Air-Water Two-Phase Flow through a Pipe Junction*

(Effect of the Reynolds Number on the Local Void Fraction Distribution)

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The distribution of the local void fraction across a section of a conduit was studied experimentally in air-water two-phase flow flowed through a pipe junction with the branching angle of 90° and the area ratio of unity. As in the previous report, the main conduit of the pipe junction was set up vertically, and upward air-water bubbly and slug flows were produced in the main upstream section. If the flow regime, the quality and the ratio of lateral mass flow discharge of water to total mass flow discharge of water are equal, the larger the Reynolds number is, the more violent the variety of the local void fraction distribution adjacent to the branching point in the lateral conduit is. However, the variety in the main downstream section is hardly influenced by the Reynolds number.

Key Words: Multiphase Flow, Experimental Study, Pipe Junction, Reynolds Number, Local Void Fraction Distribution

1. Introduction

It is very important to know the dividing gas-liquid two-phase flow mechanism in a pipe junction for industrial plant and atomic furnace systems design. The importance of understanding the mechanism has been gradually acknowledged.

Recently, some investigations on the phase distribution or phase separation of two-phase flow in a pipe junction—relations between the rate of mass flow discharge of gas in the lateral conduit to total mass flow discharge of gas and the rate of mass flow discharge of liquid in the lateral conduit to total mass flow discharge of liquid—have been published in succession^{(1)~(5)}. However, the local void fraction distribution across a section of the conduit, which is one of the most important factors influencing the performance of the plant device, has rarely been determined.

Thus, in the previous report⁽⁶⁾, the author reported the experimental results of the distribution of the

local void fraction across a section of a conduit adjacent to the branching point for air-water two-phase flow. In the present report, the experimental results for two-phase flow similar to those reported in the previous report are described in detail in order to demonstrate effect of the Reynolds number on the local void fraction distribution.

The pipe junction under the experiment has a branching angle of 90° and the area ratio of unity because the internal diameters of the main and lateral conduits are the same. The main conduit of the junction is set up vertically, and upward air-water bubbly and slug flows are produced in the main upstream section.

2. Experimental Setup and Procedure

The experimental setup and procedure were similar to those described in the previous report⁽⁶⁾. The pipe junction of the experiment was made of sheets of clear acrylic plastic plate so that the flow patterns could be easily observed. The internal diameters of the main and lateral conduits d were both 21 mm. The Reynolds number Re_w for water flow in the upstream section of the main conduit and the ratio of mass flow

* Received 29 th May, 1991. Paper No. 90-0338 B

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discharge of water G_{w2}/G_{w1} were regulated by valves V_1 to V_6 , shown in Fig. 1 of the previous report. The quality X_1 in the upstream section of the main conduit was regulated by valves V_8 to V_{10} , shown in Fig. 1 of the previous report.

The local void fraction α_{oc} was measured by the electrical resistivity probe method which was developed by Iida et al.⁽⁷⁾ The number of bubbles passing through the probe per unit time n was measured by means of switching the circuit of the multichannel pulse height analyzer under experiment. The installed positions of probes were $l_1/d=3.0$ for the upstream section of the main conduit, $l_2/d=1.0, 2.0, 3.0, 5.0, 10.0$ and 20.0 for the lateral conduit, and $l_3/d=0.0, 1.0, 3.0, 5.0, 10.0$ and 20.0 for the downstream section of the main conduit. Here, l_i denotes the distance from the branching point—the intersecting point of the axes of the main and lateral conduits—to the probe position. However, subscripts $i=1, 2$ and 3 identify the conduit shown in Fig. 1; that is, 1 and 3 denote the upstream and downstream sections of the main conduit, respectively, and 2 the lateral conduit. The probe was positioned 1 mm by 1 mm from the axis to the wall of the conduit on the radii r_i of the plane $\delta=0^\circ-180^\circ$, which contains the axes of the main and lateral conduits, and of the plane $\delta=90^\circ-270^\circ$, which is perpendicular to the plane $\delta=0^\circ-180^\circ$, as shown in Fig. 1. Here, δ denotes the probe-mounting angle, as shown in Fig. 1.

Moreover, the local void fraction α_{oc} is defined by Eq. (1).

$$\alpha_{oc} = \sum_i t_{ai} / T \quad (1)$$

Here, t_{ai} and T are the gas contact period and total sampling time.

3. Experimental Results

In the experiments, the distribution of α_{oc} and n across the section of the conduit were measured at the probe installed position when the Reynolds number for water flow in the section of the main conduit $Re_{w1}(=u_{w1}d/\nu_w)$ was constant, the ratio of lateral mass flow discharge of water to total mass flow discharge of

water G_{w2}/G_{w1} was changed from 0.0 to 1.0 at the intervals of 0.2 and the quality X_1 was varied. Here, u_{w1} denotes the superficial velocity of water in the main upstream section, ν_w the kinematic viscosity of water and G the mass flow discharge through the conduit per unit time. The subscripts a and w refer to the values for air and water, and 1, 2 and 3, the names of the above-mentioned conduits, respectively. The total sampling time at each measuring point is 10×5 (times).

