OFF-TAKE EXPERIMENT AT T-JUNCTION BETWEEN HEADER AND FEEDER PIPES IN CANDU REACTORS

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ABSTRACT

An experimental study has been performed to investigate the off-take phenomena at the horizontal pipes branched with various angles, $\pm 36°$ and $\pm 72°$ between the fuel channel header and feeder pipe in a CANDU 6 reactor. In safety analyses for transient simulation, the current horizontal stratification entrainment model (HSEM) inside RELAP5/MOD3.3 code cannot predict the exact mass qualities at specific angle branches because it can be applied only at the bottom, top and side branches. Therefore, the geometrical characteristics between header and feeder pipes requires different approaches to safety analysis from the current simulation codes developed for light-water cooled reactors. To develop a best-estimated transient simulation code for CANDU reactors, there is a need to develop the HSEM based on actual angles.

In this experimental study, off-take experiments are carried out using the experimental facility of 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 to a CANDU-6 reactor considering the geometric effect of branching angles. 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 and the experimental results of previous studies are validated by the present experimental data for three branch orientations. The data of onset of off-take shows agreements with the existing correlations. However, the experimental results show that HSEM does not show good agreement of the present onset data of the specific branch angles, $\pm 36°$ and $\pm 72°$, and the quality data show discrepancies in top and bottom branches.

1. INTRODUCTION

The liquid entrainment and vapor pull-through models of horizontal pipe in 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. KfK [2] reported 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. UCB [3] also presented the results of an experimental investigation of both air-water and steam-water discharge from a stratified upstream region through small diameter breaks oriented at the bottom, top and side of the horizontal pipe. These two experimental results are implemented into the horizontal stratification entrainment model (HSEM) in RELAP5/MOD3.3. However, the geometrical structures of the CANDU reactors are different from those of light water cooled reactors. There are five-angled types at T-junctions between header and feeder pipes; 0°, 36°, 72°, 108°, 144° from the horizontal line. Therefore, the current horizontal stratification entrainment model in RELAP5/MOD3.3 cannot predict the exact mass qualities at specific angle branches.

In the present study, off-take experiments are carried out using the experimental facility of 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. In the first phase of the study, the onset of liquid/gas entrainment and quality at the branch with top, side and bottom branches for stratified flow in the horizontal pipe including the comparison with the previous studies such as KfK and 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.

2. EXPERIMENTAL STUDY

2.1 Experimental Apparatus

The scaling analysis is performed to design the off-take test facility on the prototype of CANDU-6. 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. In the scaling of flow rates, the similitude of Froude number, Fr and void fraction are considered. The branch pipes are designed into three diameters scaled down from the feeder pipes as shown in Table 1.

Figure 1 shows the overall schematic diagram of the test facility, which consists of air-water tank, horizontal pipe, branch pipes, air-water separator and collecting tank of entrained water. At the branch junctions, 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.

2.2 Off-Take Experiment

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. 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). All injected air/water are discharged through the branch pipe because of no exit flow in the horizontal pipe.

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 of 2-8 bar. The number of data at ±36, ±72° branches is more than that at top, side and bottom.

3. RESULTS AND DISCUSSIONS

The experimental studies in this paper are divided into three categories; (i) Onset of liquid/gas entrainment at top, side and bottom branches, (ii) Branch quality at top, side and bottom branches, and (iii) Onset of liquid/gas entrainment at branches with ± 36, $\pm 72^{\circ}$. The present experimental data at top, side and bottom branches are compared with the previous results for the SB-LOCA for verification but the data at branches with ± 36, $\pm 72^{\circ}$ are compared with the existing correlations.

3.1 Onset of Liquid Entrainment (O.L.E.)

Top Branch

As the gas flow increases, the droplets are generated from the end of the entrained crest. The entrained liquid reaches the entrance of branch and thereafter discharges through the branch. This point is defined as the onset of liquid entrainment (O.L.E.). In Figure 3 (a), the HSEM predicts well the data although they are comparatively in lower ranges of h_b/d.

Side Branch

Increasing the gas flow, the deflection of the interface is occurred due to the Bernoulli effect in the vicinity of the branch wall. As an increase of the liquid level, a thin ascendant film of water determines the onset of liquid entrainment and the entrained liquid is discharged. In Figure 3 (b), while UCB data has a little scattering, the experimental data are agreed with the previous experimental data and those of KfK (HSEM in RELAP5/MOD3.3).

