TRANSITION FROM BUBBLING TO JETTING AT SINGLE ORIFICES

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The transition from bubbling to jetting at single holes was studied experimentally. Transient jetting in addition to the six different regimes reported by Muller et al. was noticed. Empirical equations predicting the steady to pulsating and the pulsating to transient jetting transitions are obtained in terms of the dimensionless liquid depth, the modified Froude number and the Bond number, which have been proposed by Payne et al., and the state diagram showing the transition from bubbling to jetting is given by considering both the previous and the authors' results at single orifices.

Introduction

The perforated plate is one of the simplest types of gas-liquid contacting devices. It is being used increasingly in industry. At low gas flow rates and high liquid depths, the dispersion formed on a plate will be liquid continuous (froth), while it will be gas continuous (spray) at high gas flow rates and low liquid depths. Recently, the operation of industrial plates has come to require relatively large free areas for the cleaning of waste gases containing dust and for the desulfurization of flue gases because large amounts of gas are treated. On these plates, liquid holdup is low and the dispersion will be froth or spary, depending on operational conditions. The plate efficiency can be strongly influenced by the hydrodynamic regime in which the plate is operating. Accordingly, for the design and the operation of gas-liquid contacting devices treating a large amount of gas, knowledge of the froth-to-spray transition is very important. Nevertheless, there is still a lack of information on this transition.

The regimes of froth and spray on a perforated plate can be considered to correspond to those of bubbling and jetting at a submerged orifice. On the basis of qualitative considerations regarding the bubbling and jetting regimes, they have been empirically divided into six distinct regimes—meniscus, steady jetting, pulsating jetting, deformed bubbling, perfect bubbling and imperfect bubbling—according to liquid depth and gas velocity. Then, Payne et al. have studied the transition using the residual pressure drop criterion.

In the present work, experimental results are reported for the transition from bubbling to jetting at a single orifice for the purpose of quantifying the phenomena of the transition from froth to spray on a perforated plate. From the results, transient jetting, which had not been found previously, was noticed between pulsating jetting and deformed bubbling. Further, a quantitative state diagram showing the transition from bubbling to jetting at single orifices is obtained by use of both the authors' and previous results.

1. Phenomena of Bubbling and Jetting Regimes

Figure 1 is the state diagram showing the six different flow regimes and their dependence on gas velocity and liquid depth obtained by Muller et al.:

1) Liquid meniscus
   At very low depth, surface tension forces hold a liquid to the plate and maintain a stable hole above the plate orifice. Droplets are not produced.

2) Steady jet regime
   As gas velocity increases at low depth, it will start interacting with the liquid, stripping off droplets from the interface. The jet diameter is almost equal to the orifice diameter.

3) Pulsating jet regime
   Increasing the liquid depth at constant gas velocity will cause closer interaction between liquid and gas jet, leading to instability. The gas jet diameter varies from the orifice diameter to a few times that size.

4) Imperfect bubbling
   At high liquid depth and low gas velocities, bubbles will begin to break the surface before they are fully deformed.

5) Perfect bubbling
   At high liquid depth and low gas velocities, discrete bubbles of approximately spherical or spheroidal
shape will be noticed.

6) Deformed bubbling

Although this regime is often confused with perfect bubbling, the bubbles become more and more distorted at high gas velocities and high liquid depth.

Figure 2 shows the mechanism of pulsating jet as modeled by Nielsen et al.\(^7,8\) on the basis of high-speed cine photography. The gas channel enlarges near the plate but remains stationary near the liquid surface (a, b), reaches a maximum diameter (c), and decreases, with a liquid ligament forming and issuing droplets from its top (d–f).

In steady jetting, which is essentially different from pulsating jetting, the jet diameter is approximately equal to the orifice diameter, and the liquid is continuously atomised at the hole by the high-velocity gas streams.

In the present study, we shall be considering the steady and the pulsating jet experimentally for the purpose of obtaining a quantitative state diagram showing the transition from bubbling to jetting (Fig. 1).

2. Experimental Apparatus and Procedure

2.1 Experimental apparatus

The experimental apparatus is shown schematically in Fig. 3. Air from the compressor (1) passed through the air filter (2) and was maintained at a regulated pressure by means of the pressure regulator (3). A steady supply of gas was ensured by means of the buffer tank (4). Controlled air contacted a liquid at the orifice (7) and flowed out of the apparatus. The main apparatus (25 × 25 × 80 cm) was constructed of transparent acrylic resin. The baffle plate (8) prevented droplets from flowing out of the apparatus.

