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Improvement of Safety Analysis Methodology for CANDU Reactors: Off-take Experiment at T-junction between Header and Feeder Pipes with Arbitrary Angles in CANDU

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Abstract

An experimental study has been performed to investigate the off-take phenomena at the horizontal pipe with the branch pipes installed between the header pipe and feeder pipe in CANDU 6. The horizontal stratification entrainment model (HSEM) in RELAP5/MOD3.3 is developed based on data generated for only three branch orientations (top, side, bottom). This study shows whether it can be applied to the branch pipes with actual angles and supports experimental data for the improvements of model applicable to the geometric effect of branching angles. Scaling analysis is performed to scale down the experimental facility to CANDU 6. Three different diameters and seven different angles of branch pipes are used to verify their scale and geometry effects. The off-take phenomena – liquid/gas entrainment – are observed for various angles between the header pipe and feeder pipe. The HSEM used in RELAP5/MOD3.3 and the experimental results of previous studies are validated by the present experimental data at the only three branch orientations. The data of onset of off-take shows agreement with the existing correlations while the quality data show discrepancies in the top and bottom branches. For specific angled branches, the onsets of off-take data are only obtained. Especially, the HSEM does not show good agreement of the present onset data of the specific branch angles, $\pm 36°$ and $\pm 72°$.

1. Introduction

The liquid entrainment and vapor pull-through models of horizontal pipe of RELAP5/MOD3 are models for predicting branch quality of T-junction. They are generally called as the off-take model because a phase is entrained by another continuous phase. Zuber [1] indicated that currently used thermal-hydraulic computer codes cannot predict satisfactorily either the amount of liquid or gas entrainment or the beginning of entrainment in the field of nuclear reactor safety the occurrence of a small break in a horizontal coolant pipe. Several models and correlations were developed by experimental studies. KfK [2] reported the results of experiments designed to determine the mass flow rate and quality through a small break at the bottom, top and side of a main pipe with stratified gas-liquid flow. The break diameters are 6, 8, 12, 20 mm and the main pipe diameter is 206 mm. These experiments were performed with air-water flows at ambient temperature and a maximal pressure of 0.5 MPa. UCB [3] also presented the results of an experimental investigation of steam-water discharge from a stratified upstream region through small diameter breaks oriented at the bottom, top and side of the horizontal pipe. The main pipe was 102 mm in diameter and the break tubes were 4, 6, and 10 mm in diameter and 123 mm in length. Both air-water and steam-water were used at pressures up to 1.07 MPa. These two experimental results are implemented into the horizontal stratification entrainment model (HSEM) in RELAP5/MOD3.3, which accounts for the phase separation phenomena and computes the onset and the quality of liquid and gas entrainment at branches attached to a horizontal pipe. The structures of the CANDU reactors are different from those of the water cooled reactors. A lot of the pressure tubes penetrate the CANDU reactor and include the fuel bundles. The 380 fuel bundles divided into the 95 fuel bundles as four groups are connected with the feeder pipes in order to transport the coolant for heat exchange. Especially, there are five-angled types at T-junctions between header and feeder pipes; 0°, 36°, 72°, 108°, 144° from the horizontal line. Unfortunately, the current horizontal stratification entrainment model in RELAP5/MOD3.3 cannot predict the exact mass qualities at specific angle branches because it can be applied only at the bottom, top and side branches. The geometrical characteristics between the header and feeder pipes of the CANDU require different approaches to safety analysis from the existing simulation codes developed for light-water cooled reactors.

In the present study, off-take experiments are carried out using the experimental facility of the horizontal pipe with 7 angled branch pipes. The header and feeder pipes in CANDU 6 are scaled down to design the off-take test facility. This paper deals with air/water experiments with the top, side and bottom branches and describes the flow phenomena, the onset of liquid/gas entrainment and quality at the branch entrance for stratified flow in the horizontal pipe including the comparison with the previous works, KfK, UCB. Especially, the research focuses on the off-take phenomena at branch pipes with four specific angles as well as the verification of three branches (top, side and bottom) with previous results. The latter works are mainly introduced in this paper and the former works are still in progress. The former works for the off-take at four specific angles are also described in this paper.

2. Development of Experimental Facility

2.1 Scaling Factor Analysis

The scaling analysis is performed to design the off-take test facility on the prototype of CANDU6. The major scaling parameters are the diameter (D) and length (L) of the header pipe and the diameter of the feeder pipes (d). The header and feeder pipes are simulated as the horizontal and branch pipes, respectively. The phenomena related to the off-take are considered in the scaling analysis: flow regime in the horizontal pipe and the onset of off-take at the branch pipes.

