

(2)

For a round jet, the above equation can be written in the dimensionless form,

\[ V_c^2 \pi x \int_0^r \rho_1 V_1^2 (r) (r) dr = \text{constant} \]

(3)

Substituting for \( V/V_r \) from Eq. (1), one gets

\[ V_c^2 \pi x \int_0^r \rho_1 f_z (r) (r) dr = \text{constant} \]

(4)

Since the integral of Eq. (4) has a constant value at a given value of \( x \), it can be said that

\[ V_c^2 \pi x = \text{constant} \]

(5)

This constant is equal to the jet momentum at any cross-section of the jet. The jet momentum at the tip of the nozzle being known, it can be written that,

\[ V_c^2 \pi x \alpha \rho_1 V_0 \pi r_n^2 V_{in} \]

(6)

or,

\[ V_c = C_j \left( V_{in} r_n / x \right) \]

(7)

where \( C_j \) is the proportionality constant for momentum transfer.

It has been pointed out earlier that when a liquid jet impinges on the surface of the same liquid, it entrains surrounding air along with it. It has been found experimentally that at a constant liquid flow rate and initial height of liquid, the length of the mixing zone remains constant with very little fluctuation\(^{11}\). Hence it may be assumed to be in dynamic equilibrium. Therefore it can be said that

\[ p_l (x) = p_g (x) + 4 \left[ \delta_i / D_i (x) \right] \]

(8)

where \( p_l (x) \) is the liquid pressure at any length, \( p_g (x) \) is the pressure in the bubbles formed, \( (4G/D (x)) \) is the surface tension force on the bubbles and \( D (x) \) is the average diameter of the bubbles at any \( x \). Assuming that the surface tension forces are negligible compared to \( p_g (x) \), the Eq. (8) reduces to

\[ p_l (x) = p_g (x) \]

(9)

Supposing the length of the mixing zone for a particular \( V_{in} \) and \( L_j \) is \( L_{in} \), it can be said that up to height \( L_{in} \) of the column, the pressure of the fluid \( p_l (L_{in}) \) is proportional to the kinetic energy of the jet and the pressure of the gas, \( p_g (L_{in}) \) is proportional to weight per unit area of mixing zone of length \( L_{in} \). Hence, it may be written that,

\[ p_l (L_{in}) = C_1 \left[ \rho_1 V_c^2 / 2 \right] \]

(10)

and

\[ p_g (L_{in}) = C_2 \left[ \rho_1 L_{in} \right] \]

(11)

It may be noted that though \( C_1 \) is a constant, \( C_2 \) depends on momentum of the jet and other physical and dynamic variables of the system. By incorporating the values of \( p_l (L_{in}) \) and \( p_g (L_{in}) \) in Eq. (9), one gets

\[ \rho_1 V_c^2 / 2 = C_3 \left[ \rho_1 L_{in} \right] \]

(12)

By substitution of \( V_c \) from Eq. (7), one gets

\[ C_j^2 \rho_1 \left[ V_{in} \pi r_n^2 / 2 \pi x \right] = C_3 \left[ \rho_1 L_{in} \right] \]

(13)

Since \( x = L_j + L_{in} \), so,

\[ C_j^2 \rho_1 \left[ V_{in} \pi r_n^2 / 2 \left( L_j + L_{in} \right)^2 \right] = C_3 \left[ \rho_1 L_{in} \right] \]

(14)

Now the momentum of the jet at the nozzle tip is

\[ M_j = \pi r_n^2 V_{in} \rho_1 \]

(15)

So Eq. (14) reduces to,

\[ \left( L_{in} / d_n \right) \left[ \left( L_j + L_{in} \right) / d_n \right] = \left( M_j / C_j \right)^{2 / 2 \pi C_3 \left[ \rho_1 d_n \right]} \]

(16)

or,

\[ K_j = \left[ 2 \pi C_3 \left[ \rho_1 L_{in} \right] \left( L_j + L_{in} \right)^{2 / 2 \pi C_3 \left[ \rho_1 d_n \right]} \right]^{0.5} \]

(17)

where, \( K_j = (C_j / \sqrt{C_j}) \) and is dependent upon physical and dynamic variables of the system.

