Journal of the Korean Nuclear Society
Volume 36, Number 2, pp.142 ~ 152, April, 2004

Modeling of Liquid Entrainment and Vapor Pull-Through in Header-Feeder Pipes of CANDU

Yong Jin Cho
Korea Institute of Nuclear Safety
19 Guseong-Dong, Yuseong-gu, Daejon 305-338, Korea

Gyoo Dong Jeun
Hanyang University
17 Haengdang-dong, Sungdong-gu, Seoul 133-791, Korea
yjcho@kins.re.kr

(Received November 20, 2003)

Abstract

The liquid entrainment and vapor pull-through offtake model of RELAP5/MOD3 had been developed for SBLOCA (Small Break Loss of Coolant Accident). The RELAP5/MOD3 model for horizontal volumes accounts for the phase separation phenomena and computes the flux of mass and energy through a branch when stratified conditions occur in the horizontal pipe. In the case of CANDU reactor, this model should be used in the coolant flow of 95 feeders connected to the reactor header component under the horizontal stratification in header. The current RELAP5 model can treat the only 3 directions junctions; vertical upward, downward, and side oriented junctions, and thus improvements for the liquid entrainment and vapor pull-through model were needed for considering the exact angles. The RELAP5 off-take model was modified and generalized by considering the geometric effect of branching angles. Based on the previous experimental results, the critical height correlation was reconstructed by use of the branch line connection angle and validation analyses were also performed using SET. The new model can be applied to vertical upward, downward and angled branch, and the accuracy of the new correlations is more improved than that of RELAP5.

Key Words : thermal-hydraulics, liquid entrainment and vapor pull through, take-off, CANDU, header-feeder

I. Introduction

In Korea, four CANDU reactors, a type of pressurized heavy water reactor (PHWR), have been imported from Canada. It becomes important to ensure the operational safety of the CANDU reactor while the four plants are under operation. One of the ways to ensure operational safety and protect from unlikely events during the reactor life time is to have analysis tools that can

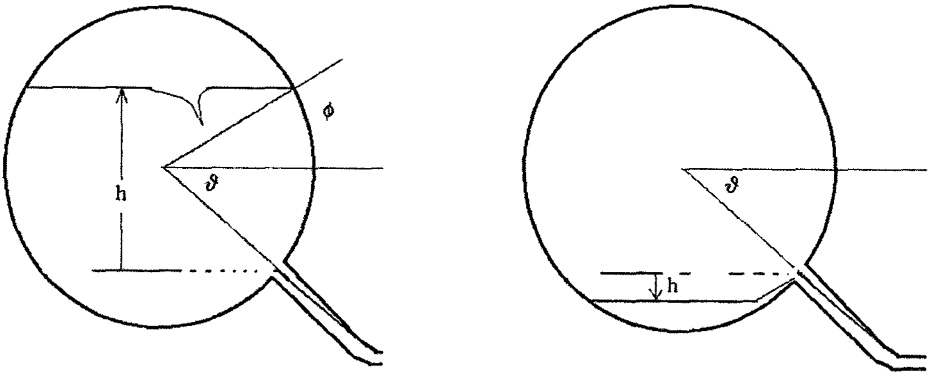


Fig. 1. Conceptual Sketches for Liquid and Vapor Pull-Through Model

cover all accidents from minor events to serious D_2O leakage accidents. This analysis technology and capability build a sound regulatory foundation and can help the correct regulatory actions. In the current situation, most analysis tools for regulatory purpose depend on USNRC regulatory codes and technologies. However, there is no CANDU reactor in US and thus no analysis tool for the CANDU reactor in USNRC [1,2]. Although the CATHENA code[3] had been introduced from AECL, it is undesirable to use a vendor's code for regulatory auditing analysis. Therefore it is important to develop an independent auditing code for the CANDU reactor, implementing regulatory aspects during the development stage. One way of developing a thermal hydraulic auditing code for CANDU reactor is to modify the models of existing PWR auditing tool [1]. In the CANDU reactor, the liquid entrainment and vapor pull-through model (Off-take model) becomes so important that it controls the coolant flow of 95 feeders connected to the reactor header component where the horizontal stratification may occurs [1]. The current RELAP5 model is able to treat the only three directions; vertical upward, downward, and side oriented junctions, and thus improvements for the off-take model was needed for modeling the exact angles.