At first, the diameter of the horizontal pipe (D) is scaled down as 1/2, which results in 0.184 m as the value of D. This scaling-down ratio of D is determined in considerations of experimental (space, facilities) and financial limitations. From this ratio, the overall scale of the test facility is determined. The wave growth and propagation on the stratified water interface is possible to be affected by the pipe length, which is considered to the scaling of the length of the horizontal pipe (L). Kang et al. [4] performed the counter-current flow limitation (CCFL) experiment using various pipe diameters and lengths. They concluded the L/D similitude is the most preservative to the flow regime transition such as CCFL. However, the actual header pipe has various lengths according to the locations of each feeder pipe. Therefore, the L/D similitude is only suggested as scaling methodology here, and the length of the horizontal pipe is designed to be suitable of the experimental conditions. The flow rates inducing an off-take are related to the Froude number in case of the horizontal stratified flow. Basically, the void fraction is preserved in horizontal stratified flow: geometrical similitude. In the scaling of flow rates, the similitudes of the Froude number and void fraction are considered, which result in the similitude of CCFL: $[j_g^*]_R = [Fr \bullet a]_R$. It results in the ratio of volume flow rates as the following relation: $[Q_k]_R = [D^{5/2}]_R$. These scaling results satisfy the preservation of the branch quality ($[x]_R$ =1) [5]. The existing correlation for the onset of off-take is used for the scaling of the diameter of the branch pipe. If the velocity is preserved in the branch pipe, the ratio of branch diameter ($[d]_R$) is the same with $[D^{5/4}]_R$. The branch pipes are designed into three diameters scaled down from the feeder pipes on the basis of the above scaling result. Table 1 summarizes the scale of the test facility compared with the prototype (CANDU6).

Table 1 The test facility scaled by scaling analysis

	CANDU6	Test Facility	Scaled-down ratio
Header diameter	0.3683 [m]	0.184 [m]	0.5
Header length	6.00 [m]	0.8 [m]	0.5
Feeder diameter-1	3.81 [cm]	1.60 [cm]	0.420
Feeder diameter-2	4.93 [cm]	2.07 [cm]	0.420
Feeder diameter-3	5.90 [cm]	2.48 [cm]	0.420
Gas/liquid flow rate			0.177

2.2 Experimental Facility

The test facility has been designed and constructed based on the scaling analysis. Figure 1 shows the overall schematic diagram of the test facility, which consists of air-water tank, horizontal pipe, branch pipes having three different diameters, air-water separator and collecting tank of entrained water. Additionally, the air compressor system, water pump, their control panel sets and various measuring instruments are installed to the test facility. The horizontal main pipe and the branch pipe are scaled down to represent the header pipe and the feeder pipes of the CANDU6, respectively. All the test facility is made of stainless steel as a design pressure of 10 bar. Visual windows are installed for observation in the T-junction in the horizontal main pipe and air-water separator. At the T-junction, the circular branches with diameters of 16, 20.7, 24.8 mm can be installed and removed for different branch diameters and angles. The branch angles are 0°, ±36°, ±72°, ±90° from the horizontal line and illustrated in Figure 2. The diameter and length of the horizontal pipe are 184 mm and 775 – 1,035 m, respectively. The honey-comb at the inlet of the horizontal main pipe is installed for flow stabilization. Compressed gas and water flows are supplied by the air compressor and water pump, respectively. In the case of a liquid entrainment, the two-phase branch flow is separated into entrained water and gas flow in the air-water separator. Thereafter, the entrained air/water is collected and measured by different methods according to the amount of those. The scale comparison of the real plant and the test facility is summarized in Table 1. Water levels in the horizontal pipe are measured at both front and real positions of the T-junction. Water levels in the air-water separator are measured for calculating the quality. Orifice-meters and vortex-meter are used for measuring air flow rates and magnetic flow meters are installed in order to measure water flow rates.

2.3 Experimental Conditions

The experiment is performed at room temperatures and maximal pressure of 8 bar. The maximum air flow rate and water flow rate used in the tests is up to 70×10^{-3} kg/s, 3.5 kg/s, respectively. Water levels in the horizontal pipe can be controlled by inlet/outlet valves of flow pipes, controlling water pump power and dam in outlet the horizontal pipe. To obtain the data of the onset of liquid/gas entrainment, the input and branch mass flow rate of air/water are fixed and the interface level increases/decrease very slowly (1 mm/min). Therefore, the experiments can be assumed to be at steady state. All injected air/water are discharged through the branch pipe because of no exit flow in the horizontal pipe.

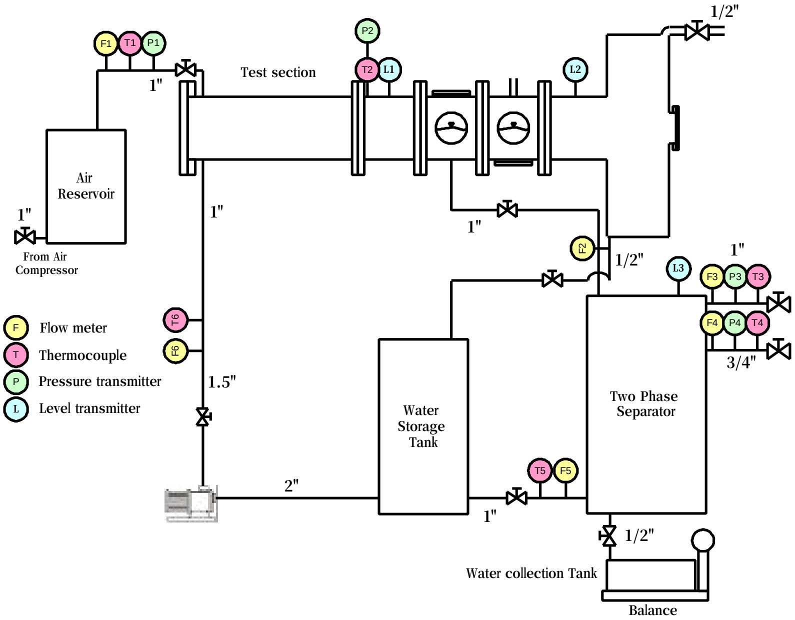


Figure 1 Schematic diagram of the test facility

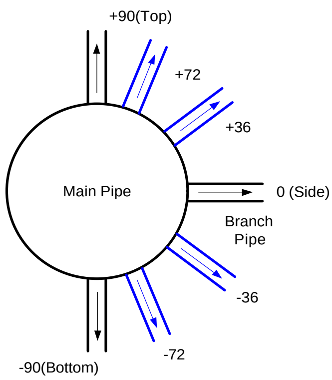


Figure 2 Side view of T-junctions

3. Results and Discussion

The experimental studies in this paper are divided into three categories as follows:

