UNIFORM DISTRIBUTION CONDITIONS OF TWO-PHASE FLOW IN HORIZONTAL HEADER TO VERTICAL BRANCH PIPES WITH HORIZONTAL ENTRANCE CONNECTIONS

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ABSTRACT

Experiments were conducted to study distribution behaviors of two-phase flow in horizontal header to vertical branch pipes with or without horizontal entrance connections. The experimental apparatus were made of transparent acrylic resin for the observation. With a small amount of bubbles, the water distribution rate to the first pipe rapidly increased and the rates to the others decreased in the header without horizontal entrance connections. By increasing the airflow rate in the header inlet further, the flow rate to the first pipe takes a maximum and then tends to decrease. By using horizontal entrance connections, the stratified flow in the header could be formed. In the stratified flow, the gas-liquid interface formed near at the each inlet of branch pipes could assure the gas flow not only to the first branch pipe but also the others. Calculation results indicated that the differential pressure ΔP at the vertical section of branch pipe generally decreased to the minimum point, and after that, increased with increasing the gas flow rate at a given water flow rate. When the gas flow rate was less than the minimum point, the more amount of gas flow to a certain branch pipe decreased the ΔP and increases the flow rate furthermore. So it was difficult to obtain the stable uniform distribution at the smaller gas flow rate less than the minimum point even in the stratified flow.

INTRODUCTION

Flow header to distribute a fluid to small multiple pipes is commonly used in steam generators, boilers and heat exchangers. It is recommended to avoid bubbles in the header to obtain a uniform water flow rate to each branch pipe. But in some cases, the header has to be used to distribute gas and liquid two-phase flows. How to achieve the uniform distribution of two-phase flow is very important issue for the stable and design-based operation of systems.

The previous studies have focused on a phase separation behavior at T-branches of piping (Hwang et. al. [1]; Suu [2]). The systematic study for the two-phase distribution to multiple branch pipes is scarce. Collier [3] introduced the systematic study undertaken in Harwell but the detail has not been published. The present authors studied experimentally distribution behaviors of two-phase flow in a horizontal header with four vertical branch pipes [4, 5]. It was confirmed that the water distribution rate to the first pipe rapidly increased and the rates to the others decreased with a contamination of a small amount of bubbles. With the airflow rate increasing in the header inlet further, the flow rate to the first pipe took a maximum value and tended to decrease. A sufficient amount of water supply to the header was necessary to assure enough water to all the pipes when the header was contaminated with a small amount of bubbles.

By protruding the branch pipe into the horizontal header, the stratified flow in the header could be successfully formed. The non-uniform distribution of water was suppressed because the gas-phase entered not only the first pipe but also the others in the stratified flow pattern [5, 6]. The best result was obtained when the four branch pipes were protruded into the center of header. However an unstable distribution behavior was also reported in some cases even when the stratified flow was established in the header.

The experiment was conducted to study another method to obtain the uniform distribution of two-phase flow in horizontal header to vertical branch pipes. The effects of horizontal entrance connections of branch pipes to the horizontal header were studied and discussed. The usage of horizontal entrance connection to branch pipes is preferable for the formation of stratified flow as well as the protruding branch pipe header. Distribution behavior of water with or without a horizontal entrance connection was studied experimentally in a horizontal header with four vertical pipes.

EXPERMIMENTAL APPARATUS AND METHOD

Shown in Fig.1 is a schematic diagram of the experimental apparatus. The experimental apparatus consisted of horizontal header, four vertical branch pipes with horizontal entrance connections and separators made of transparent acrylic resin. The branch pipes were connected to the header at an interval of 130 mm with or without horizontal entrance connections. The horizontal entrance length of branch pipes was 110 mm and turned upward with bends to vertical sections of 1060 mm in length. The inner diameter of branch pipe was 10 mm. The horizontal length of 110mm was tentatively adapted as more than 10 times of the branch pipe diameter. Water and air supplied in the upstream of header was distributed into the four branch pipes. Two kinds of header with the cross sections of 40×40 and 40×10 mm in height×width were used for the parametric study. The water was collected in the separators at the end of branch pipes and air was released to the atmosphere. The water flow rate q to each branch pipe was obtained by noting the time interval to accumulate a known level of water in the separator. The distributed water flow ratio

q/Q was calculated with the total water flow rate Q. The air was supplied from a compressor and measured with an orifice or float-type flow meters before entering the header.

