Experimental Study on Gas-Liquid Flow Distributions in Upward Multi-pass Channels

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Abstract
The gas-liquid flow distributions in multi-pass upward parallel channels and pressure inside headers were examined experimentally. Attention was directed to the influences of the back-pressure condition and of the flow-inlet condition on the gas-liquid distributions to the branches. Experiments were conducted in an isothermal air-water flow system. The influence of the backpressure condition changed depending on the flow-inlet condition. In the mist-flow inlet, the water distribution uniformity was improved. The pressure in headers was nearly uniform.

Key words
Air-Water Flow, Multi-pass Channel, Flow Distribution, Outlet Pressure, Inlet Flow Pattern

1. Introduction
The multi-pass channels are often used for evaporators of an air-conditioning system to improve their thermal performance. Nakamura et al. [1] reported that, in those multi-pass channels, the gas-liquid flow mal-distribution from the header to the branches (refrigerant tubes) often occurs and the thermal performance of the evaporator is greatly affected. Many studies have been conducted to date on this subject [2-11] and recently, Lee [12] presented an extensive review of researches on the gas-liquid flow distributions in a T-junction and multi-pass channels. However, few systematic results of flow distributions have been obtained because the gas-liquid distribution characteristics change in a complex manner depending on many parameters. Among those parameters, the pressure condition at the branch outlets and the flow-inlet condition at the header entrance would be the most important factors. In most studies conducted to date, however, these conditions have been determined quite arbitrarily and this would be one of the reasons for the scatter of the existing flow-distribution data.

Thus, in this study, we examined the gas-liquid flow distribution characteristics in multi-pass upward channels with attention to the influences of the pressure condition at the branch outlets and of the flow-inlet condition at the header entrance on the gas-liquid distributions. Also, we measured the pressure distributions in the headers to clarify the proper backpressure condition at the branch outlets in measuring the gas-liquid distribution ratios.

2. Experimental Setup
Figure 1 is a schematic diagram of the air-water distribution experimental apparatus. The experiments were conducted with an isothermal air-water flow system at 20°C. The test channel has a horizontal dividing header with a square cross section of 20mm×20mm, and ten upward branches of 20mm×2mm are connected to it at intervals of 20mm. In order to examine the influence of the pressure on the flow distributions, we tested two outlet conditions as shown in fig. 2; Case A is the non-uniform pressure condition, and Case B is the uniform pressure condition. In Case A, a gas-liquid separator and an air-flow meter are connected to each branch and the pressure in the separator, i.e., outlet pressure of each branch, is measured by a pressure gauge. In this case, the pressure in the separator varies depending on the flow distribution. In Case B, one branch to measure the flow distribution is connected to the separator, and other branches are connected to a combining tank. The valves at the exits of the separator and the tank are adjusted so that the pressure difference between them becomes zero. Since the combining tube is quite large, the pressure in it is considered constant. Therefore, in Case B, one can measure the flow distribution to the branches under the uniform outlet pressure condition for all the branches.

Figure 3 is a schematic diagram of the experimental apparatus for confirmation on the pressure distribution inside the dividing and combining headers of the test channel. The size of the test channel is basically the same as tested channel in Fig. 1, except this channel was connected to a horizontal combining header with a square cross section of 20mm×20mm. There are 2 exits at the combining header’s left and right ends, connected to regulation valves. As in Fig. 3, we measured the pressure at 9 points of each header. Each pressure transducer (with silicon enclosure at sensor) was allocated in the middle of the header wall on top and beneath of all branches except the no. 1 branch. The measurement range of the pressure transducer is -30 ~ 30 kPa. The sampling frequency was 10 Hz and the measuring time was 60 seconds. There are two flow exit conditions tested. The parallel flow which the flow starts from the inlet of the dividing header goes up

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3. Result and Discussion

3.1 Influence of backpressure condition of branches

The inlet flow condition at the header entrance is set with stratified flow. First, the influence of the superficial air velocity is addressed. Figure 5(a) shows the typical results of the air and water distribution ratios obtained under the outlet condition of Case A, under which non-uniform backpressure distribution is imposed on the branches. The abscissa shows the branch number and the first branch denoted as 1 is located 40 mm downstream the header entrance. The ordinate shows the air distribution ratio $M_{gi}/M_g$ and the water distribution ratio $M_{li}/M_l$ in the $i$th branch. The pressure at the outlet of the $i$th branch $P_i$ is shown separately in Fig. 5(b), in which $i = 1$ to 10. The superficial water velocity at the header entrance $j_l$ is fixed at 0.03 m/s, and the superficial air velocity $j_g$ is changed from 1.0 m/s to 5.0 m/s.