2. Experimental Apparatus

The schematic diagram of the experimental setup is shown in Fig. 1. It consists of an ejector assembly, \( E \), an extended pipeline contactor, \( C \), a gas-liquid separator, \( SE \) and other accessories like a centrifugal pump, \( PU \), a pressure gauge, \( P \), manometers, \( M_1 \) - \( M_n \), control valves \( V_1 \) - \( V_n \), quick closing solenoid valves \( SV_1 \) - \( SV_n \), a rotameter, \( R \), a thermometer, \( Th \) and storage tank, \( T \). For visual observation of the flow and mixing patterns, the ejector assembly was made of perspex glass. The divergent end of the diffuser has a diameter of 51.6 mm and is fitted with a flange so that an extended contactor can be easily attached to it. Two extended contactors of lengths 2030 mm and 760
mm have been used in the experiments. The major dimensions of the apparatus are given in Table 1. In the present setup the optimum dimensions of the ejector were used as reported by Mukherjee et al. The forcing nozzle, N is of a straight hole type and is precision-bored to obtain a smooth passage and to avoid any undue shock and losses. The dimensions of the nozzles used are given in Table 2. An extended pipeline contactor C was provided as shown in Fig. 1 for gas-liquid two-phase downflow. The lower end of the contactor projected 300 mm into the separator, SE.

This arrangement enabled uniform downflow movement of two phases and also easy separation of the bubbles from the main stream. The air-liquid separator is a rectangular mild steel vessel of 320 mm x 320 mm size and 855 mm height and is sufficiently large to minimize the effect due to liquid going out of the system or due to air-liquid separation. There were three outlets provided at the top, bottom and centre of the separator. The bottom and centre outlets allowed the liquid to flow out while the top outlet allowed the air to escape from the separator. By operating the valves

Fig. 1 Schematic diagram of experimental setup

Table 1. Dimensions of ejector-contactor assembly (dimensions: mm.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of throat, ( d_1 )</td>
<td>19.0</td>
</tr>
<tr>
<td>Length of throat, ( L_1 )</td>
<td>284.0</td>
</tr>
<tr>
<td>Angle of divergence of diffuser ( \gamma )</td>
<td>7°</td>
</tr>
<tr>
<td>Length of divergent diffuser, ( L_2 )</td>
<td>204.0</td>
</tr>
<tr>
<td>Diameter of contactor, ( d_c )</td>
<td>51.6</td>
</tr>
<tr>
<td>Diameter of gas inlet, ( d_t )</td>
<td>12.5</td>
</tr>
<tr>
<td>Length of contactors</td>
<td>2030.0 &amp; 760.0</td>
</tr>
</tbody>
</table>

Table 2. Dimensions of nozzles

<table>
<thead>
<tr>
<th>Nozzle diameter, ( d_n ) (mm.)</th>
<th>Area ratio, ( A_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.96</td>
</tr>
<tr>
<td>2</td>
<td>4.76</td>
</tr>
<tr>
<td>3</td>
<td>5.55</td>
</tr>
<tr>
<td>4</td>
<td>6.35</td>
</tr>
<tr>
<td>5</td>
<td>7.93</td>
</tr>
<tr>
<td>6</td>
<td>9.53</td>
</tr>
</tbody>
</table>

Table 3. Physical Properties of fluids at 303 K

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density, ( \rho ), [kg/m³]</th>
<th>Viscosity, ( \mu ), [kg/m.s]</th>
<th>Surface Tension, ( \sigma ), [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>995.7</td>
<td>0.797 \times 10^{-3}</td>
<td>0.0710</td>
</tr>
<tr>
<td>Kerosene</td>
<td>829.5</td>
<td>2.991 \times 10^{-3}</td>
<td>0.0292</td>
</tr>
<tr>
<td>Paraffin</td>
<td>808.9</td>
<td>5.682 \times 10^{-3}</td>
<td>0.0290</td>
</tr>
<tr>
<td>Air</td>
<td>1165</td>
<td>1.863 \times 10^{-5}</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 2 Experimental Procedure
Fig. 3 Variation of jet coefficient for momentum transfer with liquid Reynolds number

$V_L$ and $V_G$ (Fig. 1), the liquid level inside the separator can be maintained. The front and back side of the separator are fitted with transparent perspex sheets so as to enable viewing of the inside of the separator.

3. Experimental Technique

The nozzle, the ejector assembly and the contactor were perfectly aligned in a vertical position to obtain an axially symmetric jet. The nozzle was fixed at the optimum position at a distance of one throat diameter from the entry of the throat. This distance was decided from our earlier experiments with horizontal and vertical liquid-gas systems\(^6\).