In the experiment, the flow conditions of the upstream section of the main conduit were arranged as follows: $Re_{w1} \approx 1.55 \times 10^4$, $u_{w1} \approx 0.81$ m/s, pressure $P_1 \approx 0.238$ MPa absolute at $l_1/d=43.7$, water temperature $T_{w1} \approx 290$ K (T_{w1} was approximately constant during the experiment), quality $X_1 \approx 0.25\%$ (the superficial velocity of air u_{a1} was approximately equal to 0.07 m/s), 0.050 2% (0.14 m/s), 0.060 5% (0.17 m/s), 0.071 8% (0.2 m/s), 0.092 1% (0.26 m/s) and 0.111 7% (0.32 m/s). The experiments were also carried out in the same manner as mentioned above under the following flow conditions: $Re_{w1} \approx 6.2 \times 10^4$, $u_{w1} \approx 3.22$ m/s and $X_1 \approx 0.025\%$ ($u_{a1} \approx 0.29$ m/s).

Certain aspects of the experimental results are shown in Figs. 2 to 4. Before the experiments to

Fig. 1 Probe-mounting angle δ

Fig. 2 Experimental results of the rates between mass flow discharge of air and water

determine the local void fraction distribution were performed, experiments to observe the relationship between the ratios of mass flow discharge of water G_{w2}/G_{w1} and mass flow discharge of air G_{a2}/G_{a1} were made in cases in which X_1 was changed and Re_{w1} was kept constant, and Re_{w1} was changed and X_1 was kept constant. The results obtained are shown in Figs. 2(a) and (b). Moreover, Figs. 3 and 4 show some parts of the experimental results for the local void fraction distribution across the section of the conduit. Figures 3(a) and 4(a) show the experimental results obtained in the lateral conduit. Figures 3(b) and 4(b) show the experimental results obtained in the downstream section of the main conduit. In Figs. 3 and 4, the values of the abscissa r_i/d from 0.0 to 0.5 correspond to $\delta=0^\circ$ or 90° and those from 0.0 to -0.5 correspond to $\delta=180^\circ$ or 270° .

The experimental results for α_{loc} and n obtained in the upstream section of the main conduit coincide fairly well with those measured at $Re_{w1} \approx 3.1 \times 10^4$ as reported previously⁽⁶⁾. However, when $Re_{w1} \approx 1.55 \times$

10^4 , the flow regime is observed to be bubbly flow if X_1 is less than or equal to 0.050 2% and is observed to be slug flow if X_1 is greater than or equal to 0.071 8%. Although the experimental value of X_1 governing the transition from bubbly to slug flow is 0.050 4% for $Re_{w1} \approx 3.1 \times 10^4$, it is 0.060 5% for $Re_{w1} \approx 1.55 \times 10^4$. When $G_{w2}/G_{w1} \approx 0.442$ 2, $Re_{w1} \approx 1.03 \times 10^4$ and 5.7×10^3 , and the air discharge Q_{a1} was very slight, the conduit walls were illuminated for observation by a beam sheet parallel to the centerline plane. The flow patterns close to the centerline plane of the junction were recorded on film. The experimental results were compared with the results calculated according to the free-streamline theory⁽⁸⁾. Both results coincide fairly well similar to the case for $Re_{w1} \approx 3.1 \times 10^4$ ⁽⁶⁾. However, the separation of real flow in the lateral conduit increases with increasing Re_{w1} .

4. Discussion of Results

4.1 Mass flow discharge ratio of water and air

As in the previous report⁽⁶⁾, in the experimental

Fig. 3 Some examples of the experimental result for the local void fraction distribution. (Case of constant Reynolds number and varying quality.)

range, the ratio of the mass flow discharge of air in the lateral conduit to the total mass flow discharge of air, G_{a2}/G_{a1} , is usually greater than the ratio of the mass flow discharge of water in the lateral conduit to the total mass flow discharge of water, G_{w2}/G_{w1} , independent of the values of Re_{w1} and X_1 , as shown in Figs. 2(a) and (b). That is, more air in the main upstream section flows into the lateral than into the main downstream section.

