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GAS-LIQUID FLOW DISTRIBUTION UNIFORMITY PARAMETERS IN UPWARD MULTI-PASS COMPACT EVAPORATOR

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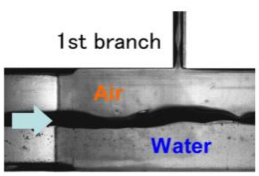
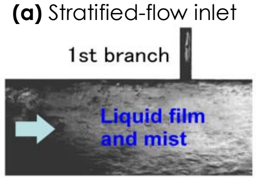
Graphical abstract



(a) Stratified-flow inlet



(b) Mist-flow inlet

Figure Flow-inlet conditions at the header entrance

Abstract

The gas-liquid flow distributions in multi-pass upward parallel channels that simulate the evaporator for the automobile air-conditioner system were examined experimentally. In this paper, the attentions are (1) To study the influences of the backpressure condition at the branch outlets and of the flow-inlet condition at the header entrance on the gas-liquid distributions to the branches, (2) To discover the most influenced parameter to the flow distribution uniformity by using design of experiment method. Experiments were conducted in an isothermal air-water flow system. The influence of the backpressure condition on the flow distributions changed depending on the flow-inlet condition. In the stratified-flow inlet, the backpressure condition was highly influential in both the air and water distributions, and the uniform water distribution that was ideal for the evaporators could not be achieved even if air was distributed uniformly to all branches. In the mist-flow inlet, the water distribution was insensitive to the backpressure conditions and its uniformity was improved in comparison with that in the stratified-flow inlet. The flow distribution uniformity for gas phase is influenced mostly by superficial air velocity, and the flow distribution uniformity of liquid phase is mostly influence by 2-way interaction of parameters which are flow pattern and superficial air velocity.

Keywords: Mal-distribution, Stratified flow, Mist flow, Backpressure, Design of Experiment

1.0 INTRODUCTION

Multi-pass channels with parallel flow circuits have been used in automobile air-conditioning system to improve their thermal performance. In those multi-flow type evaporators; thezz mal-distribution of gas and liquid from the dividing header to the branches (refrigerant tubes) often occurs, and in extreme cases no liquid is provided in some branches. The thermal performance of the evaporator is greatly affected by the flow distribution characteristics of the channel, and a uniform distribution of liquid to the branches is essential to avoid the dry-out phenomena in the refrigerant tubes [1]. Therefore, the two phase flow distribution in multi-pass channels has been an imperative problem in the development of compact heat exchangers. Many studies have been conducted to date on this subject in real refrigerant flow system [2][3][4][5][13][14] or in isothermal air-water flow system [6][7][8][9][12][15].

In those studies conducted to date, however, few systematic results of flow distributions have been obtained because the gas-liquid distribution characteristics are very complicated and they change depending on many parameters. Among those parameters are: (i) the pressure distribution in the combining header, i.e., pressure distribution at the branch outlets, and (ii) the flow pattern in the dividing header, i.e., flow-inlet condition at the header entrance, would be the especially important factor. In most studies conducted to date, however, these conditions at the inlet and outlet of the channel have been quite obscure, and this is considered as one of the reasons for the scatter of the existing flow-distribution data.

In this study, we already experimentally examined the gas-liquid flow distribution characteristics in multiple upward channels that simulate the compact evaporator used in the small air-conditioning system, focusing on the influences of the backpressure conditions at the branch outlets and the influences of flow-inlet conditions at the entrance of the dividing header on the gas-liquid distributions as reported recently [10]. The gas-liquid flows of the refrigerant have been simulated by the air-water