The flow characteristics in the off-take phenomena can be figured as presented in Figure 1. Theoretical and experimental studies of two-phase flow through small branches in horizontal pipes under stratified-flow conditions have been carried out mostly during the past twenty years. After the importance was first proposed by Zuber in 1980[4], Smoglie and Reimann[5], Schrock et al.[6], Yonomoto and Tasaka [7,8], and Micaelli and Memponteil [9] performed experiments using air-water and steam-water mixtures. Hassan et al [13] also performed an experiment, characterized by an angled branch line.

In this study, a base formulation for a new correlation was developed based on a point-sink method considering feeder pipe angle. The new correlations for vertical upward, downward, and angled branch were developed and the verification/validation were performed using available separate effect test data.

2. Theoretical Approach

The configuration under consideration in the present analysis is shown in Figure 2. Stratified layers of immiscible fluids with density ρ and $\rho+\Delta\rho$ are contained in a large reservoir whose wall is inclined at an angle θ from vertical. Discharge is induced from the lighter fluid through the branch with mass flowrate $\dot{m}$. The purpose of the

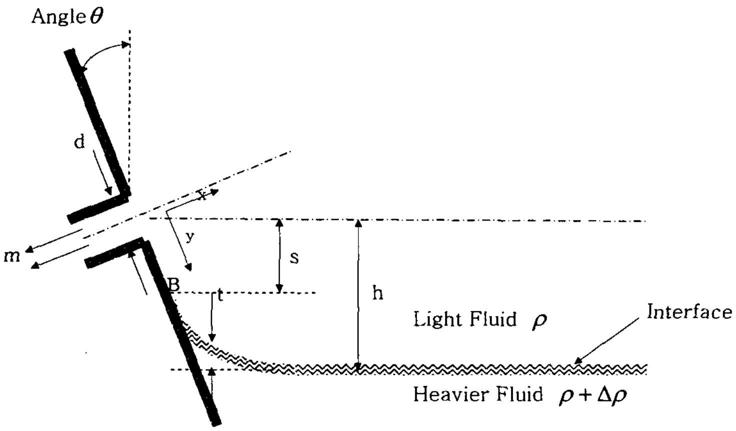


Fig. 2. Schematic Drawing for Theoretical Apporoach

analysis is to predict the critical height h at which the heavier fluid starts flowing into the branch.

The present analysis assumes that the dominant forces are the inertia and gravity forces and the effect of viscosity and surface tension are negligible. Both fluids are assumed to be incompressible and steady-state potential flow is assumed in the lighter fluid, while the heavier fluid is stagnant. The present analysis followed Craya's[11] approach, applied successfully by Armstrong et al.[12], and Hassan et al.[13] where equilibrium of interface and the velocity field in the lighter fluid are determined first and then equality of the velocity and its gradient at linking point B (see Figure 1) are later imposed as conditions for the onset of liquid entrainment.

Applying Bernoulli equation on a stream line coincident with the interface from the side of the lighter fluid, we get:

$$P+\frac{\rho V^2}{2}+\rho g t=C \qquad (1)$$

where C is an arbitrary constant, V is fluid velocity, g is gravitational constant, ρ is density, P is pressure, and t is the distance between the liquid level and the liquid/wall contact point. Along the same streamline from the side of the heavier fluid, the Bernoulli equation gives:

$$P+(\rho+\Delta\rho)gt=C \qquad (2)$$

Subtracting equation (2) from the equation (1), we get:

$$\frac{V^2}{2}=\frac{\Delta\rho}{\rho}gt \qquad (3)$$

If we consider a branch line point corresponding to the location on the interface where $t=h-s$, equation (3) gives:

$$\frac{V_B^2}{2}=\frac{\Delta\rho}{\rho}g(h-s) \qquad (4)$$

If we define n as a strength, the relation between n and $\dot{m}$ are;

$$n=\frac{\dot{m}}{2\pi\rho} \qquad (5)$$

In developing the velocity field in the lighter fluid, the presence of heavier stationary fluid is ignored. Therefore, the fluid field is treated as a semi-infinite medium extending over $0\leq x\leq\infty$, $-\infty\leq y\leq\infty$, and $-\infty\leq z\leq\infty$. The three dimensional flow is symmetric around the x-y plane which passes through the sink. Therefore,