3.2 Onset of Gas Entrainment (O.G.E.)

Side Branch

As a liquid flow increases, the liquid phase generates a small vortex and the thin hose of gas reaches in the vicinity of the branch. When the onset of gas entrainment is determined, the small bubbles are discharged through the branch. The HSEM predicts the data although they are scattered around the correlation as shown in Figure 4 (a). However, the present data is not scattered large compared to the previous data and is a little deviation from the correlation of UCB.

Bottom Branch

As liquid phase generates continuously very small bubbles, they are discharged through the branch or disappeared toward interface level. As the interface level decreases, thin gas hose is formed with a great vortex and move to the entrance of the branch. Thereafter the onset of gas entrainment takes place. At this point, a lot of gas is swept out as vortex-free flows. The KfK correlation by the first hose gas predicts well the data shown as Figure 4 (b). However, the correlation of UCB has a little deviation from the present data. In Figure 5, the critical point of quality for the onset of gas entrainment is defined as a point of h/h_b, which means the beginning of the transition from vortex flow to vortex- free flow shown. In this study, h/h_b is about 0.31, which is similar to the KfK's correlation.

3.3 BRANCH QUALITY

Top Branch

In Figure 5 (a), the branch quality becomes nearly 1.0 because the liquids are discharged through the branch as type of 'droplets' at the low of gas flow rate. As a gas flow increases, a transition from stratified flow to slug occurs in the horizontal pipe and interface levels becomes unstable. Thereafter a lot of liquids are entrained as 'lump' of water and makes the quality drop into low quality fields. The present data are compared with the previous correlations and data as shown in Figure 8 (a). In the low quality fields and transition from the high quality to the low quality fields, there are large deviations between the present data and the correlation of UCB (RELAP5/MOD3.3.). This means 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 to predict well the quality at top branch.

Side Branch

Both the liquid entrainment and gas entrainment can be observed according to the interface levels as shown in Figure 5 (b). In Figure, the present data agree with the existing data and correlations for liquid entrainment. The present data show more consistency with KfK's correlation than that of UCB although the number of data is less than those of the previous works.

Bottom Branch

In Figure 5 (c), the present quality data are compared with those of UCB and KfK. 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. The proposed definition of the onset of gas entrainment is related to the critical point of quality increase from zero as shown Figure 6. 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 7.

3.4 Onset of Liquid/Gas Entrainment

The off-take experiments for specific angled ($\pm 36°$, $\pm 72°$) branches are currently in progress. At present study, onset of liquid entrainment and onset of gas entrainment are investigated in accordance with specific angles of the branch pipes to identify the off-take model using arbitrary angle, θ, instead of the existing model (HSEM).

Onset of Liquid Entrainment (O.L.E.)

For the branches with +72°, $\pm 36°$, the liquid entrainment phenomena are observed. In Figure 8 (a), the off-take phenomena from the interface for the branches with +72° are similar to both those of top branch and side (0°). As for -36° branches, the off-take phenomena for the branches with $\pm 36°$ 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. The data at branches with +72°, +36° are the correlation at the between top and side branch since the friction in the inner wall of the horizontal pipe and the entrainment from the interface determine simultaneously the onset of entrainment.

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 of a difficulty to observe in specific angled branches unlike the bottom branch. Therefore, the new definition on the onset of gas entrainment is proposed for the first bubble gas entrainment. While the phenomena at branches with ±36° are similar to those at side branch, those at both bottom and -72° branches are almost the same as shown in Figure 8 (b). The deviation between HSEM at the side branch and the data at the branch with +36° is seen clearly. While the data at the branch with -36° are on the line of the KfK correlation, they are away from the data at the branches with -72° and -90°.

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:

(1) The onset and quality of liquid/gas entrainments at top, side and bottom branches are verified using the previous results. Overall comparisons between the present and previous results are agreed except for a few results at specified conditions.

(2) The onsets of off-take data at three orientations are well agreed with the existing correlations. At bottom branch, the new onset definition of gas entrainment is proposed to identify the different onset criteria in previous studies.

(3) 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 KfK correlations.

(4) The onsets of off-take data are obtained using four specific angles (±36, ±72°) are compared with the previous correlations, respectively. As results, 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.

ACKNOWLEDGEMENT

This study has been carried out as a part of the R&D program titled "Establishment of Safety Assessment System and Development of Safety Issue Relevant Technology for CANDU Reactors" supported by Korea Ministry of Science & Technology.