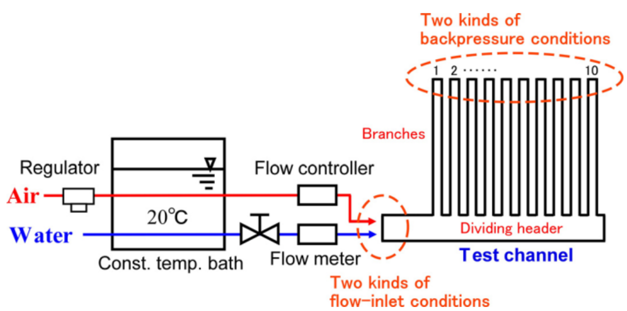
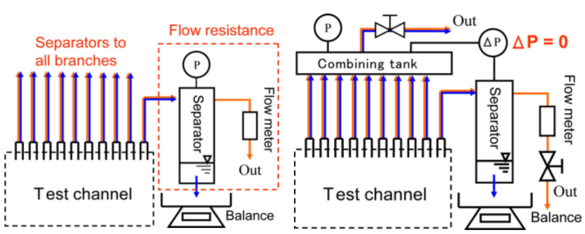


Figure 1 Schematic diagram of the experimental apparatus (Razlan, Z.M. el., IHTC14. 3: 913-921)



(a) Case A (Non-uniform backpressure) **(b)** Case B (Uniform backpressure)

Figure 2 Outlet pressure conditions at the branch exits (Razlan, Z.M. el., IHTC14. 3: 913-921)

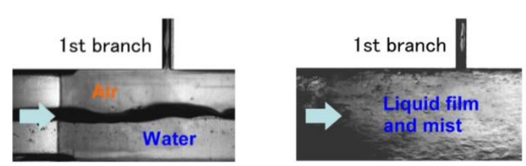
two-phase flows under isothermal condition that are suitable for grasping fundamental flow characteristics in the channel. The distribution ratios of air and water in the branches have been measured under the upward parallel flow condition. It is expected that the data of gas-liquid distributions obtained under these specified inlet and outlet conditions are helpful not only to understand the fundamental two-phase flow characteristics in the multi-pass channels but also as a database to examine the reliability of results obtained by numerical simulations.

2.0 METHODOLOGY

This paper focuses on analysis from the result of standard deviation of gas and liquid phase (flow distribution uniformity) that has been done from experimental result using experimental apparatus as in Figure 1 and 2 and reported recently as in Figure 4 and 5 [10]. The parameters selected as in Table 1, are simulated from the range of mass flow rate, i.e. 30 -150 kg/hr, flow pattern, pressure condition, header and branch attitude, of car air-conditioner that use multi-pass compact evaporator and HFC-134a as the working fluid [10].

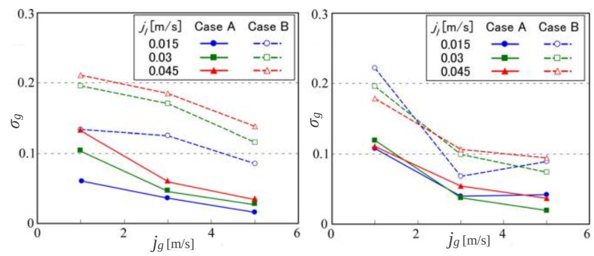
Table 1 Summary of the experimental conditions or parameters (Razlan, Z.M. el., IHTC14. 3: 913-921)

Fluids	Isothermal air and water
Superficial air velocity at the header entrance j_g	1.0 m/s, 3.0 m/s, 5.0 m/s
Superficial water velocity at the header entrance j_l	0.015 m/s, 0.03 m/s, 0.045 m/s
Pressure condition at the branch outlets	Case A (non-uniform) Case B (uniform)
Flow-inlet condition at the header entrance	Stratified-flow inlet Mist-flow inlet
Header attitude	Horizontal
Branch attitude	Upward



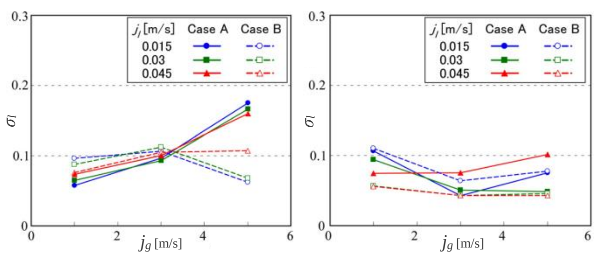
(a) Stratified-flow inlet **(b)**Mist-flow inlet