Table 1. Experimental Data Used to Determine Correlation Constants

Experimental Conditions	Smoglie/ Reimann[5]	Schrock et al.[6]	Hassan et al.[13]	Anderson et al.[15]	Andreychek et al[16]
1. Tank/Branch					
- Angle	90°, 0°,- 90°	0°,- 90°	0°, 45°, 90°	0°,90°	0°,45°,60°,90°
- Size(mm)	0.6, 0.8, 1.2	0.375, 0.396, 0.632	0.635	0.81	31.75, 57.15, 69.85
- d/D	0.029~0.097	0.021~0.03	0.0228	0.034~0.052	0.12,0.17,0.32
2. T/H condition					
- Pressure (MPa)	0.2~0.5	0.109~0.913	0.316, 0.517	3.45, 4.4, 6.2	0.1
- Temperature (℃)	20	20~Saturation Temperature	20	Saturation Temperature	20
3. Simulant	Air/Water,	Air/Water, Steam/Water	Air/Water	Steam/Water	Air/Water
4. No. of Data/used	264	174	6	9	50

some analogy exists with the case of a two-dimensional flow, thereby allowing the introduction of a stream function and a velocity potential. Following Milne-Thomson [14], the potential function in the x-y plane, which is perpendicular to the reservoir wall, is given by :

$$\phi = -\frac{n}{r} \tag{6}$$

where r is the radial distance from the sink.
The radial velocity V_r at any point in the x-y plane can be obtained as:

$$V_r = -\frac{\partial\phi}{\partial r} = -\frac{n}{r^2} \tag{7}$$

At front point of the liquid surface, the velocity corresponds;

$$\frac{V_B^2}{2} = \frac{1}{2}\left[\frac{n}{(s/\cos\theta)^2}\right]^2 \tag{8}$$

In order to get critical height, we combine two equations (4) and (8), and from combining the two eguations, we can get;

$$\frac{\rho}{\Delta\rho} g(h-s) = \frac{1}{2}\left[\frac{n}{(s/\cos\theta)^2}\right]^2 \tag{9}$$

To get the information of s, first derivatives of equation (9) with respect to s, and some manipulation, we can get equation, which contains s and other physical parameters. Thus this equation introduce in equation(9) and with some manipulation, we can get the critical height *h*:

$$\begin{aligned} h &= C_1\left[\frac{\dot{m}}{\sqrt{g\rho\Delta\rho}}(\cos\theta)^2\right]^{0.4} \\ &= C_1\left[\frac{\dot{m}}{\sqrt{g\rho\Delta\rho}}\right]^{0.4}(\cos\theta)^{C_2} \end{aligned} \tag{10}$$

Equation (10) indicates that for a single discharge with fixed flow rate and fluid properties, *h* varies with wall inclination θ according to$(\cos\theta)^{C_2}$. The exponent of $\cos\theta$ was regarded as unknown constant that is determined by experiment, in order to focus on the angled branch and be compared with large number of

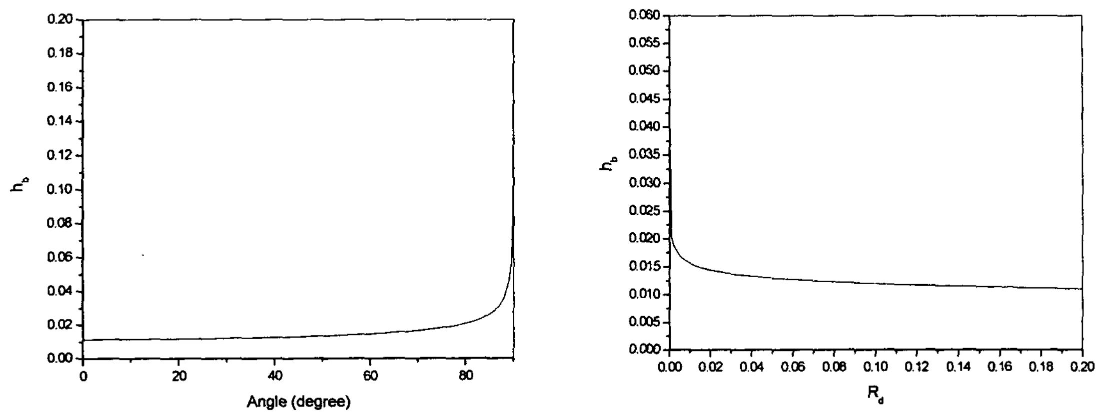


Fig. 3. New Correlation Results for Inclination Angle and Diameter Ratio

experimental data.