- Onset of liquid/gas entrainment at top, side and bottom branches,
- Branch quality at top, side and bottom branches,
- Onset of liquid/gas entrainment at branches with ± 36, $\pm 72°$.

The present experimental data at top, side and bottom branches are compared with the previous results of the break flow of SB-LOCA for verification. The data at branches with ± 36, ± 72 are also fitted for comparisons with the results from the existing correlations. The data of the onset of liquid/gas entrainment are well fitted by the correlation given by HSEM in RELAP5/MOD3.3 except at bottom branch. At the bottom branch, the data agrees with the correlation for the onset of vortex-induced flow (one of definitions by KfK). In the present study, the new definition of the onset of gas entrainment at the bottom branch is proposed and the new correlation is developed. The data for the onset of entrainment are obtained visually for each branch. For the quality data also are well fit by the correlation given by HSEM in RELAP5/MOD3.3. A little deviation from the previous correlations is found at top and bottom branch, but overall data distributions are agreeable. The results of the onset of entrainment and quality are verified well at top, side and bottom branches. The onset data with ± 36, ± 72 branches are deviated from the existing correlations. The results and analyses are described according to each category.

The test matrices are shown as Table 2 and Table 3. Two branches with diameters of 16, 24.8 mm are used at the onset of liquid/gas entrainment experiments; 16 mm diameter branch is used at branch quality experiments with top, side and bottom branch. The experiments with ± 36, ± 72 branches are performed with all three diameters branches. The system pressure ranges 2-8 bar. The number of data at ± 36, ± 72 branches is more than that at top, side and bottom because they are obtained for the first time.

Table 2 Test matrices for the onset of entrainment experiments

type	È( )	d (mm)	P (MPa)	$\dot{m}_g$ or $\dot{m}_l$ (kg/s)	h_b/d	# of data
L.E.	+90 (top)	16, 24.8	0.226 - 0.808	6.2 - 70.9	0.92 - 3.4	17
	+72	16 - 24.8	0.255 - 0.810	4 - 79	1.31 - 3.04	34
	+36	16 - 24.8	0.188 - 0.674	21.7 - 75.9	0.94 - 2.4	40
	0 (side)	16, 24.8	0.177 – 0.541	16.3 - 67.7	0.7 - 1.81	18
	-36	16 - 24.8	0.158 - 0.609	15.1 - 84.2	0.75 - 1.58	50
G.E.	+36	16 - 24.8	0.133 - 0.547	0.32 - 3.04	0.81 - 1.84	43
	0 (side)	16, 24.8	0.137 - 0.758	0.46 - 3.66	0.78 - 3.18	26
	-36	16 - 24.8	0.334 - 0.810	0.57 - 3.09	2.64 - 7.39	43
	-72	16, 20.7	0.304 - 0.810	0.63 - 2.6	5.5 - 10.17	34
	-90 (bottom)	16, 24.8	0.397 - 0.804	1.26 - 3.3	5 - 10.85	29

Table 3 Test matrices for the branch quality experiments

type	È( )	d (mm)	P (MPa)	h/h_b	x	# of data
L.E.	+90 (top)	16	0.197 - 0.544	0.4 - 0.89	0.03 - 0.99	16
	0 (side)		0.205 - 0.371	-0.24 - -1.02	0.12 - 0.97	15
G.E.	0 (side)		0.491 - 0.548	0.1 - 0.85	0 - 0.04	14
	-90 (bottom)		0.399 - 0.572	0.44 - 3.04	0 - 0.15	32

3.1 Onset of Liquid/Gas Entrainment at Top, Side and Bottom Branches

1) Onset of liquid entrainment: O.L.E.

a. Top branch

The liquid entrainment at top branch occurs in the following way as shown Figure 3. (a) A weak entrainment with vorticity is observed at branch entrance, but disappears again. And the entrainment points are not always same because of vorticity. (b) As the gas flow increases, the droplets are generated from the end of the entrained crest, but do not reach the entrance of branch and just deposited on the inner wall of horizontal pipe. (c) And next step is that the entrained liquid reaches the entrance of branch and discharges through the branch. This point is defined as the onset of liquid entrainment: O.L.E.