When $Re_{w1} \approx 1.55 \times 10^4$, the difference between G_{w2}/G_{w1} and G_{a2}/G_{a1} —the difference between the experimental mean curve and the line SF which presents the same flow ratio of air and water in the lateral conduit as in the main conduit—becomes largest near G_{w2}/G_{w1} of 0.4 if X_1 is less than or equal to 0.071 8% and it becomes largest near G_{w2}/G_{w1} of 0.5 if X_1 is 0.092 1% or 0.111 7%, as shown in Fig. 2(a). When X_1 is constant, the difference between G_{w2}/G_{w1} and G_{a2}/G_{a1} at any value of G_{w2}/G_{w1} for $Re_{w1} \approx 1.55 \times 10^4$ is less than that for $Re_{w1} \approx 3.1 \times 10^4$, and the value

of G_{w2}/G_{w1} at which the maximum difference between the mean experimental curve and the line SF occurs for $Re_{w1} \approx 1.55 \times 10^4$ is larger than that for $Re_{w1} \approx 3.1 \times 10^4$.

Figure 2(b) indicates the experimental results between G_{a2}/G_{a1} and G_{w2}/G_{w1} when X_1 remains constant and Re_{w1} varies. The flow regime in the upstream section of the main conduit is bubbly flow in all cases. Generally, the value of G_{a2}/G_{a1} at the same value of G_{w2}/G_{w1} is dependent on Re_{w1} if the flow regime and the value of X_1 are the same.

The experimental results shown in Figs. 2(a) and (b) coincide qualitatively with those obtained by Collier⁽⁹⁾ and Rubel et al.⁽³⁾ due to the horizontal pipe junction with the branching angle of 90° .

The previous report⁽⁶⁾ explains that the relationships between G_{a2}/G_{a1} and G_{w2}/G_{w1} shown in Figs. 2(a) and (b) are the pressure gradients from the main upstream section to the main downstream section, and those from the main upstream section to the

Fig. 4 Some examples of the experimental result for the local void fraction distribution, (Case of constant quality and varying Reynolds number.)

lateral, the difference of the inertia magnitudes of air and water, the secondary flow peculiar to the junction and the pressure drop in the lateral caused by the flow separation from the upstream corner of the lateral entrance. Furthermore, the Reynolds number has recently been found to be one of the contributing factors through the experimental results indicated in the present paper.

4.2 Local void fraction distribution

Certain aspects of the experimental results for the local void fraction distribution obtained in the lateral and the downstream section of the main conduits are shown in Figs. 3(a) and (b) for the case in which the Reynolds number Re_{w1} is approximately equal to 1.55×10^4 and the quality X_1 is varied. Also shown in Figs. 4(a) and (b) is the case in which the quality X_1 remains constant and the Reynolds number Re_{w1} is varied.

The experimental results reported in the present report coincide qualitatively with those reported in the previous report⁽⁶⁾. Although the aspects of the variation of the local void fraction distribution adjacent to the branching point are very complex, the experimental results obtained on the plane $\delta = 90^\circ - 270^\circ$ are almost symmetrical with the axis of the junction independent of Re_{w1} , G_{w2}/G_{w1} , the flow regime and X_1 . The experimental results obtained in the upstream section of the main conduit are similar to those presented in the previous report.

The experimental results have the following general features.

4.2.1 "Case 1:" constant Reynolds number and variable quality When $Re_{w1} \approx 1.55 \times 10^4$, the flow regime in the upstream section of the main conduit is bubbly flow if X_1 is less than or equal to 0.0502%, slug flow if X_1 is greater than or equal to 0.0718% and transient from bubbly to slug flow if X_1 is equal to 0.0605%, as mentioned above.

When the flow regimes are bubbly and transition flows, generally, although the aspect of local void fraction distribution in the lateral conduit and the downstream section of the main conduit has its own particular characteristics, the magnitude of α_{oc} is only associated with the value of X_1 , as shown in Figs. 3(a) and (b). When X_1 increases and the flow regime becomes slug flow, the shape of the distribution of α_{oc} tends to uniformity across the section of the conduit.

In the lateral conduit, the value of α_{oc} in the immediate downstream section of the branching point becomes large because of the pressure drop caused by the flow separation, as shown in Fig. 3(a). Moreover, owing to the gravity effect, the bubbles in the lateral conduit rise and crowd around the bottom of the top

of the conduit as the lateral conduit lies in the horizontal plane. Therefore they are only observed on the plane $\delta = 180^\circ$, and stratified or wavy flow is formed in the downstream direction. Generally, the distance from the branching point to the place where stratified or wavy flow is formed increases with increasing X_1 and G_{w2}/G_{w1} .