In this study, an experimental database was constructed and the results were reviewed carefully. The experimental data were gathered from Smoglie and Reimann [5], Schrock et al.[6], Ibrahim G.Hassan et al.[13], J. L. Anderson et al.[15], and T.S.Andreychek, et al[16]. All effective experimental data were over 500 points including upward, downward, and side branch with downward angle (θ=0°, 45°, 60°, 90°). The detailed experimental parameters are shown in Table 1.

Among the selected sensitivity parameters, the results of diameter ratio between branch line and main horizontal pipe, d/D, shows some dependency on the ratios. The ratios of correlation and experimental results according to the diameter ratio were investigated. Due to the lack of experimental results for an angled branch, the results from T.S.Andreychek, et al.[16] were used, but this experiment could be characterized by large diameter ratio between a branch line and main horizontal pipe. The experimental results show the dependency of the diameter ratio between the branch line and main horizontal pipe, d/D.

$$R_d = d / D \qquad (11)$$

where d is the branch line diameter, and D is the main line pipe diameter.

Through these evaluations, the basic correlation form had been determined, based on the previous analysis, as follows;

$$\begin{aligned} h_b &= C_1 (\cos\theta)^{C_2} (R_d)^{C_3} h \\ &= C_1 (\cos\theta)^{C_2} (R_d)^{C_3} \left[\frac{\dot{m}_k}{\sqrt{g \rho_k \Delta\rho}} \right]^{0.4} \end{aligned} \qquad (12)$$

where C_1, C_2, C_3 are constants, h is introduced from equation (10) and subscript k represents the continuous phase.

In a statistical treatment to determine the above constants, C_1, C_2, C_3, nonlinear fitting method was used for the determination of correlation constants with experimental data. The experiments were divided into 3 groups, upward, downward, and other angles including side branch, The

Table 2. Constants of Critical Height Correlation by Nonlinear Fitting Methods

Constants	Upward Orientation	Downward Orientation	Angled Orientation
C1	0.77	1.20	0.49
C2	0.	0.	-1.14
C3	-0.24	-0.07	-0.114

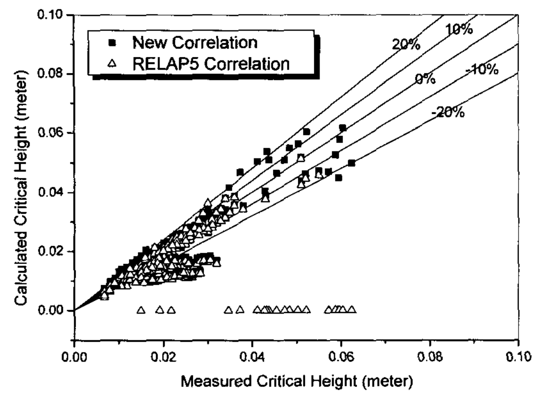


Fig. 4. Angled Branch Correlation Comparion

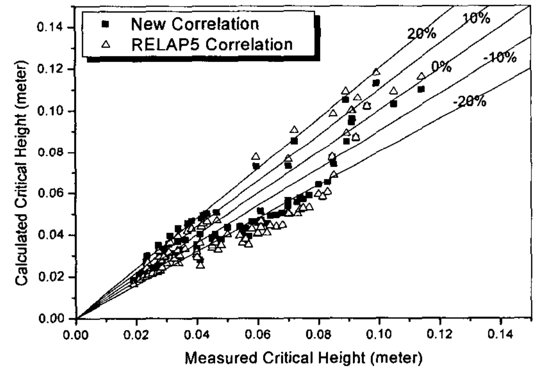


Fig. 5. Vertical Downward Branch Correlation Comparison

determined coefficients are as shown in Table2.