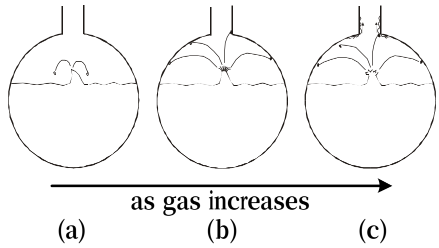


Figure 3 Development of liquid entrainment at the top branch

HSEM in RELAP5/MOD3.3 predicts well the data although they are comparatively in lower ranges of h_b /d as shown in Figure 7 (a). The present data are scattered because the phenomena occurs when the entrained liquid has the vorticity and the interface level includes wave.

b. Side branch

As a gas flow increases, the liquid entrainment at side branch occurs as shown Figure 4. (a) The Bernoulli effect is first evidenced by the deflection of the interface in the vicinity of the branch wall but disappears again. (b) With further increase of the liquid level, a thin ascendant film of water, not influenced by vorticity, determines the onset of liquid entrainment. The liquid vorticity on the interface level can be hardly observed because of the inner wall friction in the horizontal pipe. (c) Finally, a lot of the entrained liquid is discharged intermittently or continuously. The observation at side branch is easier than that at top branch because of the phenomena is stable.

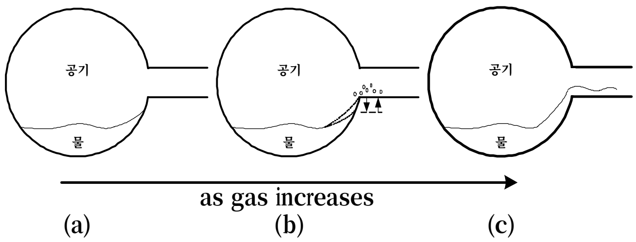


Figure 4 Development of liquid entrainment at the side branch

The data are on the line of the correlation given by HSEM in RELAP5/MOD3.3. The present data are consistent unlike the previous experimental data shown as Figure 7 (b). UCB data has a little scattering. UCB correlation also agrees with that of KfK.

2) Onset of gas entrainment: O.G.E.

a. Side branch

As a liquid flow increases, the gas entrainment at side branch as shown Figure 5: (a) The continuous liquid phase generates a very small vorticity, which is difficult to be observed and then disappears again, (b) As the liquid increases, thin hose of gas reach the vicinity of the branch and determine the onset of gas entrainment. The small bubbles are discharged through the branch. The wall friction prevents the vorticity from developing and after short intermittences the gas is in direct contact with the wall, (c) If the interface level becomes lower, lots of gas is swept out instead of vortex flow.

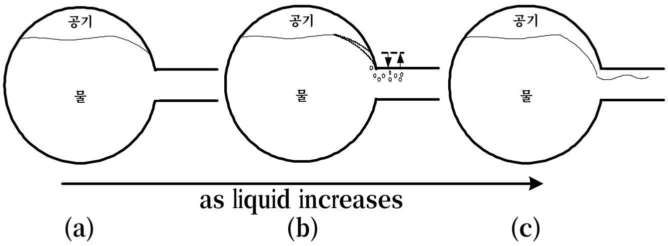


Figure 5 Development of gas entrainment at the side branch

HSEM in RELAP5/MOD3.3 predicts the data although they are scattered around the correlation shown as Figure 7 (c). The present data scatter is not large compared to the previous data. The data and correlation of UCB have a little deviation from the present data.

b. Bottom branch

The gas entrainment at bottom branch in the following way, as shown figure 6: (a) Continuous liquid phase generates very small bubbles, they are discharged through the branch or disappeared toward interface level. It may takes a long time until another bubble is formed, (b) As the interface level decreases, thin gas hose is formed with a great vorticity, and also reaches the entrance of the branch and determines the onset of gas entrainment. At this time, the vortex flows with vorticity are clearly seen and the position at which gas hose is formed changes, (c) If the interface level becomes lower, the gas hose becomes thicker and more stable. The water flow pattern changes from vortex flow to vortex-free flow. A reason for the transition from a vortex to vortex-free flow field is the increasing influence of the wall friction with decreasing interface levels. At this point, lots of gas is swept out as vortex-free flows.

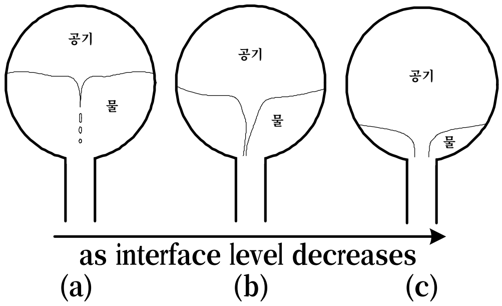
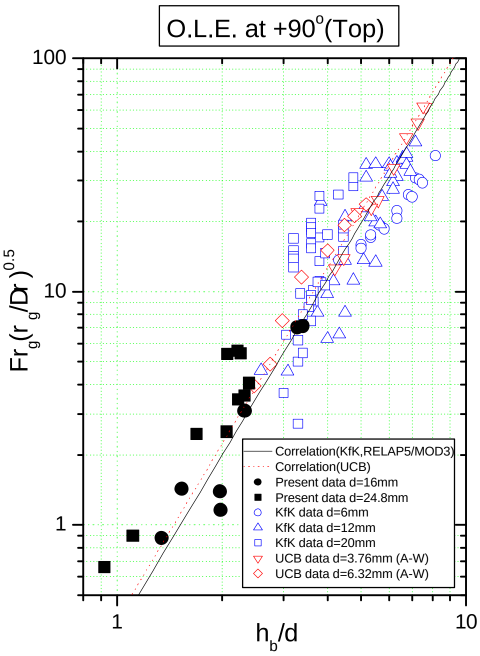
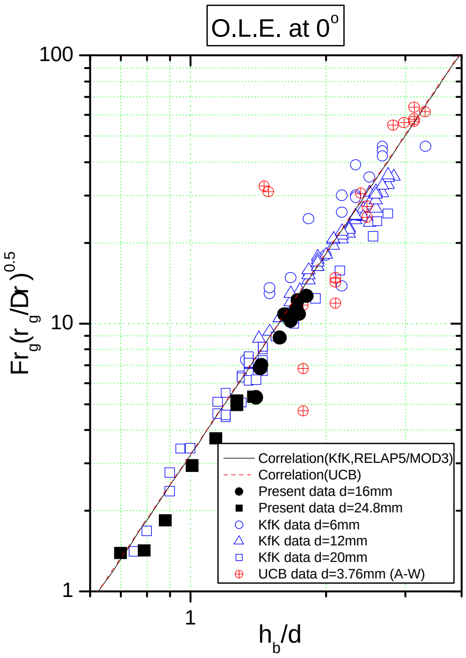