Preliminary experiments have shown (Fig. 2) that when the jet is not arrested and is allowed to pass through the apparatus, it travels straight through the ejector and vertical column and then directly hits the bottom of the gas-liquid separator. For such a situation, it has been found that there is no aspiration of gas in the ejector (Fig. 2a). If a certain level of liquid is maintained in the gas-liquid separator, the jet plunges into the liquid and it forms a plunging jet system (Fig. 2b). In this case also, there is no aspiration of air from the secondary inlet the ejector. It is only when the liquid level reaches the extended contactor and the jet plunges into the liquid that secondary air gets entrained (Fig. 2c). When the liquid height is raised in the column, an intense mixing zone followed by a zone of two-phase bubbly downflow is observed (Fig. 2d). The distance of the liquid level in the contactor from the tip of the nozzle is $L_j$ while $L_m$ is the length of the intense mixing zone or the distance up to which the jet penetrates the liquid in the contactor.

For a particular flow through the nozzle when the jet plunges into a liquid in the column maintained at a particular height by adjusting pressure in the separator, secondary air is entrained and two-phase mixing takes place in the mixing zone. The two-phases flow into the separator and get separated. When the system reaches steady state, Data on length of the intense mixing zone, $L_m$, separator pressure, $P_s$, gas entrainment, $Q$, and liquid flow rate, $Q_L$, were noted. Data were collected for different nozzles, height of liquid inside the column and liquid flow rate. Experiments have been carried out with three different liquids. These are water, kerosene and paraffin and their physical properties are given in Table 3.

4. Results and Discussion

4.1 Correlation for $K_j$

It has been pointed out that $K_j$ is influenced by $L_m$, $L_j$ and $M_j$ which are in turn affected by the following variables: Physical variables : properties of liquid and gas, $\rho_L$, $\mu_L$, $\sigma_L$, $\rho_g$ and $\mu_g$.

Geometric variables : ejector dimensions, $d_e$, $d_s$, and $h_s$, and Dynamic variables : volumetric flow rates of liquid and gas, $Q_L$ and $Q_G$.

Hence $K_j$ can be written as,

$$K_j = f_i(Q, \rho, \mu, \sigma, Q, \rho, \mu, d_e, d_s, h_s, g)$$  \hspace{1cm} (18)

In this case, since experiments have been carried out with gas aspiration, it was found that $Q_g$ is a direct function of $Q$. Further, since only air was used as a secondary fluid, $\rho_g$ and $\mu_g$ are constants. Hikita et al.\(^8\) have also reported that gas phase properties have no significant effect on gas holdup. Considering all these, the terms $Q_g$, $\rho_g$ and $\mu_g$ have been neglected and the Eq. (18) has been rewritten as,

$$K_j = f_i(Q, \rho, \mu, \sigma, d_e, d_s, h_s, g)$$  \hspace{1cm} (19)
A dimensional analysis leads to,

\[ K_j = \lambda_j \left( Re_{\infty}, A_r, H_m, S_{\mu}, Mo \right) \]  

(20)

In order to establish the nature of the function relationship between \( K_j \) and the different dimensionless groups, log-log plots were made of \( K_j \) against \( Re_{\infty} \), \( A_r \) and \( H_m \) for a particular gas-liquid system. A typical plot of \( K_j \) against \( Re_{\infty} \) is shown in Fig. 3. The relation is linear and similar relations have been obtained for other variables. Hence, Eq. (20) may be written as,

\[ K_j = c_{1j} Re_{\infty}^{b_1} A_r^{b_2} H_m^{b_3} S_{\mu}^{b_4} Mo^{b_5} \]  

(21)

Equation (21) was fitted to the values of \( K_j \) calculated from experimental data with the help of Eq. (17) by multiple linear regression. The correlation obtained may be expressed as,

\[ K_j = 3.04 Re_{\infty}^{0.59} A_r^{1.26} H_m^{0.10} S_{\mu}^{2.65} Mo^{1.12} \]  

(22)

By applying statistical techniques, the correlation coefficient and overall standard deviation were calculated and found to be 0.88 and 16.78\%, respectively. The \( (K_j)_{\text{exp}} \) and \( (K_j)_{\text{cal}} \) plot is shown in Fig. 4. By substituting the values of various physical and dynamic variables into Eq. (22), the value of \( K_j \) can be obtained. The length of mixing zone, \( L_m \) can then be calculated from Eq. (17).