In Figure 2, the h_b behaviors for angle θ and as R_d are shown. The conditions in Figure 2 are $\dot{m}=0.276kg/sec$, $\Delta\rho=996.252kg/m^3$, $\rho_k=\rho_l=998.356kg/m^3$, $g=9.8m/sec^2$, $R_d=0.0508$ and θ was variable. Theoretically, the correlation range can be specified as $-90° < \theta < 90°$, but in practice, the experimental verification was performed at $60° \leq \theta \leq 0°$ for side branch. This range should be applicable range. Although new correlation is still valid at the range, $-90° < \theta < 90°$, theoretically, in the out side of $-60 \leq \theta \leq 0°$ the correlation is regarded as in valid, practically, due to the absence of experimental verification. In the case of R_d, the experimentally verified range was $0.0291 \leq R_d < 0.39$.

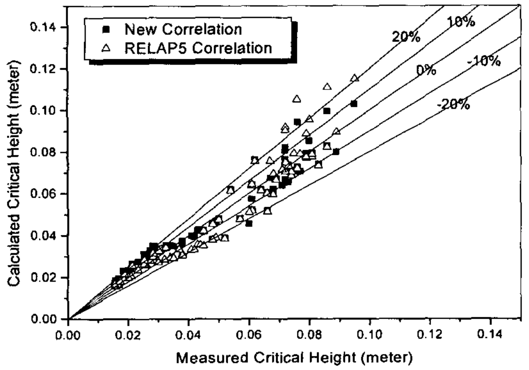


Fig. 6. Vertical Upward Branch Correlation Comparison

Figure 4 shows that the RELAP5 correlation Could not predict the critical height at angled branch line but the new correlation could predict the experimental results with reasonable accuracy. In Figure 4, the results of RELAP5 as zero mean that RELAP5 cannot deal in the angled branches except 0 degree. Also, when the angled branch results in 0 degree, the new correlation results were more accurate than that of RELAP5.

The vertical upward and downward results are shown in Figures 5 and 6 and the Figures show that new correlation could give a more accurate prediction than RELAP5. Originally, the RELAP5 correlation could not predict the angled branch configuration, but the proposed correlation can predict the beginning of liquid entrainment and gas pull-through.

3. Application and Validation Results

The newly developed correlation described in previous section was applied to RELAP5/ CANDU. In order to simulate the general angled branch, the liquid entrainment and vapor pull-through model in horizontal pipe should be improved in terms of geometrical consideration for the stratified liquid level, angled branch elevation, Critical Depth Correlation for angled branch configuration, and a non-dimensional correlation for flow quality suitable for angled branch configuration. The RELAP5 model also on has offtake flow quality correlation and this can affect the flow quality behavior. Because the new correlation was developed under the same theoretical assumptions and approch, the original offtake flow quality correlation oppears to be valid.

In the case of a side branch, void fraction 0.5 is used as the criterion for choosing between liquid entrainment correlation and vapor correlation. If the perfect horizontal stratification is achieved, the void fraction α_g^*, where the water level reaches the feeder branch, can be defined as follows;

$$\alpha_g^* = \frac{1}{\pi}\left[\left(\frac{\pi}{2}-\theta\right) - \sin\left(\frac{\pi}{2}-\theta\right)\cos\left(\frac{\pi}{2}-\theta\right)\right] \qquad (13)$$

where for the side branch, θ equals zero and α_g^* equals to 0.5. For the upward branch, θ and α_g^* are equal to $\pi/2$, and 0.0, respectively. For the downward branch, θ and α_g^* are equal to $-\pi/2$, and 1.0, respectively.

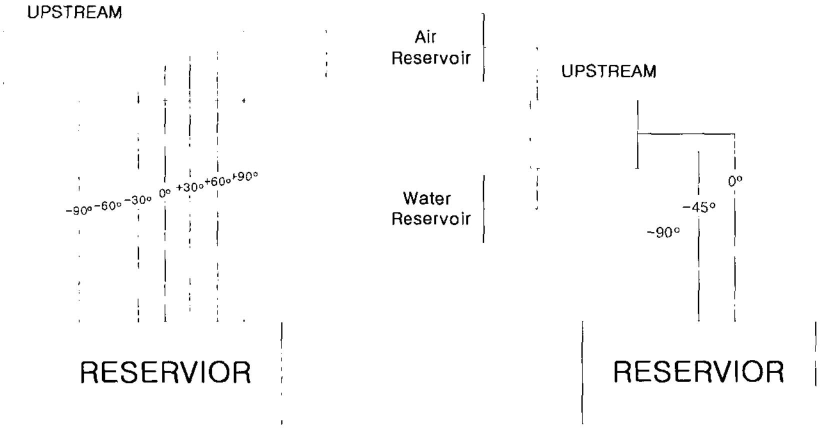
The water level, h_c, can be defined, using the following geometrical relation

$$h_c = \left(\frac{D}{2}\right)(\sin\phi - \cos\theta) \qquad (14)$$

where ϕ is the angle between the water level and center horizontal line.