Figure 3 Flow-inlet conditions at the header entrance (Razlan, Z.M. el., IHTC14. 3: 913-921)



(a) Stratified-flow inlet **(b)** Mist-flow inlet

Figure 4 Standard deviations of the air distribution ratios σ_g (Razlan, Z.M. el., IHTC14. 3: 913-921)



(a) Stratified-flow inlet **(b)** Mist-flow inlet

Figure 5 Standard deviations of the water distribution ratios σ_l (Razlan, Z.M. el., IHTC14. 3: 913-921)

3.0 RESULTS AND DISCUSSION

In this paper, an analysis of parameters or factors that influenced the uniformity of flow distribution is discussed. The liquid superficial velocity has been observed clearly to have a small influence to the uniformity of flow distributions, it has been decided to focus the analysis with these sources; (1) Flow pattern, (2) Backpressure, (3) Superficial air velocity (4) 2-way and 3-way interactions between parameters. This analysis is important in discovering the most valuable parameter that contributed to the uniformity of the flow distribution and the best setting of the parameter level to archive the lowest σ_g and σ_l.

As in the previous study [10], total of 36 combinations of test configuration with 4 parameters has been done and σ_g and σ_l has been calculated and being plotted as in Figure 4 and 5. Superficial water velocity j_l has a minor influence to the uniformity of flow distribution and by considering only 3 parameters as in Table 2. The σ_g and σ_l that are to be analyzed are reduced to 8 combinations. By repeating the combination 3 times which are the first 8 combinations, second 8 combinations and third 8 combinations; the test data generate at j_l = 0.015 m/s, 0.030 m/s and 0.045 m/s. The total data to be analyzed are 24 combinations. By using the "Design of Experiment" method, or in mathematics and statistics study in area of "Analysis of Variance (ANOVA)"[11], the analysis has been done by using Minitab 15 statistical software.

First, the result of gas phase flow distribution uniformity analysis is addressed. An ANOVA table as in Table 3 has been developed by using General Linear Model in Minitab 15 software from the 24 combination results of σ_g. Table 3 clearly shows only backpressure and j_g are the main parameters contributing to the uniformity of gas phase flow distribution as the *P-value* in the table is less than 0.05. *P-value* is calculated from *F* ranging from 0 to 1. It is a hypothesis test to check the parameter is significant to the contribution of the uniformity of the flow distribution, i.e., *P-value*< 0.05≡significant and *P-value*> 0.05≡not significant.

For further understanding on how large the contribution of these parameters is, by calculating the percentage of *SS* value to the *SS* total from Table 3; a simplified Pareto chart can be plotted to show clearer contribution of each parameter and its interaction among each other to the uniformity of gas phase flow distribution as in Figure 6. The abscissa shows the sources which are the parameters and its interaction combinations. The ordinate shows the percentage of contribution to the uniformity of the gas phase flow distribution. From the chart, the total of contribution by all the parameters to the uniformity of flow distribution of gas phase is 89.82%. The other 10.18% is the experimental error. From this 89.82% of contribution, the j_g with 47.07% continuing with backpressure with 40.28% contributes the most for the uniformity of gas phase. The other parameters and all the interaction shall be classified as not significant to the contribution of uniformity of flow distribution.