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Table 1 Scaled Geometry of Test Facility

	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	0.42
Feeder diameter-2	4.93 cm	2.07 cm	0.42
Feeder diameter-3	5.90 cm	2.48 cm	0.42
Gas/liquid flow rate			0.177

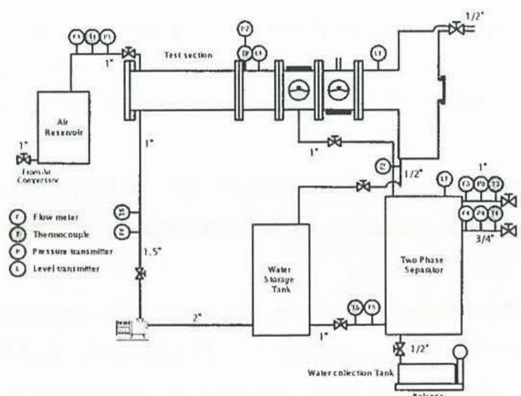


Figure 1 Schematic diagram of the test facility

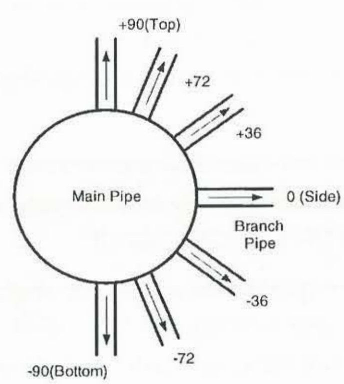
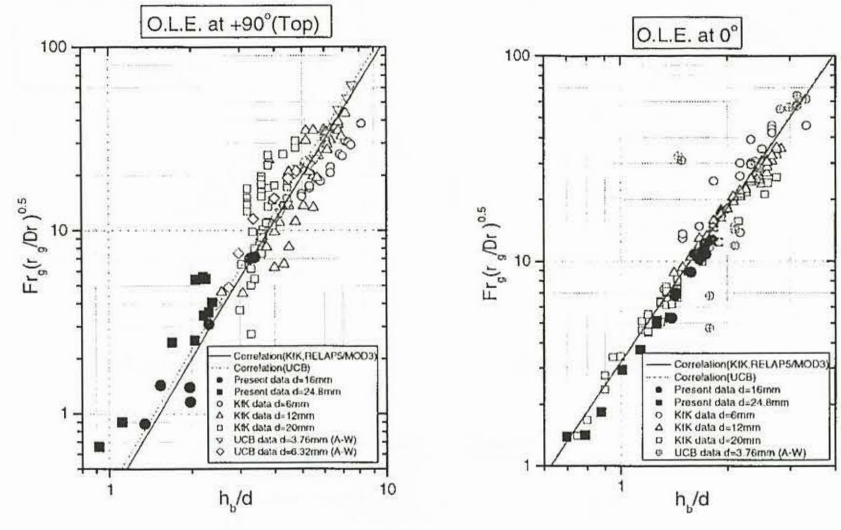
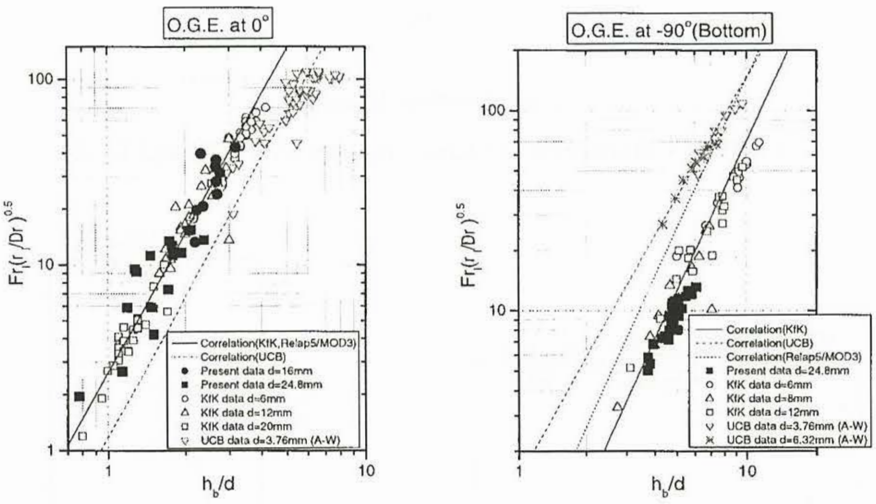