PREDICTION METHOD OF DISTRIBUTION

The header pressures before and after the branch pipe, i, counted from the header inlet are define as P_i and P_{i+1}, respectively, as shown in Fig.2. The ratio of the header flow area, A, to the branch pipe flow area, A_S, is defined as $m(=A/A_S)$. By using the pressure recovery coefficient, η, the pressure difference, P_i - P_{i+1}, is expressed as follows;

$$p_{i+1} - p_i = \eta \frac{\rho_L}{2}\left(j_{L,i}{}^2 - j_{L,i+1}{}^2\right) \quad (1)$$

where j is superficial velocity, ρ is density and a suffix L indicates water. It is reported that η is approximately 1 for the flow area ratio, m, of the present experimental apparatus and gradually decreases with a decrease in m [7]. In the present calculation, η was fixed as 1.

The pressure difference between the inlet and outlet of the branch pipe is,

$$p_i - p_a = R\frac{\rho_L}{2}\left(j_{L,i} - j_{L,i+1}\right)^2 m^2 + \rho_m g h \quad (2)$$

where g is acceleration due to gravity, h is vertical length of branch pipe and suffix a indicates atmosphere. The first term on the right hand side is the pressure loss and the second one is the static pressure difference. The parameter R is a pressure loss coefficient defined as,

$$R = \frac{\xi + \varsigma}{(1-\alpha)^2} + 4\lambda\frac{h'}{d}\Phi_L^2 \quad (3)$$

where d is the inner diameter of branch pipe, Φ_L is the two-phase multiplier, h' is branch pipe length and α is void fraction.

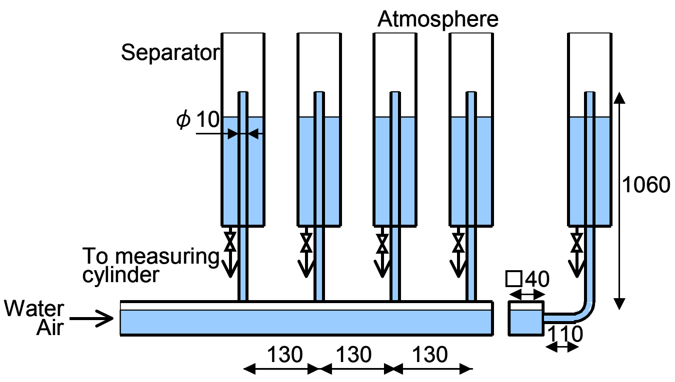

Fig. 1 Experimental apparatus

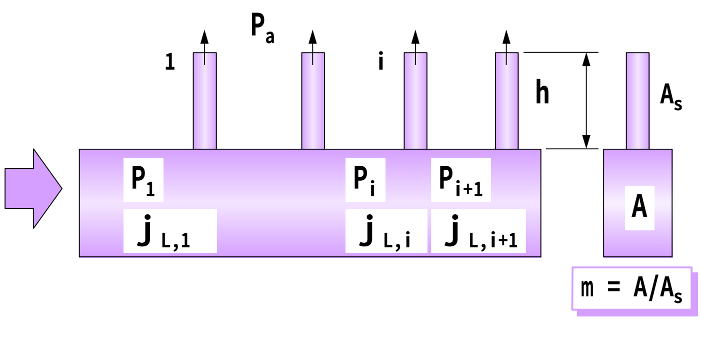

Fig. 2 Notation for calculation procedure

The inlet distribution loss coefficient ξ was assumed as 0.5 in the present calculation. As a uniform distribution can be obtained with a larger value of R [4], 0.5 is used as a conservative value. The bent pipe loss coefficient ζ was assumed as 0.132 for the horizontal connection. The friction loss coefficient λ is defined as,

$$\lambda_L = 16/Re \quad \text{(laminar)} \quad (4)$$

$$\lambda_L = 0.079\,Re^{-0.25} \quad \text{(turbulent)} \quad (5)$$

where Re is the Reynolds number in a branch pipe($=ud/\nu_L$), u is water velocity in branch pipe.