Liquid from the reservoir (9) was circulated with the pump (10) and controlled by the valve (11). Part was circulated to the reservoir as overflow and part flowed to the weir box (8), contacted air at the orifice (7), and dispersed into air as droplets. Liquid flow rates were measured by the orifice flow meter (12). The weir boxes (5) (5 cm diameter) were made of transparent acrylic pipe, the heights of which were 8.7 and 9.5 cm.

Geometries of the orifices employed and physical properties of liquids are listed in Tables 1 and 2, respectively. Surface tension, density and viscosity of liquids were measured by surface tension balance (Shimadzu ST-1), densimeter and viscometer, respectively.

2.2 Experimental procedure

As shown in Fig. 3, liquid and gas flow rates were set by the needle valves (13) and (14), respectively. When a liquid was supplied to the weir box at a steady rate, then for a given air velocity through the hole, the liquid level would eventually settle down to a steady value. The amount of entrained liquid falling back into the weir box was negligibly small. After steady state was reached, the liquid depth was measured by using the cathetometer (15). As there was no overflow, the entrainment was then equal to the rate of liquid supply. This procedure was employed by Nielsen et al.\(^7,8\) and Muller et al.\(^6\).
Table 1. Geometries of orifices

<table>
<thead>
<tr>
<th>Orifice number</th>
<th>Hole diameter $D$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2.02 \times 10^{-3}$</td>
</tr>
<tr>
<td>2</td>
<td>$3.01 \times 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>$3.66 \times 10^{-3}$</td>
</tr>
<tr>
<td>4</td>
<td>$4.08 \times 10^{-3}$</td>
</tr>
<tr>
<td>5</td>
<td>$4.52 \times 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>$6.06 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of liquids

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Density $\rho_i$ [kg/m$^3$]</th>
<th>Viscosity $\mu_i$ [Pa·s]</th>
<th>Surface tension $\sigma$ [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>999</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$73.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Ethanol</td>
<td>970</td>
<td>$2.32 \times 10^{-3}$</td>
<td>$35.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Millet jelly aq. soln.</td>
<td>1161</td>
<td>$6.12 \times 10^{-3}$</td>
<td>$63.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

3. Experimental Results and Discussion

3.1 Flow mechanism

Photographs of flow patterns at an orifice are shown in Fig. 4.

Figure 4(a) shows the meniscus regime noted in Fig. 1. No droplets are visible, and surface tension forces maintain a stable hole above the plate orifice. The steady jet regime is found in Fig. 4(b). Very small droplets strip off from the interfaces as a mist without liquid ligament. The jet diameter is constant and equal to the hole diameter, approximately. In Fig. 4(c), larger droplets and a ligament are observed with increasing liquid depth. The jet diameter becomes larger as compared with that of steady jet. This is the pulsating jet. The discontinuity of the gas jet is noticed with increasing liquid depth as shown in Fig. 4(d). This phenomenon was not reported by Muller et al. We will call this jetting regime transient jetting.

3.2 Free entrainment

Figure 5 shows a comparison of the present data for free entrainment with the previous results at an orifice of about 6 mm in diameter. The two results show satisfactory agreement.

Figure 6 shows the free entrainment at an orifice of 3.01 mm in diameter. It can be seen that the free entrainment, which of course depends on gas velocity, increases with liquid depth. The broken lines in this figure show the transitions from steady to pulsating and from pulsating to transient jetting. The determination of the transition points was ensured by the change of entrainment rate for steady to pulsating transition, and by finding the discontinuity of a jet and the change of the free entrainment rate whose data have no reproducibility, for pulsating to transient jetting transition. Similar results mentioned
above were also noticed in aqueous millet jelly and ethanol solution systems.