Figure 6 Development of gas entrainment at the bottom branch

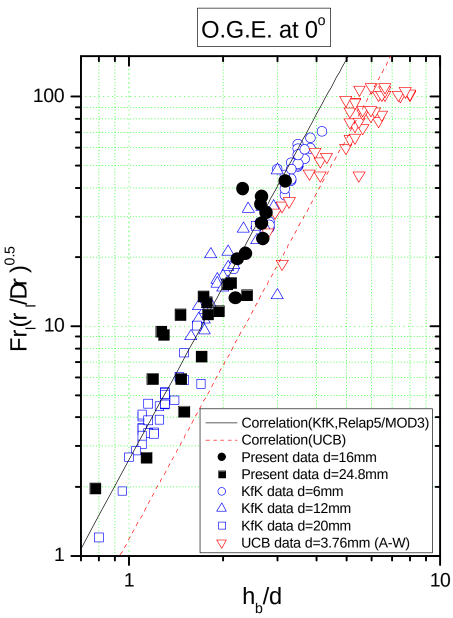
The KfK correlation by the first hose gas predicts well the data shown as Figure 7 (d). The data and correlation of UCB by the first bubble pull-through have a little deviation from the present data. In previous works, the experimental studies about vortex flow and vortex free flow were presented. Those studies account for the gas entrainment phenomena, but their onset criteria ambiguous as an aspect of application to the safety analysis. The present study newly defines the onset of gas entrainment. The new definition of the onset of gas entrainment is related to the critical point of quality increase from zero as shown Figure 8. The point of h/h_b is about 0.31, whose correlation is similar to the KfK's correlation that means the beginning of the transition from vortex flow to vortex- free flow as shown Figure 9.