The two-phase multiplier Φ_L by Lockhart-Martinelli [8] is described as,

$$\Phi_L = \left(1 + \frac{C}{X} + \frac{1}{X^2}\right)^{1/2} \quad (6)$$

where C is Chisholm[9] parameter defined as 21 in this study. The parameter X can be defined as,

$$X = \sqrt{\frac{dp_L}{dp_G}} \quad (7)$$

where dp_L and dp_G is the single-phase frictional pressure loss evaluated with a superficial liquid and gas velocity, respectively.

The average density of two-phase ρ_m is,

$$\rho_m = \alpha\rho_G + (1-\alpha)\rho_L \quad (8)$$

The void fraction α can be estimated with the following drift flux model by Zuber-Findlay[10], which is applicable to the wide range of gas volume fraction in pipes.

$$\alpha = \frac{j_G}{1.13(j_L + j_G) + 1.18\left[\frac{\sigma(\rho_L - \rho_G)g}{\rho_L{}^2}\right]^{1/4}} \quad (9)$$

(10)

In the present study, the superficial gas velocity in the header was assumed as,

$$j_{G,i+1} = R_C j_{G,i} \quad (11)$$

where R_C is carryover rate of gas phase which is not absorbed into the branch pipe. The non-dimensional pressure and velocity are defined as,

$$p_i^* = \frac{p_i - p_a - \rho_L g h}{\rho_L j_{L,1}{}^2/2} \quad (12)$$

$$j_{L,i}^* = \frac{j_{L,i}}{j_{L,1}} \quad (13)$$

So Eqs.(1)(2) become

$$p_{i+1}^* - p_i^* = \eta\left(j_{L,i}^{*\,2} - j_{L,i+1}^{*\,2}\right) \quad (14)$$

$$p_i^* = Rm^2\left(j_{L,i}^* - j_{L,i+1}^*\right)^2 - \frac{\alpha(\rho_L - \rho_G)gh}{\rho_L j_{L,1}{}^2/2} \quad (15)$$

The above Eqs.(14) and (15) are the basic equations to give a flow distribution in the header. The important parameters in the equations are the flow area ratio, m, pressure recovery coefficient, η, and the pressure loss coefficient, R. Shown in Fig.3 is an iteration procedure to obtain the distributions of velocity and pressure in the header. The calculation starts at the velocity condition, $j^*_{L,1}$=1 and an assumed pressure, P^*_1, at the header inlet. Equations (14) and (15) give the next non-dimensional velocity and pressure in the header. This procedure yields the whole distribution of pressure and velocity in the header. After that, the assumed initial pressure is modified to give zero velocity in the header just after the last branch pipe. The iteration is continued until zero velocity at the end of header is obtained.