The next analysis is to find the best combinations of parameters and its level to create the best setting for the best uniformity of flow distribution. By using Minitab 15 software again with design of experiment cube plot tool, the result yields as in Figure 7. This cube plot shows the mean value of σ_g at each combination of the 3 parameters and their level as in Table 2. From the cube plot, the smallest mean value of σ_g is 0.02720 which is located at the left, back and upper side of the plot. Thus to ensure the σ_g at minimum level, the setting of each parameter should be as follows: the backpressure should be at non-uniform condition, j_g should be set at 5.0 m/s and flow pattern should be set with stratified flow. It is noted that the flow pattern is not considered a significant parameter as explained in Table 3 and Figure 6, thus this makes the differential of σ_g value

Table 2 Summary of the selected analyzed parameters and their level

Parameter	Level
Flow pattern at header entrance	Stratified-flow, Mist-flow
Backpressure	Non-uniform, Uniform
j_g (m/s)	1.0 m/s, 5.0 m/s

Table 3 Summary of the ANOVA table for σ_g.

Source	DF	SS	MS	F	P-value
Flow Pattern	1	0.000043	0.000043	0.08	0.7860
Backpressure	1	0.035378	0.035378	63.30	0.0000
j_g	1	0.04134	0.04134	73.97	0.0000
flow pattern *backpressure	1	0.000241	0.000241	0.43	0.5210
Flow pattern *j_g	1	0.001049	0.001049	1.88	0.1900
Backpressure *j_g	1	0.000276	0.000276	0.49	0.4920
Flow pattern *backpressure *j_g	1	0.000552	0.000552	0.99	0.3350
Error	16	0.008942	0.000559		
Total	23	0.08782			

Table 4 Summary of the ANOVA table for σ_l.

Source	DF	SS	MS	F	P-value
Flow Pattern	1	0.0038346	0.0038346	9.80	0.0060
Backpressure	1	0.039629	0.039629	10.13	0.0060
j_g	1	0.0013102	0.0013102	3.35	0.0860
flow pattern *backpressure	1	0.0002948	0.0002948	0.75	0.3980
Flow pattern *j_g	1	0.0062611	0.0062611	16.00	0.0010
Backpressure *j_g	1	0.0047	0.0047	12.01	0.0030
Flow pattern *backpressure *j_g	1	0.0043281	0.0043281	11.06	0.0040
Error	16	0.006261	0.0003913		
Total	23	0.0309525			

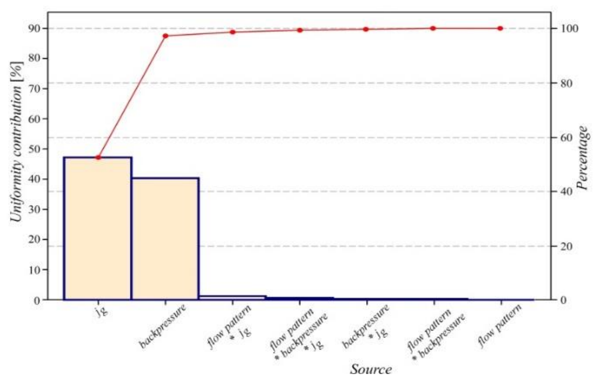


Figure 6 Pareto chart of sources (parameters) contributing to the uniformity of gas phase flow distribution

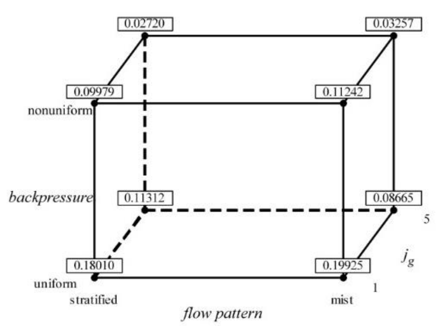


Figure 7 Cube plot with means value of σ_g at each combination of setting level for each parameter.