Implementing the above new model into RELAP5/CANDU, the subprogram, HZFLOW, which determine the liquid entrainment and vapor pull-through, was modified. For the related branch angle input processing, the input subprograms RBRANCH, RSNGLJ,and RVALVE were modified and the extended model can be used in single junction, branch and valve component.

For validation of the modified model, two approaches were selected ; the first one is a conceptual problem and the second is a limited SET (Separate Effect Test) problem. The conceptual problem objective is to investigate that the errors can be induced by the modifyed procedure and whether the off-take phenomena can be predicted physically reasonable by the modified model. The SET problems are selected to evaluate the new model performances in



a) Verification (90°~-90°)

a) Verification (0°~-45°)

Fig. 7. Nodalization for New Model Verification and Validation

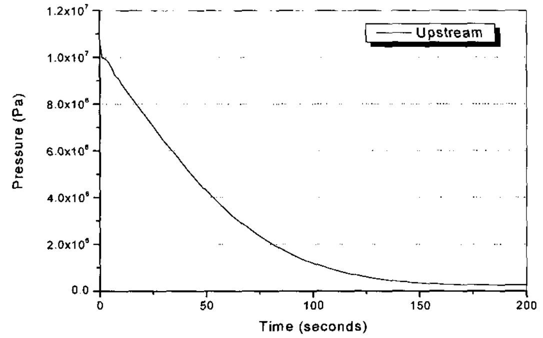


Fig. 8. Upstream Pressure Behavior for Verification

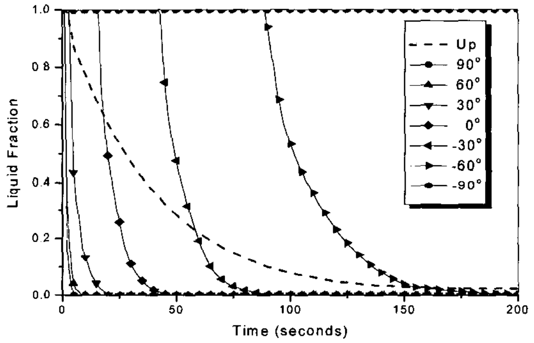


Fig. 9. Branch Line Liquid Fraction Results for Verification

comparison voith the experimental results.

As a conceptual problem [1], the discharge from a reservoir was selected. The reservoir had saturated heavy water and 7 branches were connected to the reservoir with various angles (-90° ~90°). As described above, the reservoir was filled with saturated 100 bar heavy water. After the discharges start, reservoir pressure decreased and the water level of the reservoir also decreased due to flashing of the saturated water. This problem can be defined as the higher branch flow transition occurred from liquid to vapor earlier than that of the lower branch, as the reservoir level decreased. Nodalization of this problem is shown in Figure 7 a), and the results are also shown in Figure 8 to 10. As shown in Figure 8, at about 200 seconds after the initiation of flow through seven branches, the reservoir pressure completely depressurized. Comparisons of void fractions and mass flowrates for each branch line are shown in Figures 9 and 10, respectively. The transition starts at the upper branches and propagates to the lower branches.

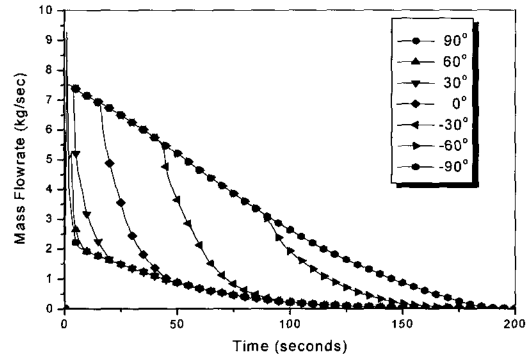


Fig. 10. Branch Line Mass Flowrate Results for Verification

In Figure 9, the differences among each branch's vapor entrainment timing became larger as the reservoir level decrease. Initially, the liquid leaked out through all of 7 branches and the pressure including water head was large. As the pressure decrease, the level decreasing rate became slower and the amount of time increased after upper branch was uncovered. The vapor pull-through occurred before the water level did not reach the entrance of branch. For example, in the case of 0° branch the vapor pull-through was observed at 0.34 void fractions before the void fraction reaches 0.5. This result shows that the geometric modeling concept is reasonably correct and consistent with the physical phenomena.