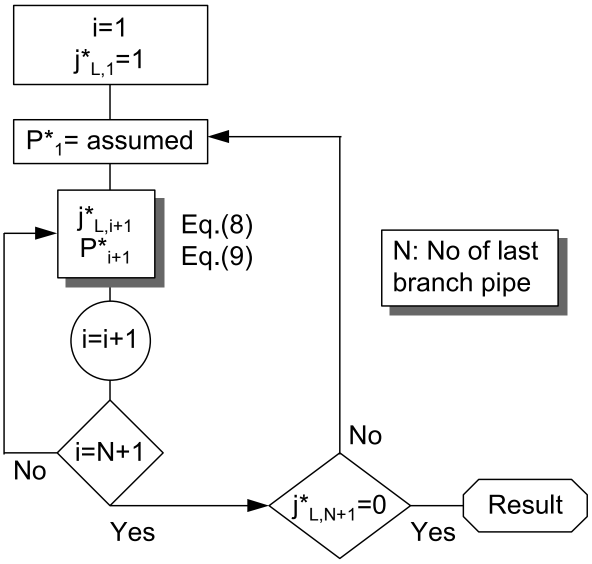

Fig. 3 Iteration procedure

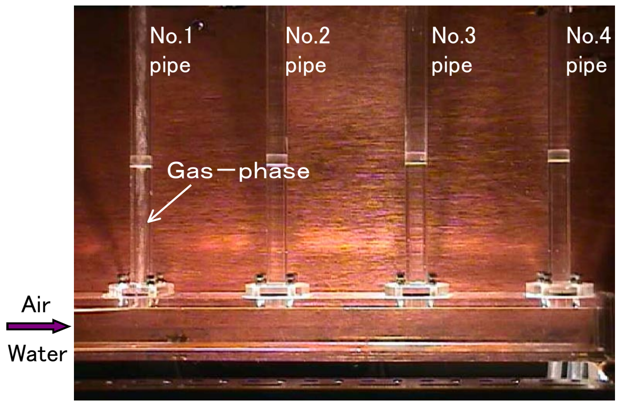

Fig. 4 Two-phase flow in horizontal header

Table. 1 Gas carryover rate

$j_{L,1}$ (m/s)	R_C
0.07	0.002
0.085	0.005
0.1	0.008

WITHOUT HORIZONTAL CONNECTION

Shown in Fig. 4 is a typical flow pattern observed in the two-phase header of 40×40 mm in height×width. The air bubbles flowed along on the upper wall of header and the most was absorbed into the first pipe as indicated as white streams in the photograph. A few amounts of bubbles were carried beyond the first branch pipe. So the gas flow rate to the first pipe was the largest in the four pipes. The flow pattern in the vertical branch pipe was bubbly or slug flow. In the present calculation, the carryover rate defined by Eq.(11) was assumed as Table.1. This indicates the almost of gas phase were absorbed in the first branch pipe.

Shown in Fig. 5 is the relation of water distribution rate to each pipe and the air velocity, $j_{G,1}$, at the water velocity, $j_{L,1}$, of 0.07m/s in the header of 40×40 mm. The lines are predictions for the distribution rates to the first pipe and the other pipes. The predicted flow rates to the third and fourth pipe were approximately the same. With a small amount of bubbles, the water distribution rate to the first pipe rapidly increases and the rates to the others decrease. As the bubbles are absorbed only into the first pipe, the average two-phase density in the first pipe decreases. The decreased pressure head promotes the water flow into the first pipe such as in an airlift pump. By increasing the airflow rate in the header inlet further, the flow rate to the first pipe takes a maximum and then tends to decrease. The increased airflow rate in the first pipe increases the two-phase pressure loss in the pipe and results in a reduction of the water flow rate. The present calculation method assuming the gas carryover in the header predicted well the general distribution behavior.

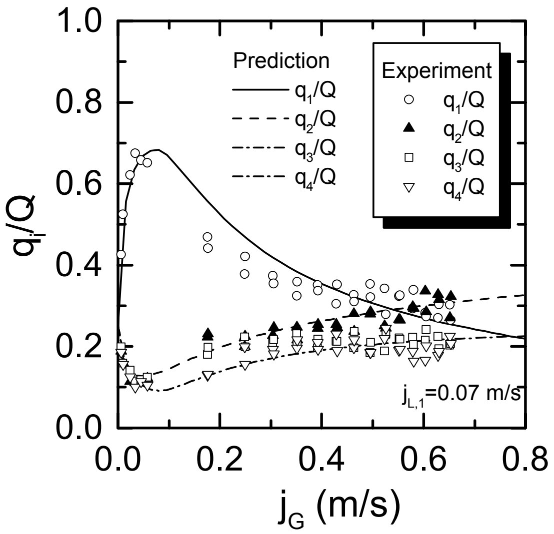

Fig. 5 Water distribution rates to branch pipes from header without horizontal connection at inlet velocity of 0.07 m/s