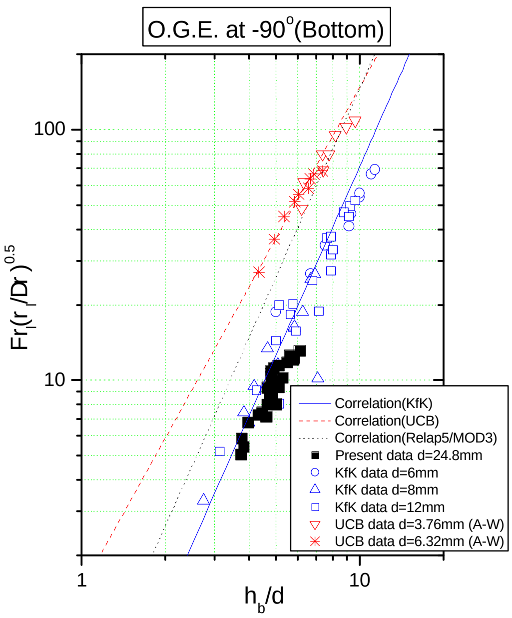
(a) O.L.E at top branch



(b) O.L.E at side branch

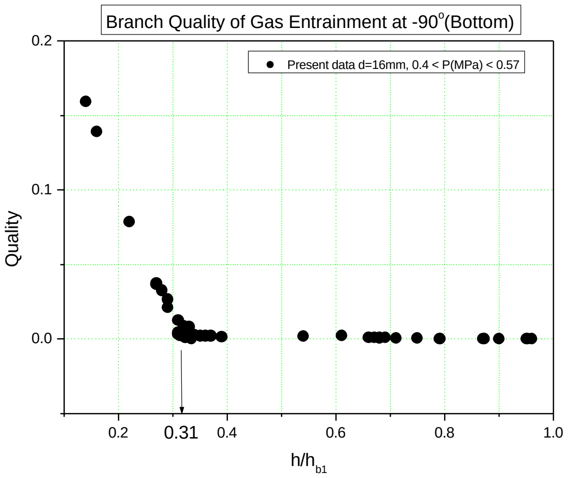


(c) O.G.E at side branch



(d) O.G.E at bottom branch

Figure 7 Comparison of Present onset data with KfK and UCB



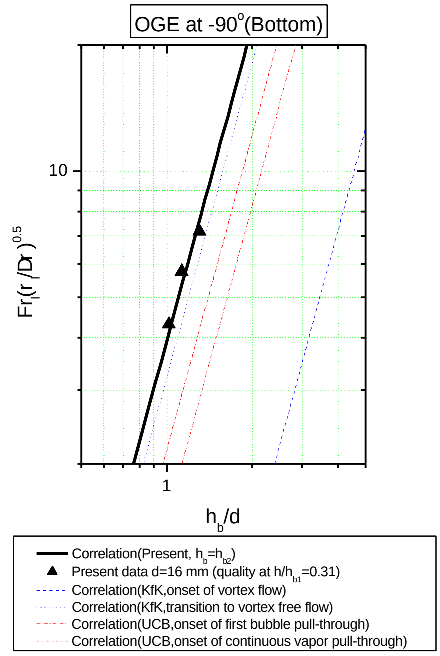


Figure 8 Quality data for the new onset definition at bottom branch

Figure 9 Comparison of newly developed correlation with KfK and UCB correlations

3.2 Branch Quality at Top, Side and Bottom Branches

a. Top branch

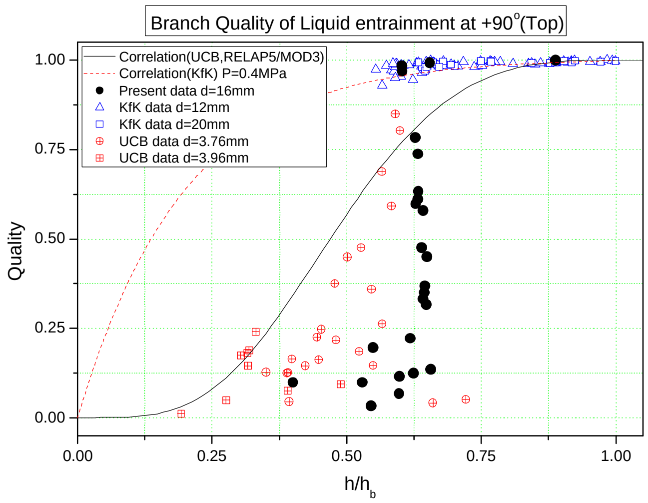
As shown in Figure 10 (a), branch quality has a tendency of drops from high quality fields near 1.0 to low quality fields. The quality becomes nearly 1.0 because the liquids are discharged through the branch as type of ‘droplets’ when a gas flow rate is relatively low. As a gas flow increases, a sudden transition from stratified flow to slug occurs in the horizontal pipe and interface levels becomes quite unstable, and then, a lot of liquids are entrained as ‘lump’ of water, which makes the quality drop into low quality fields. The present data are compared with the previous correlations and data as shown in Figure 10 (a). The quality correlation in RELAP5/MOD3.3 implemented by UCB was developed by using the high quality data by KfK as well as their own data; the present data have quite large deviations from the correlation are seen in low quality fields and transition from the high quality to the low quality fields. From Figure 10 (a), it can be seen that the quality at the top branch depends on the flow regime in the horizontal pipe. Therefore, the new modeling including the flow regime effect is needed in order to predict well the quality at top branch.

b. Side branch

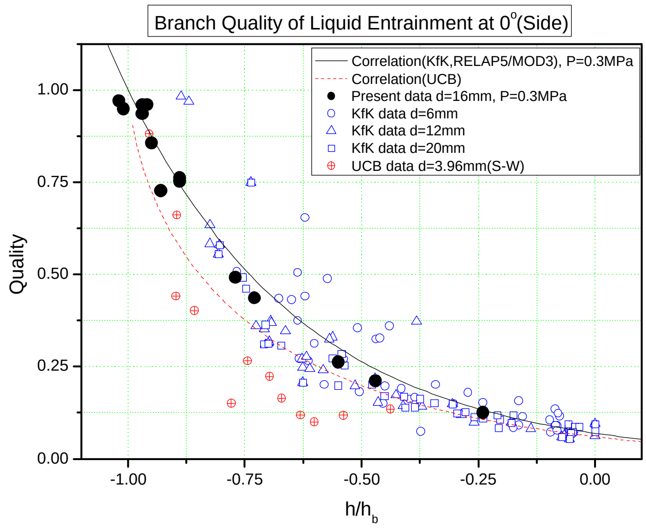
For side branch, liquid entrainment as well as gas entrainment can be observed according to the interface levels. The data are obtained in both cases as shown in Figures 10 (b) and 10 (c). For liquid entrainment, the present data agree with the existing data and correlations in Figure 10 (b). The present data show more consistency with KfK’s correlation although the number of data is less than those of the previous works, which is resulted from the use of the accurate instruments and the maintenance of more stable conditions of steady states. The present data are closer to the correlation of KfK than that of UCB. It is proper that RELAP5/MOD3.3 adopted the KfK’s correlation as the correlation for the quality at side branch. For gas entrainment, the present data are represented with the existing data and correlations in Figure 10 (c). A little deviation from the existing correlations is found, but the data profile is similar to the correlation by KfK. It is caused by the difference in onset criteria on the gas entrainment. The KfK's correlation for both liquid and gas entrainments well predicts the quality at side branches except for a slight discrepancy by onset criteria. Therefore, it can be said that the off-take model in the RELAP5/MOD3.3 code predicts well the quality at the side branch.