At the lowest air velocity of $j_g = 1.0$ m/s, larger amount of air is distributed to branches located nearer the header entrance. The water distribution ratio $M_{li}/M_l$ also shows relatively large values in upstream branches. At this lowest $j_g$, the downstream region of the header was nearly blocked by stagnant water and very little amount of air and water was distributed to the branches.

As $j_g$ is increased, air tends to be distributed to more downstream branches and at $j_g = 5$ m/s air is distributed almost uniformly to all the branches. As the air velocity at the header entrance is increased, the inertia of air becomes larger and air tends to go straight in the header passing over the entrances to the branches at dividing T-junctions. A close correlation is observed between the air distribution ratios and the pressure distribution at the outlets of the branches. This is because the pressure loss in the gas-flow meter settled at the exit of the separator increases in proportion to the air flow rate.

On the other hand, the water tends to be distributed preferentially to downstream branches as $j_g$ is increased,
These results mean that a uniform distribution of liquid that is desirable to evaporators cannot be obtained even if gas is distributed uniformly to all the branches. The present air and water distribution characteristics shown here are qualitatively similar to those reported by other researchers for upward parallel channels, i.e., Vist et al. [5] and Marchitto et al. [9].

The results obtained under the condition of Case B, the uniform backpressure condition at branch outlets, are shown in Fig. 6. The flow-inlet condition at the header entrance is the stratified flow, and \( j_l \) is fixed at 0.03 m/s. Both air and water tends to be distributed to more down-stream branches as \( j_g \) is increased. The mal-distribution of air to upstream branches is, however, more serious than that in case A. Such an influence of the backpressure condition on the air distribution characteristics as described above can be explained as follows. In general, the amount of air distributed to a branch is determined by the balance of the static pressure in the dividing header and the backpressure at the branch outlet. In Case A, the back-pressure at the branch outlet becomes higher as the air distribution ratio is increased. Thus, the air distribution is suppressed automatically if excessive amount of air is distributed to a branch, and consequently \( M_{gi}/M_g \) is determined at some moderate value. In Case B, the backpressure distribution at the branch outlets does not change depending on the air distribution. As a result, the air distribution cannot be suppressed even if larger amount of air is distributed to a branch, this causes larger values of \( M_{gi}/M_g \) in branches located near the header entrance.

The preferential distribution of water to downstream branches observed at higher \( j_g \) in Case A is remarkably relieved in Case B. These results suggest that, under the stratified-flow inlet, the uniform backpressure condition is
favorable to relieve the mal-distribution of water to the branches.

Next, the influence of superficial water velocity \( j_w \) on air-water distribution characteristics is discussed. Figure 7(a) show \( M_{w0}/M_{w} \) and \( M_{w0}/M_{i} \) obtained for Case A. \( j_w \) is fixed at 5 m/s, and \( j_i \) is changed from 0.015 m/s to 0.045 m/s. Both air and water distribution ratios do not change depending on \( j_i \), and it follows that air-water distribution characteristics are determined solely by superficial air velocity in Case A.

The results in Case B are shown in Fig. 7(b). The air distribution shows qualitatively similar characteristics for all \( j_i \), but \( M_{w0}/M_{w} \) in the upstream branches become larger as \( j_i \) is increased. This tendency holds good for the water distribution; as \( j_i \) is increased, \( M_{w0}/M_{i} \) in the 4th and 5th branches increases remarkably while that in the 8th - 10th branches decreases. Thus, comparatively, \( j_w \) exerts greater influence on the water distribution to branches.