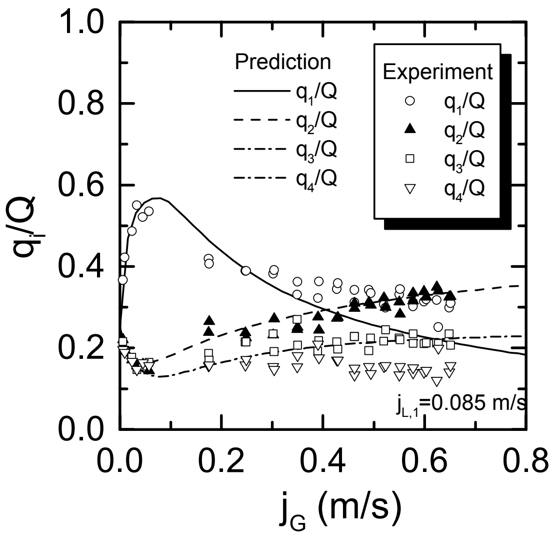

Fig. 6 Water distribution rates to branch pipes from header without horizontal connection at inlet velocity of 0.085 m/s

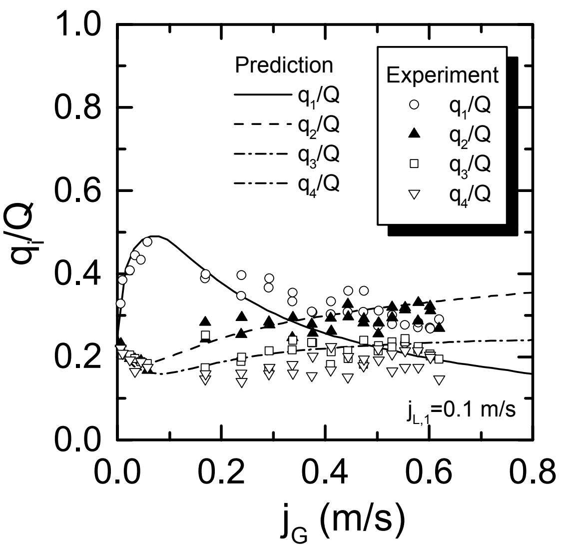

Fig. 7 Water distribution rates to branch pipes from header without horizontal connection at inlet velocity of 0.1 m/s

Shown in Fig. 6 and 7 are the relation of water distribution rate to each pipe and the air velocity $j_{G,1}$ at the water velocity $j_{L,1}$ of 0.085 and 0.1m/s, respectively, in the header of 40×40 mm. Though the general behavior is same as those observed in Fig. 5, the difference in water distribution rates between the first and the other pipes becomes smaller due to the increased water flow rate at the header inlet. The above results indicate the sufficient water supply to the header is necessary to assure enough water not only to the first pipe but also to the others when the header is used to distribute the two-phase flow.

WITH HORIZONTAL CONNECTION

Shown in Fig. 8 is a typical flow pattern observed in the two-phase header of 40×40 mm with the horizontal connection. The stable interface formed near at the inlet of branch at the middle of header sidewall can be observed. In this stratified flow made with this entrance configuration, it is possible that the air can enter not only into the first branch pipe but also into the others. The formation of the stratified flow is considered to be one of the necessary conditions for a uniform distribution of two-phase flow. Figure 9 shows a typical flow pattern observed in the smaller header of 40×10 mm with the horizontal connection. The wave crests of the air/water interface sometimes contact to the upper wall of header and the slugging of liquid could be observed. The slug flow could be recognized at the higher two-phase velocities than those in the case of Fig.8.