c. Bottom branch

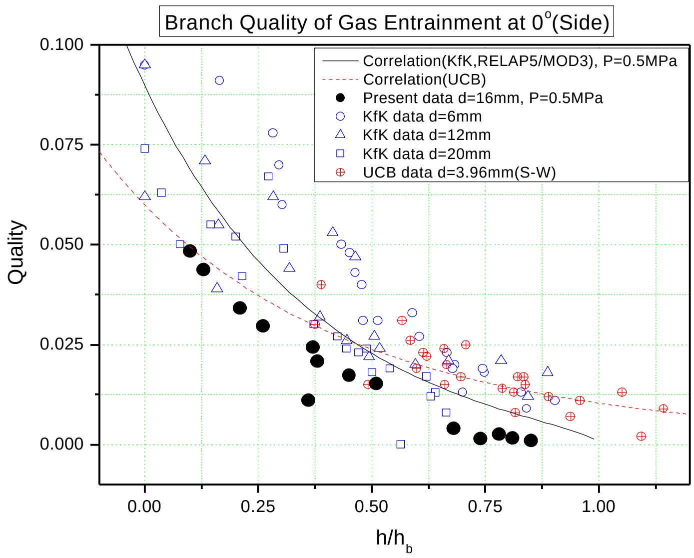
In Figure 10 (d), the present quality data are compared with the correlations and data by UCB and KfK. As described earlier, the present data are plotted using h_b by the new onset criterion. The onset of gas entrainment means that h/h_b equals to 1.0 by the newly developed correlation for onset of gas entrainment at bottom branch. As h/h_b decreases from 1.0, the quality increases from zero. From the aspect of application to the safety analysis, it is preferable because the onset of gas entrainment (h/h_b =1) indicates the initiation of effective gas discharge as well as of the onset of gas entrainment itself. It is difficult to observe the consistency in the previous data because of their quite scattering. Furthermore, large deviation between the existing correlations is found: their predictions of quality are different even 2 times. Such discrepancies are resulted from the inconsistency of onset criteria, which represents the importance of onset criterion especially to the gas entrainment.



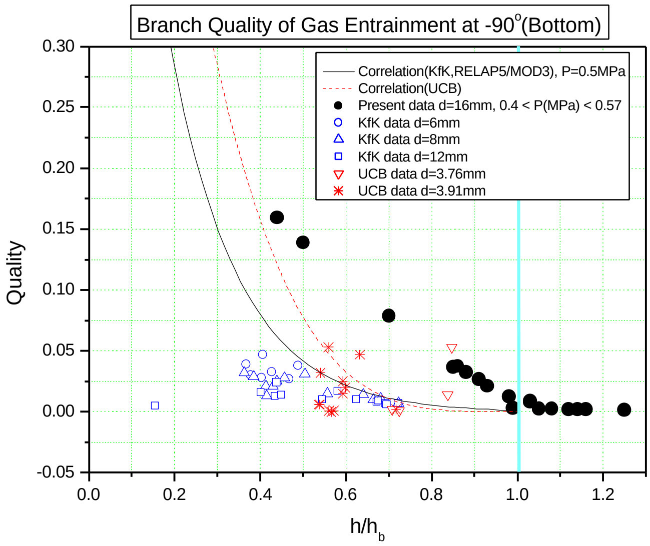
(a) Quality data at top branch



(b) Quality data at side branch (liquid entrainment)



(c) Quality data at side branch (gas entrainment)



(d) Quality data at bottom branch

Figure 10 Comparison of present quality data with KfK and UCB

3.3 Onset of Liquid/Gas Entrainment at ±36°, ±72°

The off-take experiments for specific angled (±36°, ±72°) branches are currently in progress. The quality data are not obtained yet. In this paper, we introduce the onset data at first. They are discussed in two groups: onset of liquid entrainment and onset of gas entrainment. Newly obtained onset data for specific angles of the branch pipes are analyzed as the following approaches: how they are different from existing correlations of three orientations; whether it can be possible to unify the off-take model using additional input parameter (an arbitrary angle, ?) instead of the existing model (HSEM) that is separated into four cases according to the entrained fluids and branching angles. The latter approach is expected to conclude after more experimental works. The former approach is only discussed here.

1) Onset of liquid entrainment: O.L.E.

For the branches with +72°, ±36°, the liquid entrainment phenomena are observed. The data for all three diameters of branches are obtained. It is observed that the off-take phenomena from the interface for the branches with +72° are similar to those at top branch and those at side (0°) and -36° branches are almost the same. But it is difficult to observe the vorticity on the interface at the branches with +36° because the inner wall in the horizontal pipe hinders its formation. A small deviation from HSEM in RELAP5/MOD3.3 is found as shown in Figure 11. The data are fitted closely to the correlation at the top branch for the branch with +72°. However, the data for the branches with ±36° are close to the correlation at the side branch because the inner wall in the horizontal pipe influences the onset of entrainment like the side branch. Especially, the data at branches with +72°, +36° are the correlation at the between top and side branch because friction in the inner wall of the horizontal pipe and the entrainment from the interface determine simultaneously the onset of entrainment.

2) Onset of gas entrainment: O.G.E.