On the other hand, in the downstream section of the main conduit, when G_{w2}/G_{w1} is small, the distance from the branching point to the place where the shape of the local void fraction distribution becomes almost axisymmetric is comparatively long, as shown in Fig. 3(b). It is similar to previously reported results⁽⁶⁾, although the Reynolds number Re_{w1} is different. Although $X_1 \approx 0.1117\%$ and the flow regime in the upstream section of the main conduit is slug flow, the shape of the distribution of α_{oc} at the place where the distance from the branching point to the measuring position is sufficiently long is similar to those obtained in bubbly flow, as shown in Fig. 3(b). Based on the photographs of the flow pattern, this is the reason why the small bubbles in the main upstream section flow only into the main downstream section and the large shell-shaped bubbles in the main upstream section flow chiefly into the lateral, but their tails are occasionally torn off and flow into the main downstream section. Therefore, after passing through the near-downstream section of the branching point where violent turbulence occurs, flow in the main downstream section behaves as if it were bubbly flow.

4.2.2 "Case 2:" constant quality and variable Reynolds number The experimental results shown in Fig. 4 indicate those for which the value of X_1 is approximately equal and the flow regime is bubbly flow. However, the experimental results for $Re_{w1} \approx 3.1 \times 10^4$ are the same as those previously reported⁽⁶⁾. In the lateral conduit, the aspects of the distribution of α_{oc} varies with Re_{w1} if X_1 and G_{w2}/G_{w1} are the same. Namely, the values of α_{oc} in the near-downstream section of the branching point increase with increasing Re_{w1} for both cases of $\delta = 0^\circ - 180^\circ$ and $\delta = 90^\circ - 270^\circ$. This means that the greater the value of Re_{w1} , the larger the velocity in the immediate downstream section of the branching point because of the high degree of separation originating from the upstream corner of the lateral entrance. Therefore, the greater the degree of the pressure drop, the higher the degree of the expansion of bubbles. Similar to the previous report⁽⁶⁾, the experimental results show that more bubbles combine in the separated region as the measured number of bubbles n decreases. Generally, owing to the gravity effect, stratified or wavy flow is formed up in the lateral conduit and the distance from the branching point to the place where stratified or

wavy flow is formed after flow division extends with increasing Re_{w1} and G_{w2}/G_{w1} .

In the downstream section of the main conduit, the aspects of the distribution of α_{oc} barely change as the discharge of air from the upstream section to the downstream section in the main conduit is naturally small; in addition, the value of α_{oc} is hardly influenced by the Reynolds number if X_1 remains constant. However, the presence of the pipe junction has considerable influence in the downstream section of the main conduit if G_{w2}/G_{w1} is small.

The experimental results for which $Re_{w1} \approx 1.55 \times 10^4$ and 3.1×10^4 (6) and the flow regime is slug flow indicate that the distribution of α_{oc} in the lateral and the downstream section of the main conduits are influenced by the values of Re_{w1} , X_1 , G_{w2}/G_{w1} and l_2/d or l_3/d . But they are qualitatively the same as those observed in bubbly flow, although they are peculiar to slug flow.

5. Conclusions

Air-water two-phase flow flowed through a pipe junction with the branching angle of 90° and main and lateral conduits with identical internal diameters. The main conduit of the junction was set up vertically, and upward bubbly and slug flows were produced in the upstream section of the main conduit. The distribution of the local void fraction α_{oc} in the neighborhood of the branching point was investigated experimentally when the Reynolds number Re_{w1} of water flow and the quality X_1 were varied. The results show that :

(1) more air in the main upstream section flows into the lateral rather than the main downstream section independent of the flow regime and quality. Its degree is dependent on Re_{w1} and the mass flow discharge ratio of water G_{w2}/G_{w1} ;

(2) on the plane perpendicular to the plane containing the axes of the main and lateral conduits, α_{oc} is approximately symmetrical with the axis of the conduit in the neighborhood of the branching point independent of Re_{w1} , G_{w2}/G_{w1} , the flow regime and X_1 ;

(3) generally, in the lateral conduit, the degree of variation in the distribution of α_{oc} in the immediate downstream section of the branching point for the small value of G_{w2}/G_{w1} is larger than that for larger values of G_{w2}/G_{w1} if the flow regime and X_1 are the same. The larger the value of Re_{w1} , the grater the variety of the distribution of α_{oc} as the degree of pressure drop increases with increasing flow separation from the upstream corner of the lateral entrance ;

(4) as the lateral conduit lies in the horizontal

plane, the bubbles crowd around the bottom of the top of the conduit due to the gravity effect and flow heads downstream as stratified or wavy flow. Generally, the distance from the branching point to the place where the stratified or wavy flow is formed increases with increasing Re_{w1} and G_{w2}/G_{w1} if X_1 remains constant ;

(5) in the upstream section of the main conduit, the influence of the presence of the junction is rarely observed, and the distribution of α_{oc} is hardly influenced by Re_{w1} . In the downstream section of the main conduit, the variation in the distribution of α_{oc} is less than that in the lateral conduit as more air in the main upstream section flows naturally into the lateral than in the main downstream section.

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