4.2 Correlation of gas entrainment

Achieving gas entrainment and downward flow of bubbles in a vertical downflow system is rather a difficult task. This is because the gas bubbles have a natural tendency to rise due to buoyancy effects. Therefore, to achieve a downward flow of gas bubbles, the carrier liquid velocity must be higher than the bubble rising velocity. Hence gas entrainment in a down flow bubble column is a very complex phenomena. The gas entrainment ratio, \( G_{er} \), is also influenced by the same variables, so it may be written as

\[ G_{er} = \lambda_{2j} \left( Re_{\infty}, A_r, H_m, S_{\mu}, Mo \right) \]  

(23)

The linear variations of \( G_{er} \) with respect to \( Re_{\infty} \) and \( A_r \) (Fig. 5 and 6 respectively) on a log-log scale, when all other variables remain constant, suggest the following type of relationship:

\[ G_{er} = c_{2j} Re_{\infty}^{b_{2j}} A_r^{b_{2j}} H_m^{b_{3j}} S_{\mu}^{b_{4j}} Mo^{b_{5j}} \]  

(24)

Equation (24) was fitted to experimental gas entrainment ratio data by multiple linear regression. The calculation were done using the least squares technique. This leads to

\[ G_{er} = 3.15 \times 10^{-6} Re_{\infty}^{2.87} A_r^{1.02} H_m^{1.27} S_{\mu}^{0.12} Mo^{0.78} \]  

(25)

The correlation coefficient and standard deviation are found to be 0.99 and 11.76\%, respectively. A plot of experimental and calculated values of \( G_{er} \) is shown in Fig. 7.

Conclusions

An attempt has been made to quantify the mixing
length and the jet penetration depth and gas entrainment ratio in terms of the physical and dynamic variables of the system. These are useful in the design of a downflow bubble column fitted with an ejector which combines advantages of a plunging jet and a sparger-type system.

**Nomenclature**

- \( a_c \): area of contactor [m²]
- \( a_n \): area of nozzle [m²]
- \( A_r \): ratio of area of contactor to nozzle, \( a_c/a_n \) [-]
- \( b_{1.1} \): exponents in the different regression equations [-]
- \( c_{1.2} \): coefficients in the different regression equations [-]
- \( C_r - C_h \): proportionality constants [-]
- \( C_t \): proportionality constant for momentum transfer [-]
- \( d_c \): diameter of contactor [m]
- \( d_n \): diameter of nozzle [m]
- \( d_{in} \): diameter of gas inlet [m]
- \( d_t \): diameter of throat [m]
- \( D \): average diameter of bubbles [m]
- \( f_{1.4} \): functions of the different variables [-]
- \( g \): acceleration due to gravity [m/s²]
- \( G_{fr} \): gas entrainment ratio i.e. the ratio of mass flow rate of gas to that of liquid, \( Q_g/\left(\rho_l \cdot V_l\right) \) [-]
- \( h_c \): height of liquid inside the contactor [m]
- \( H_r \): ratio of height of liquid in column to diameter of contactor [-]
- \( H_{in} \): ratio of height of liquid in column to diameter of nozzle [-]
- \( K_t \): jet coefficient for momentum transfer [-]
- \( L_d \): length of diffuser [m]
- \( L_1 \): length of jet before mixing [m]
- \( L_{in} \): length of jet after penetration in liquid column or length of mixing [m]
- \( L_t \): length of throat [m]
- \( M_j \): momentum of jet [kg m/s]
- \( M_{p} \): Morton number, \( g \cdot \mu / \left( \rho_l \cdot \sigma_{lv} \right) \) [-]
- \( p_l \): pressure of gas [N/m²]
- \( P_l \): pressure of liquid [N/m²]
- \( Q_{fr} \): volumetric flow rate of gas [m³/s]
- \( Q_{in} \): volumetric flow rate of liquid [m³/s]
- \( r \): radius from the jet axis [m]
- \( r_{o} \): radius of outer boundary of jet [m]
- \( r_{n} \): radius of nozzle [m]
- \( Re_{ci} \): Reynolds number of liquid based on contactor diameter, \( d \cdot V_l/\rho_l \cdot \mu_l \) [-]
- \( Re_{in} \): Reynolds number of liquid based on nozzle diameter, \( d \cdot V_l/\rho_l \cdot \mu_l \) [-]
- \( S \): Suraymann number of liquid based on contactor diameter, \( \rho_l \cdot \sigma_{lv}/\mu_l^2 \) [-]

**Literature Cited**