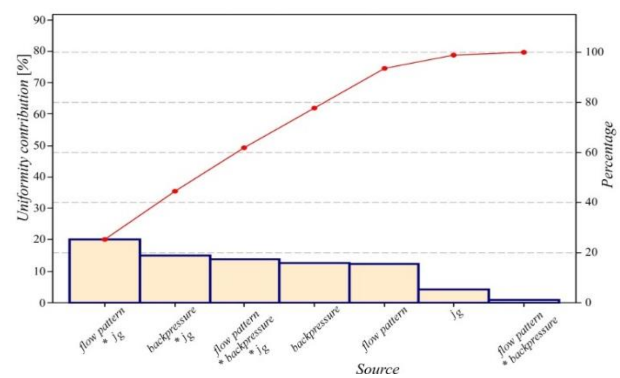


Figure 8 Pareto chart of sources (parameters) contributing to the uniformity of liquid phase flow distribution

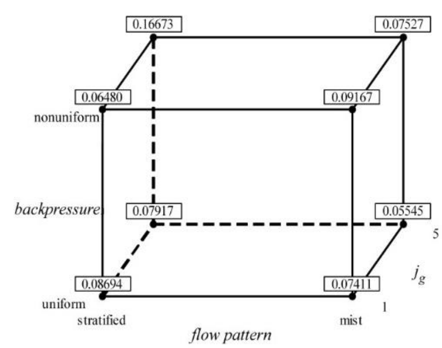


Figure 9 Cube plot with means value of σ_g at each combination of setting level for each parameter.

between mist-flow and stratified-flow in Figure 7 relatively small.

Parameters that contribute the most to the uniformity of liquid phase flow distribution shall be discussed next. As previously explained, an ANOVA table from the 24 combination of parameters experiment σ_l result has been developed in Table 4. Different from gas phase ANOVA table, in this table; the P-value for 3-ways interaction shows lower value than 0.05, meaning that it is significant to the contribution to the uniformity of liquid phase flow distribution. Only one of the 2-ways interaction combinations is not significant to the uniformity of flow distribution, i.e. flow pattern and backpressure. Nevertheless, j_g P-value is higher than 0.05, however due to its interactions among other parameters significant to the flow distribution, it makes j_g significant as a main factor as others.

Figure 8 shows a Pareto chart of contribution percentage to the uniformity of liquid phase flow distribution by its main parameters solely and also by its parameters interaction among each other. From the chart, the total of contribution by all the parameters and their interactions to the uniformity of flow distribution of liquid phase is 79.77%. The chart shows that the 2-ways interaction of flow pattern and j_g is the most influenced to the uniformity of liquid phase flow distribution that contributes 20.23% continuing with combination of backpressure and j_g with 15.18%. From this observation of Figure 8, it shows that the interaction among parameters is more important than the parameter itself to the contribution of the uniformity of liquid phase flow distribution.

Since interaction contributed more than the parameter itself, the experiment required finding the best setting for each factor that can sustain minimizing the standard deviation of liquid by a design of experiment cube plot tool as explained earlier. Figure 9 is the result of cube plot for mean value of σ_l. From the figure, to archive the smallest value of σ_l the parameters should be set as follows: flow pattern should be mist flow, the backpressure should be in uniform condition and j_g should be set at 5.0 m/s.

4.0 CONCLUSION

An analysis of variances that contribute to the uniformity of gas and liquid phase flow distribution by using Minitab 15 statistical software has been performed. The results are summarized as follows:

(1) 24 selected standard deviation's data have been analyzed by using design of experiment method through Minitab 15 statistical software. For uniformity of gas phase flow distribution, the main parameter that contributed the most is j_g. For uniformity of liquid phase flow distribution, it was the 2-way interaction between flow pattern and j_g that contributed the most.

(2) The best settings of level of each parameter for getting the best uniformity of gas phase flow distribution are:

   a) j_g should be at 5.0 m/s.
   b) Backpressure condition should be set at non-uniform.
   c) Flow pattern at header entrance should be either stratified or mist-flow.

(3) The best settings of level of each parameter for getting the best uniformity of liquid phase flow distribution are:

   a) Flow pattern at header entrance should be Mist-flow.
   b) Backpressure condition should be set at uniform.
   c) j_g should be at 5.0 m/s.

Acknowledgement

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