Shown in Fig. 10 and 11 are the relation of water distribution rate to each pipe and the air velocity $j_{G,1}$ in the header of 40×40 and 40×10 mm, respectively. In Fig.10 of 40×40 mm header, uniform distribution was obtained at the relatively large gas flow rate where the flow pattern in the header was stratified flow. However, non-uniform distribution was obtained at the relatively small gas flow rate though the stratified flow was formed in the header. When the flow pattern was not stratified flow in Fig.11 of 40×10 mm header, non-uniform distribution was expected and actually observed. Judging from these experimental observations, the stratified flow in the horizontal header is considered to be one of the necessary conditions for the uniform distribution.

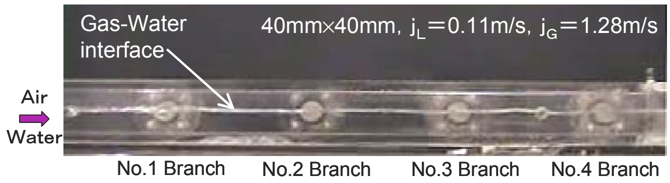

Fig. 8 Two-phase flow in horizontal header of 40×40 mm in height×width with horizontal connection

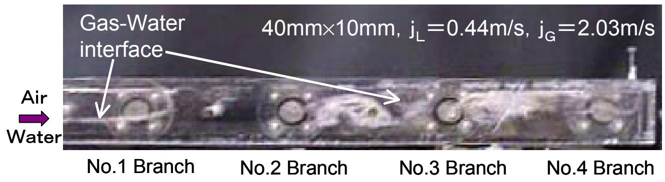

Fig. 9 Two-phase flow in horizontal header of 40×10 mm in height×width with horizontal connection

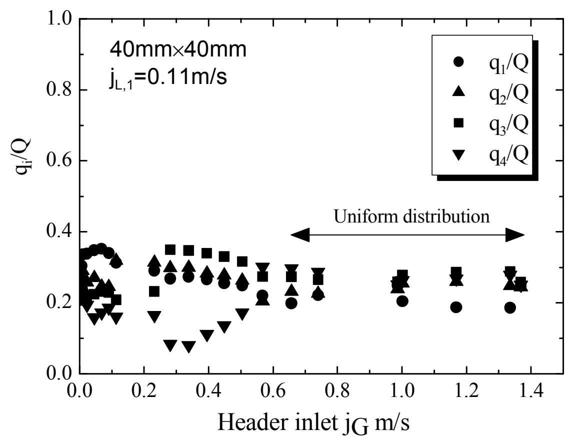

Fig. 10 Water distribution rates to branch pipes from header of 40×40 mm with horizontal connection

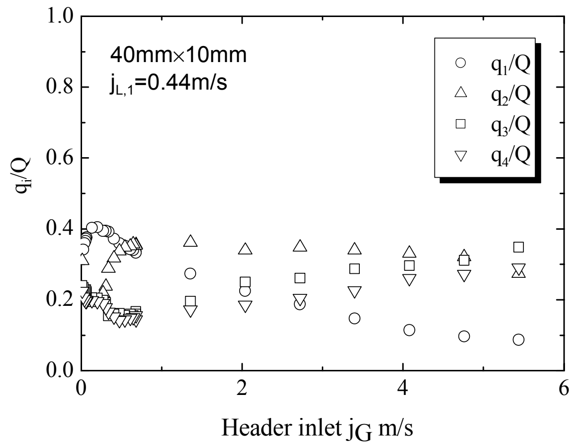

Fig. 11 Water distribution rates to branch pipes from header of 40×10 mm with horizontal connection