Figure 2 Side view of T-junctions



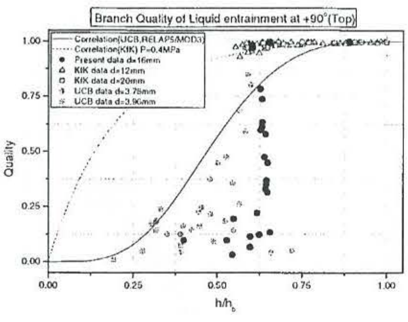
(a) at top branch (b) at side branch

Figure 3 Comparison of Liquid Entrainment Onset Results with KfK and UCB

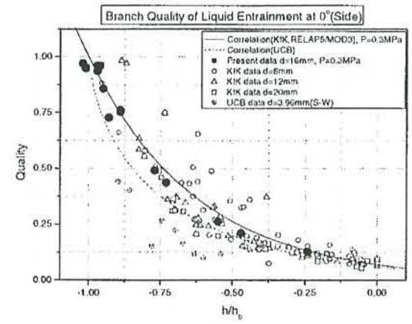


(a) at side branch (b) at bottom branch

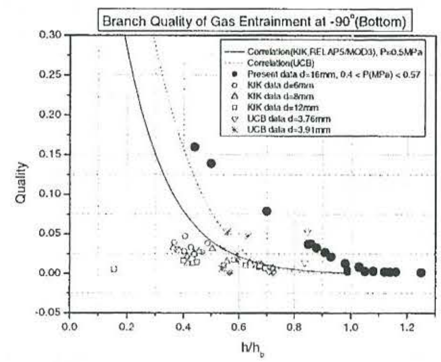
Figure 4 Comparison of Gas Entrainment Onset Results with KfK and UCB



(a) at top branch



(b) at side branch



(c) at bottom branch

Figure 5 Comparison of Quality Results with KfK and UCB

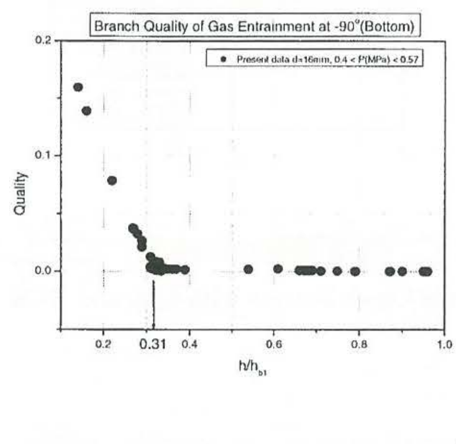


Figure 6 Quality at bottom branch

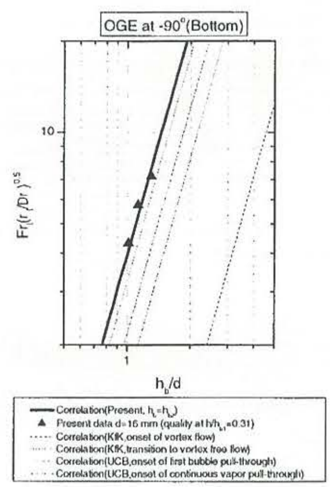
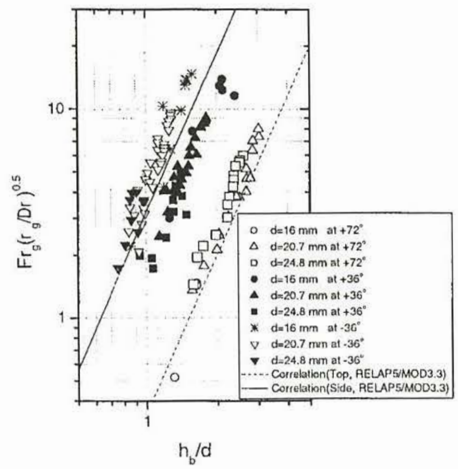
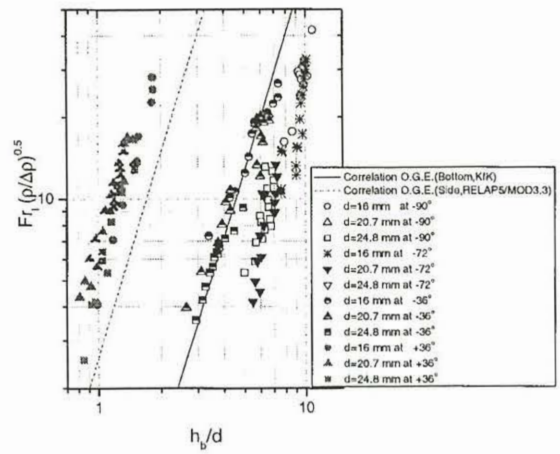


Figure 7 Comparison with KfK and UCB





(a) Comparison of the O.L.E. data (b) Comparison of the O.G.E. data

Figure 8 Comparison of the O.L.E. and O.G.E. data at +72, ± 36° branches