A Canadian experimental facility[13] was adopted as a SET. Hassan et al (1999) also performed experiment about off-take phenomena, but this experiment was characterized by angled branch line. The experiment were performed at system pressure using 316 kpa and 517 kpa in a horizontal pipe (58mm in diameter) with one branch size (d=0.635mm) and different

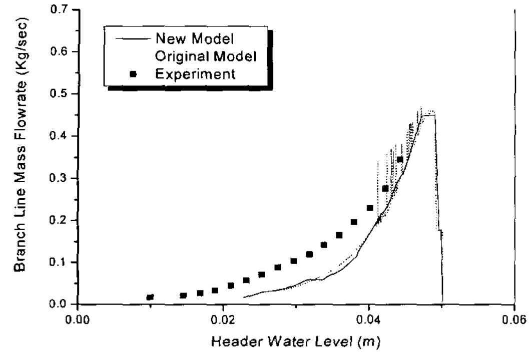


Fig. 11. New Model Validation for 0° Branch Line

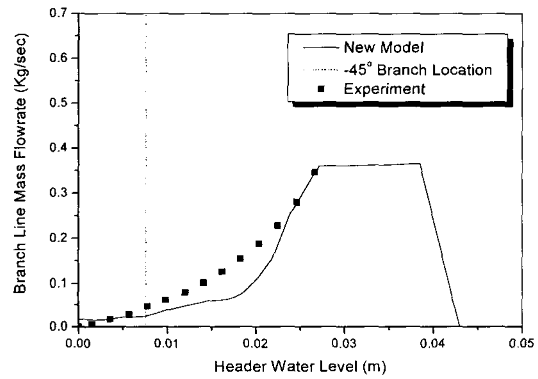


Fig. 12. New Model Validation for -45° Branch Line

orientations (0°, 45°, and 90°) using air-water mixture. The test section of the facility had a semicircular shape of 50.8mm diameter and 50.8mm length. The 0°, -45° and -90° data sets were selected among many data sets. RELAP5 nodalization was shown in Figure 7 b). In Figures 11, 12, and13, the reservoir level and branch mass flow rate were shown and the experimental results are predicted well by the RELAP5 improved model. The calculated results shows that the new model can predict the real experimental results well. In Figure 12, the results in 05 -45° shows that void appeared in branch line before the level reached at -45° elevation and this kind of behavior also shows in the results of 0° and -90°

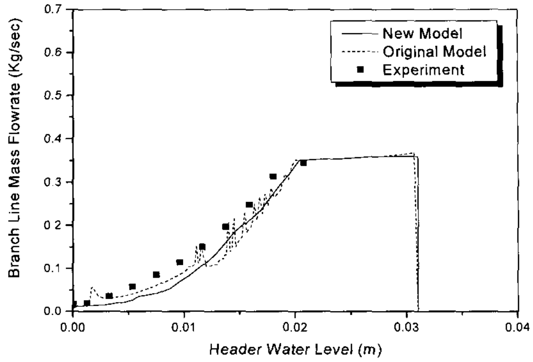


Fig. 13. New Model Validation for -90° Branch Line

in Figure 11 and 13. Moreover, in the cases of 0° and -90°, the new results show the better and stable agreement with experiments than those of the original RELAP5.