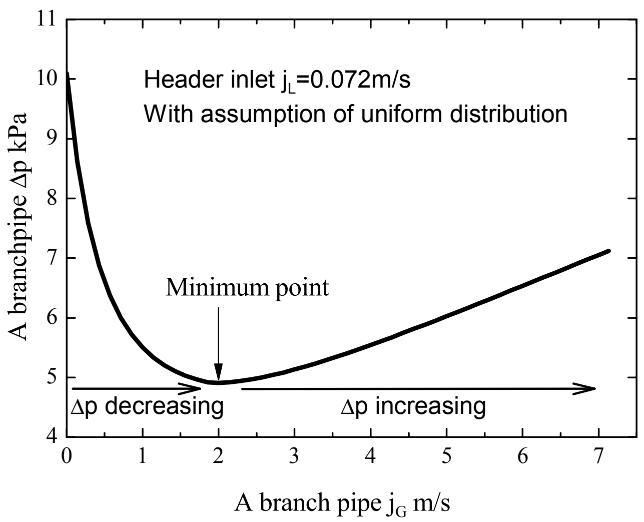

Fig. 12 Differential pressure in branch pipe with assumption of uniform distribution of two-phase flow

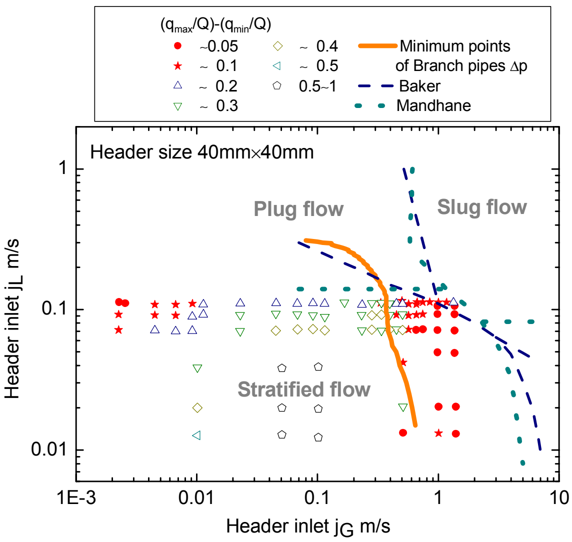

Fig. 13 Map of deviation of water flow rate in two-phase header of 40×40 mm with horizontal connection

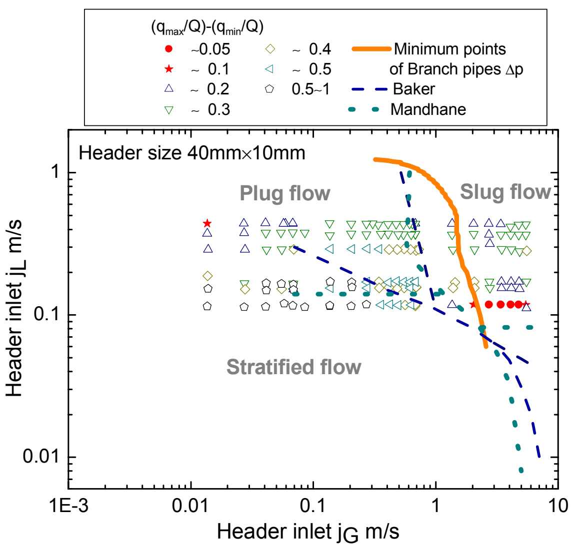

Fig. 14 Map of deviation of water flow rate in two-phase header of 40×10 mm with horizontal connection

The stability of two-phase flow in branch pipes is also very important issue for the uniform distribution. Figure 12 indicates a calculated relation of differential pressure ΔP and gas velocity in branch pipe when uniform distribution of gas flow is assumed in the calculation procedure mentioned above. Increasing the gas flow rate at a given water flow rate in a branch pipe, the differential pressure decreases to the minimum point, and after that, increases. The differential pressure is dominated with the static pressure difference term in Eq.(2) at the gas velocity less than the minimum points. So the differential pressure decreases with increasing the gas velocity due to the decrease of two-phase mixture density in the region. On the other hand, at the gas velocity larger than the minimum point, the pressure loss term in Eq.(2) dominates the pressure difference and the differential pressure loss increases with increasing the gas velocity. When the differential pressure decreases with increasing the gas velocity, it is possible that the more amount of gas flow to a certain branch pipe further decreases the differential pressure and increases the flow rate furthermore. So in this region, the unstable distribution behavior can be expected even in the stratified flow.