The detailed flow characteristic in the header has been observed. It was found that, in this flow-inlet condition, large waves are generated over the air-water interface as shown in Fig. 8, and water is distributed to the branches unsteadily when the crests of those waves swept the top wall of the header. Figure 9 shows a comparison of the water distribution ratios in the branches and the streamwise locations at which those large waves begin to occur (generation points of waves) observed at different \( j_w \) in Case B. The generation points of waves are shown by arrows in the bottom of the figure, and their colors correspond to \( j_w \). The water distribution to the branches begins after the large waves are generated over the water surface, and the generation point of those waves moves downstream as \( j_w \) is increased. This is a reason for the preferential distribution of water to further downstream branches at higher \( j_w \) observed in Fig. 5(a) and Fig. 6. It was found that \( j_w \) was more dominant to the generation point of the waves than \( j_i \), and this is the reason for the major influence of \( j_w \) on \( M_{w0}/M_{i} \) distributions.

As described above, air tends to be distributed uniformly to all the branches at high \( j_w \) in Case A while the deflection of air distribution to upstream branches still remains at the highest \( j_w \) in Case B. Therefore, it follows that the air velocity in the header in Case A is larger than that in Case B if compared at the same streamwise location of the header. This means that the large waves are generated at more downstream region of the header in Case A, and this causes the mal-distribution of water to downstream branches observed at high \( j_w \) in Case A. As shown so far, the characteristics of flow distribution to branches and influences of air and water velocities in the header on them change depending on the pressure condition at the branch outlets. This may be one of the reasons for the scatter of flow distribution data published to date.

### 3.2 Influence of flow-inlet condition at header

The influences of the flow-inlet condition at the header entrance on the flow distributions are examined. As an extremely contrastive case, we tested the mist-flow inlet. Figure 10 shows a snapshot of the flow near the entrance of the dividing header. The annular mist flow was formed near the header entrance, but air and water tended to be separated in a downstream region of the header. The large waves such as observed in the stratified-flow inlet were not generated over the water surface.

First, the influence of \( j_w \) on the flow distribution is examined. Figure 11(a) shows the air and water distribution ratios obtained under Case A, with \( j_i \) of 0.03 m/s. The results of the backpressure are shown in Fig. 11(b). The air distribution ratios \( M_{w0}/M_{w} \) show similar characteristics to those of the stratified-flow inlet except for the lowest \( j_w = 1 \) m/s, but the uniformity of the water distribution is improved especially in high air velocity conditions. In the branches located near the header entrance, water is supplied from the liquid film formed over the top wall of the header. At \( j_w = 1 \) m/s, \( M_{w0}/M_{i} \) is very low in the 4th - 7th branches and large amount of water is distributed again to the branches located further downstream. This is explained as follows. In the middle region of the header, water flows in the lower part of the header cross section and it is hardly distributed to the branches under low \( j_w \) condition. In the downstream region of the header, the header cross section is filled with water and water is again distributed to the branches. As the air...
velocity is increased, water droplets are distributed to the branches located in the middle region of the header, and relatively uniform distribution of water is achieved as observed in Fig. 11(a).

The results for Case B, uniform backpressure condition, with the mist-flow inlet are shown in Fig. 12. Similar to the results for the stratified flow inlet, air is distributed concentratedly to the upstream branches at low \( j_g \) condition. As \( j_g \) is increased, air tends to be distributed to the branches in the downstream region as well, and uniformity of the air distribution is improved in comparison with the stratified-flow inlet shown in Fig. 6.

The water distribution shows qualitatively similar characteristics to that for Case A with the mist-flow inlet. At the lowest air velocity of \( j_g = 1 \text{ m/s} \), \( M_{\text{w}}/M_{\text{i}} \) shows relatively large values in the branches located near both ends of the header. At higher \( j_g \), the water distribution ratios in the branches located in the middle region of the header increase and relatively high uniformity of water distributions to the branches is observed. From a comparison of Fig. 11(a) and Fig. 12 it is found that, under the mist-flow inlet, the backpressure condition at the branch outlets exerts minor influence on the water distributions in comparison with the stratified-flow inlet. This difference of the water-distribution dependence on the backpressure condition comes from the mechanism of water transport to the branches. In the stratified-flow inlet, as described above, the large waves generated over the water surface play the dominant role in the water distribution to the branches. The generation point of those waves is closely related to the local air velocity in the header, which changes depending on the backpressure condition because the amount of air extracted to the branches is determined by the balance of the static pressure in the header and the backpressure at the branch outlets. Therefore, the water distribution in the stratified-flow inlet is influenced by the backpressure condition. On the other hand, in the mist-flow inlet, water droplets and liquid film formed over the header walls have a direct influence on the water distribution to the branches. Since they are generated at the header entrance, it is thought that the influences of the backpressure condition and resulting local air velocity in the header on the water distribution are lessened in comparison with the stratified-flow inlet.