3.3 Correlation of bubbling to jetting transition

The transitions from jetting to bubbling or imperfect bubbling occur by a similar mechanism.\(^9\) Gas inertia stabilizes the jet, gravitational force on the liquid causes the collapse of the jet, and surface tension destabilizes the jet. A balance between gas inertial and gravitational force in single-phase flow has been given by the Froude number.\(^{11}\) However, in two-phase flow of gas and liquid, where those densities are different, we must include a density term.\(^9,^{11}\) Under these considerations, Payne et al.\(^9\) have proposed the modified Froude number for a balance between gas inertial and gravitational force and the Bond number for a balance between surface tension and gravitational force as follows:

\[ Fr^* = \left[ \frac{\rho_g V_j^2}{(\rho_l - \rho_g)gD} \right]^{1/2} \]  

\[ Bo = \frac{(\rho_l - \rho_g)gD^2}{\sigma} \]  

Therefore, we will try to correlate the transition from steady to pulsating jetting and from pulsating to transient jetting using these dimensionless numbers.

**Figure 7** shows the correlation of steady to pulsating jetting transition. The results are correlated well in terms of \(H/D\) and \(Fr^*\). The following empirical equation is obtained:

\[ H/D = 0.12(\text{Bo}^*)^{0.8} \quad 4 < Fr^* < 30, \quad 0.55 < Bo < 10 \]  

On the other hand, the transition from pulsating to transient jetting is characterized by the ratio \(H/D\), the Bond number, and the modified Froude number as shown in **Fig. 8**. The graphical equations of correlation in the transition are

\[ H/D = 0.12(\text{Fr}^*)^{1.23}(\text{Bo})^{1/2} \quad 0.55 < Bo < 4, \quad 4 < Fr^* < 30 \]  

\[ H/D = (\text{Fr}^*)^{0.65} \quad 4 < Bo < 50, \quad 1 < Fr^* < 10 \]  

The difference between Eqs. (4) and (5) is presumably attributable to the fact that the gas inertial force become a controlling factor in \(Bo > 4\). The empirical results of Muller et al.\(^6\) and Pinczewski et al.\(^10\) are also plotted in Figs. 7 and 8, respectively.

It might be noted that, Payne et al.\(^9\) found that Banerjee’s empirical results\(^2\) for the transition from imperfect bubbling to pulsating jetting may be correlated by the following empirical equation:

\[ H/D = (\text{Fr}^*)^2 - 14.6(\text{Bo})^{-0.5} + 2.2 \]  

Furthermore, Payne et al.\(^9\) determined the transition from jetting to bubbling by measuring the residual pressure drop and believed that the transition from jetting to bubbling occurs over a range of experimental conditions. However, their results are presumed to correspond to the transition from transient jetting to bubbling because they could not find transient jetting.
the empirical results of Payne et al.,9) Banerjee et al.2) and the authors. The meniscus regime reported by Müller et al.6) and the bubbling to transient jetting transition were not considered experimentally in the present study because of the difficulties of determining the transition by means of the entrainment rate criterion. However, from this chart, the mechanism of the transition from bubbling to jetting may be clarified.

Conclusion

To clarify the behavior and the characteristics of the froth-to-spray transition on a perforated plate, the bubbling to jetting transitions at single orifices were empirically studied, and the following results were obtained.

1) Transient jetting was noticed at an orifice in addition to the six regimes found by Müller et al.6)

2) Empirical equations predicting the transitions from steady to pulsating jetting and from pulsating to transient jetting were obtained.

3) The state diagram showing the transition from bubbling to jetting and its dependence on $H/D$, $Fr^*$ and $Bo$ was obtained by considering the results of previous workers and of the authors at single orifices.

Nomenclature

\[ Bo = \text{Bond number} = \frac{(\rho_l - \rho_g)gD^2}{\sigma} \quad [\text{--}] \]

\[ D = \text{hole diameter} \quad [\text{m}] \]

\[ E_f = \text{free entrainment} \quad [\text{m}^3/\text{s}] \]

\[ Fr^* = \text{modified Froude number} \quad \left( -\frac{\rho_l V_h^2}{(\rho_l - \rho_g)gD} \right)^{1/2} \quad [\text{--}] \]

\[ g = \text{gravitational acceleration} \quad [\text{m/s}^2] \]

\[ H = \text{liquid depth} \quad [\text{m}] \]

\[ V_h = \text{gas velocity through hole} \quad [\text{m/s}] \]

\[ \rho_g, \rho_l = \text{density of gas and liquid} \quad [\text{kg/m}^3] \]

\[ \sigma = \text{surface tension} \quad [\text{N/m}] \]

\[ \mu_l = \text{viscosity of liquid} \quad [\text{Pa s}] \]

Literature Cited


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