Shown in Fig.13 is the map of the maximum deviation of water flow ratio q/Q comparing with the flow pattern in the header of 40×40. The observed flow pattern roughly agreed with the previous studies by Baker and Mandhane[11]. The relatively small liquid flow rate is important for the formation of stratified flow. Solid keys are data of small deviation less than 0.05 or 0.1 and indicate the uniform distribution. The uniform distribution was obtained at the relatively small gas flow rate or the gas velocity larger than that corresponding to the minimum points of differential pressure. In the stratified flow, it is possible that the gas-liquid interface formed at the each inlet of branch pipes assure the gas flow rate not only to the first branch pipe but also to the others. However when the gas flow rate is less than the minimum point, the unstable behavior in branch pipes mentioned above can be expected even in the stratified flow. So the stable uniform distribution cannot be obtained at the region less than the minimum point. Further decreasing the gas flow rate, the effect of gas phase becomes relatively small and the uniform distribution was obtained again.

Shown in 14 is the map of the maximum deviation of water flow ratio comparing with the flow pattern in the header of 40×10 mm. The observed flow pattern roughly agreed with the previous studies also in this header. The slug flow in the header was observed at almost the region where the gas velocity is larger than the minimum point. The uniform distribution was obtained only at the relatively small liquid flow rate. It should be noted that the uniform distribution could be obtained only when the gas velocity is larger than the minimum point and the flow pattern is stratified flow in the header.

CONCLUSION

Experiments were conducted to study the distribution behaviors of two-phase flow in horizontal header to vertical branch pipes with or without the horizontal entrance connections.

1. With a small amount of bubbles, the water distribution rate to the first pipe rapidly increased and the rates to the others decreased in the header without horizontal entrance connections. By increasing the airflow rate in the header inlet furthermore, the flow rate to the first pipe takes a maximum and then tends to decrease. The present calculation method assuming the gas carryover

in the header predicted well the general distribution behavior.

2. The stability of two-phase flow in branch pipes is also very important issue for the uniform distribution. Calculation results assuming uniform distribution of gas phase into each branch pipe indicated that the differential pressure ΔP at the vertical section of branch pipe generally decreased to the minimum point, and after that, increased with increasing the gas flow rate at a given water flow rate. When the differential pressure decreases with increasing the gas velocity, it is possible that the more amount of gas flow to a certain branch pipe further decreases the differential pressure and increases the flow rate furthermore. So in this region, the unstable distribution behavior can be expected.
3. By using horizontal entrance connections, the stratified flow in the header was observed. In the stratified flow, it is possible that the gas-liquid interface formed at the each inlet of branch pipes assure the gas flow rate not only to the first branch pipe but also to the others. However when the gas flow rate is less than that corresponding to the minimum point, the unstable behavior in branch pipes mentioned above can be expected even in the stratified flow. So the stable uniform distribution could not be obtained at the region less than the minimum point. Further decreasing the gas flow rate, the effect of gas phase became relatively small and the uniform distribution was obtained again.

NOMENCLATURE

A: flow area of header
A_S: flow area of branch pipe
d: inner diameter of branch pipe
g: acceleration due to gravity
h: length of branch pipe
j: superficial velocity
m: ratio of flow area of header to that of branch pipe($=A/A_S$)
p: pressure
q: distribution water flow rate to branch pipe
Q: total water flow rate to header
R: pressure loss coefficient
Re: Reynolds number in branch pipe
α: void fraction
η: pressure recovery coefficient
λ: friction loss coefficient
ν: kinematic viscosity
ρ: density
ξ: distribution loss coefficient
σ: surface tension

subscript
G: air, L: liquid, i: branch pipe number, s: branch pipe

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