### 3.3 Evaluation of uniformity of flow distributions

The air-water distribution characteristics in the multi-pass channel changes in a complex manner depending on the backpressure condition at the branch outlet and the flow-inlet conditions at the header entrance. In this study, in order to evaluate the uniformity of the air and water distributions to the branches, we have calculated the standard deviation of the air and water distribution ratios in ten branches, \( \sigma_g \) and \( \sigma_l \), respectively, defined by the following equations; the smaller values of these standard deviations statistically correspond to the higher uniformity of the flow distributions as reported by Marchitto et al. [9].

\[
\sigma_k = \sqrt{\frac{\sum_{i=1}^{N} \left( \frac{M_{\text{h},i}}{M_k} \right) - 1}{N}} \quad (N = 10)
\]

\( k \)-phase = \( g \) (gas) or \( l \) (liquid)

Figures 13(a) and 13(b) show the standard deviations of the air distribution ratios \( \sigma_g \) obtained for the stratified-flow inlet and the mist-flow inlet, respectively. The solid lines show the results for the non-uniform backpressure condition (Case A), and the broken lines show those for the uniform backpressure condition (Case B). Under the both flow inlet conditions, \( \sigma_g \) becomes smaller as the superficial
Fig. 13 Standard deviations of the air distribution ratios $\sigma_g$

The standard deviation of the water distribution ratios $\sigma_l$ is shown in Fig. 14. In the stratified-flow inlet shown in Fig. 14(a), the influence of the backpressure at the branch outlets on $\sigma_l$ is not observed so clearly in relatively low $j_g$ conditions, but at high $j_g$ $\sigma_l$ in Case B shows smaller values than that in Case A. Under the both backpressure conditions, $\sigma_l$ is quite insensitive to $j_l$. Figure 14(b) shows the results for the mist-flow inlet condition. Systematic variations of $\sigma_l$ against the backpressure condition, $j_l$ and $j_g$ are not observed in this figure. From a comparison of Figs. 14(a) and 14(b), it is found that $\sigma_l$ in the mist-flow inlet is generally smaller than that in the stratified-flow inlet.

In compact evaporators, it is desirable that liquid is distributed to all the branches uniformly. The present results suggest that the flow pattern in the dividing header is the most important factor to the liquid distribution, and that the uniformity of the liquid distribution to the branches can be improved by generating the mist-flow inlet condition at the entrance of the header. The backpressure condition at the branch outlets is influential to the gas distribution, but the liquid distribution is relatively insensitive to the backpressure condition if gas and liquid is supplied to the header under the mist-flow condition.

3.4 Pressure distribution in headers

Confirmation of the pressure distributions inside the dividing and combining headers of actual compact evaporators is highly important, because they have much effect on the flow distributions as described so far. Figures 15 and 16 show typical results of pressure distributions in the dividing and combining headers. The abscissa shows the pressure sensor positions along each header, ranging from branch no. 2 to branch no. 10. The flow direction in the channel is the parallel flow. $j_l$ is set at 0.030 m/s, with the increment of $j_g$ from 1.0 m/s to 5.0 m/s. The pressure measured in the dividing header is shown by the solid lines and that in the combining header is shown by the broken lines. Under the both flow-inlet conditions, $P_{dhi}$ and $P_{chi}$ are almost uniform along the headers with only the tolerance of less than 0.5 kPa. This suggests that in the practical evaporators the pressure in the headers is nearly constant in
condition is favorable to the uniform distribution of air. \( \sigma \) is influenced by the flow-inlet condition, and the mist-flow inlet is advantageous to improve the uniformity of the water distribution to the branches.

(4) The pressure distributions inside the dividing and combining headers were measured. The results show uniform pressure distribution along each header, which means the backpressure condition of Case B is favorable for measuring the gas-liquid flow distributions.

The present study was conducted in the adiabatic flow system. The experiment with the boiling flow that appears in an evaporator is a subject in a future work.

**References**