The definition of the first gas hose as the onset of gas entrainment cannot be applied to the branch with -72, ±36° because it is difficult to observe the first gas hose phenomena in specific angled branches unlike the bottom branch. The different definition of the onset of gas entrainment is used, which is the first bubble gas entrainment. It is easier to be observed and be applied to the branches with -72, ±36°. Using such a different definition, the data at the branches with -72°, ±36° as well as at the bottom (-90°) branch are obtained. The phenomena at branches with ±36° are similar to those at side branch; those at both bottom and -72° branches are almost the same. No differences between bottom branch and -72° branch are shown in Figure 12. However, a deviation between HSEM of the side branch in RELAP5/MOD3.3 and the data at the branch with +36° is seen clearly. The data at the branch with -36° are on the line of the correlation developed by the KfK, however, they are away from the data at the branches with -72°, -90°. Like the onset of liquid entrainment, the inner wall in the horizontal pipe influences the data at the branch with -36°

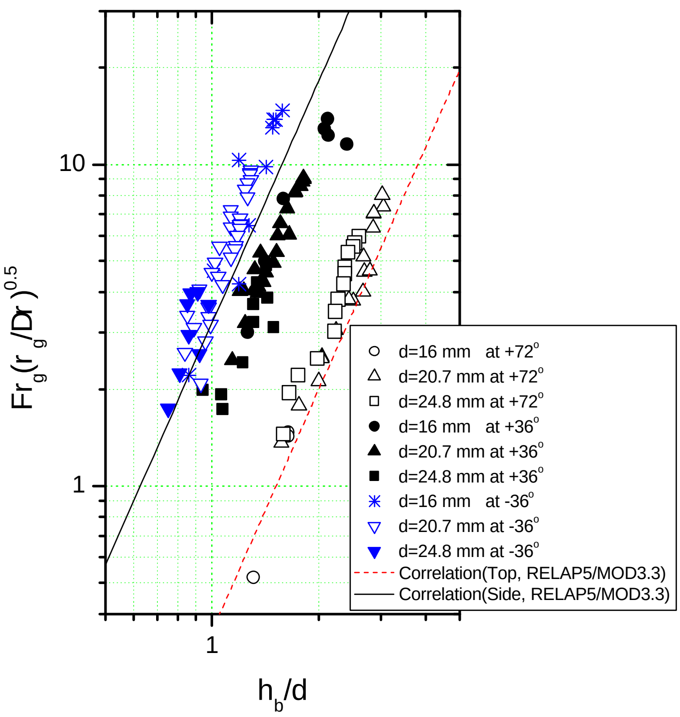


Figure 11 Comparison of the O.L.E. data at +72, ±36° branches

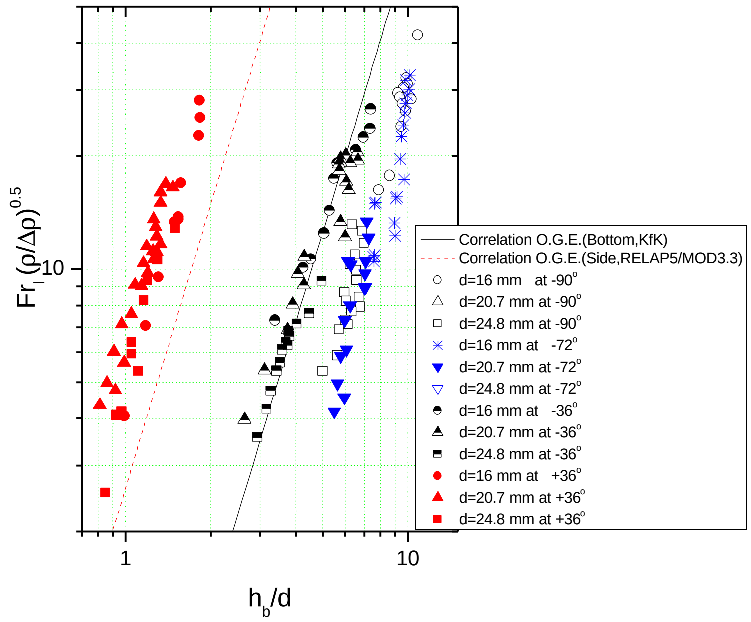


Figure 12 Comparison of the O.G.E. data at +72, ±36° branches

4. Conclusions

In the present study, the off-take phenomenon at T-junction with ±36, ±72° angled branches as well as top, side and bottom branches in the horizontal pipe are experimentally investigated. The conclusions of the present study are summarized as follows:

- The onset and quality of liquid/gas entrainments at top, side and bottom branches are verified using the previous results of the break flow for SB-LOCA. Overall comparisons between the present and previous results show agreements except for a few results at specified conditions.
- The onsets of off-take data at three orientations well agree with the existing correlations. At bottom branch, the new definition of the onset of gas entrainment is suggested to avoid an ambiguity by different onset criteria in previous studies.
- The quality data at three orientations are compared with the previous data and correlations. The quality at top branch shows a sudden drop affected by the transition from stratified to slug flow in the horizontal pipe, which is difficult to be predicted on the existing quality correlation by UCB. The qualities on the onset of liquid/gas entrainments at side branch well agree with the previous correlations, especially by KfK. The quality data at bottom branch have a value close to zero to lower h/h_b than previous data. A new onset criterion for bottom branch to represent the initiation of the effective increase of quality from zero is preferable to apply into the safety analysis.
- The onsets of off-take data are obtained using four specific angles (±36, ±72°). They are compared with the previous correlations for three orientations. As results, their onset data are deviated from the existing correlations in HSEM. A series of off-take behavior shows differences according to the angles of branch.

The off-take experiments at specific angles of branches are still in progress. It is expected to conclude whether it is feasible to unify the four existing correlations according to off-take style and branch angles, or how to group the off-take results including specific angled branches after more experimental works are performed in the future.

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