4. Conclusions

The onset of liquid entrainment and vapor pull-through model, represented by the critical height were studied in angled branch line configurations in a large pipe. The new correlation was introduced based on the point sink method, considering branch line connection angle, as a theoretical approach, and the constants of correlations were determined using the previous large number of experimental data. The new correlations were applied to vertical upward, downward, and angled branches, and the accuracy of the new correlations was more improved than that of RELAP5. In the verification, the improved model gave reasonable results in full range of branch angles. For validation, and improved results were introduced by new model in horizontal side, vertical downward and angled branch line. The new model for angled side branch was effective at the -60° $\leq\theta\leq$0° (0° means horizontal and-60° means downward branch angle) in correlation. The current improved model can be applied to CANDU header behaviors and accident analyses. As future work, more experiments are needed for the angled branch, especially for a full range of angle and ratio of main and branch line diameters.

Nomenclature

C_1, C_2, C_3	Coefficient in Equation (10) and (12)
d	Diameter of branch, (meter)
D	Upstream Pipe Diameter (meter)
g	Gravitational Force (m/sec^2)
h	Critical Height (meter)
$\dot{m}$	mass flowrate (kg/sec)
n	Strength of Point Sink (m^3/sec)
P	Pressure (Pascal)
R_d	Radius Ratio defined in Equation (11)
S	Distance defined in Figure 2
V	Velocity (m/sec)
x, y, z	Cartesian Coordinates (meter)

Greek

α	Void Fraction
θ	Inclination Angle
ρ	Density (kg/m^3)
$\Delta\rho$	Density Differences(kg/m^3)
ϕ	Potential Function (m2/sec)

References

1. B.D.Chung, et al, "Development of Best Estimate Auditing Code for CANDU Thermal-Hydraulic Safety Analysis," KAERI/CR-129/2002, KINS/HR-436, (2002).
2. B.D.Chung et.al, "Development of Preliminary PIRT (Phenomena Identification and Ranking Table) of Thermal-Hydraulic Phenomena for 330Mwt SMART Integral Reactor," KAERI/TR-912/97, September (1997).
3. B.N. Hanna " CATHENA MOD-3.5/Rev 0 ; Theoretical Manual," RC-982-3, COG-93-140 Rev 0.0, AECL, Whiteshell Lab.(1995).
4. Zuber, N., "Problems in Modeling of Small Break LOCA," Nuclear Regulatory Commission Report, NUREG-0724 (1980).
5. C. Smoglie, "Two-Phase Flow Through Small Branches in a Horizontal Pipe with Stratified Flow, KfK 3861, Kernforschungszentrum Karlsruhe GmbH (KfK), Karlsruhe, FRG, December (1984).
6. V. E. Schrock, S. T. Revankar, R. Mannheiner, and C. H. Wang, "Small Break Critical Discharge -The Role of Vapor and Liquid Entrainment in a Stratified Two-Phase Region Upstream of the Break," NUREG/CR-4761, LBL-22024, Lawrence Berkeley Laboratory, December (1986).
7. Yonomoto, T. and Tasaka, K., "New Theoretical Model for Two-Phase Flow Discharged from Stratified Two-Phase Flow Discharged from Stratified Two-Phase Region Through Small Break," J. Nucl.Sci.Tech., 25, 441-455 (1988).
8. Yonomoto, T. and Tasaka, K., "Liquid and Gas Entrainment to Small Break Hole from a Stratified Two-Phase Region," Int. J. Multiphase Flow, 17, 745-765 (1991).
9. T. Maciaszek and A. Menponteil, "Experimental Study on Phase Separation in a Tee Junction for Steam-Water Stratified Inlet Flow," Paper C2, European Two-Phase Flow Working Group Meeting, Munich, FRG, June 10-13, (1986).
10. Thermal Hydraulics Group "RELAP5/MOD3 Code Manual Volume 4 : Models and Correlations," Scientech, Inc. , NUREG/CR-5535 (1998).
11. Craya, A., "Theoretical Research in the flow of Non-Homogeneous Fluids," La Houille Blanche, pp. 44-55, January-February (1949).
12. Armstrong,K.F., et al., "Theoretical and Experimental Study of the Onset of Liquid Entrainment During Dual Discharge from Large Reservoirs," Int. J. Multiphase Flow,

18, 217-227 (1992).

13. Ibrahim G.Hassan, Hassan M. Soliman, Grant E. Sims and Janusz E. Kowalski, "The Onset of Liquid Entrainment during Discharge from Two Branches on an Inclined Wall," The Canadian Journal of Chemical Engineering, Volume 77, June, (1999).
14. Milne-Thomson, L.M., "Theoretical Hydrodynamics," 5th Ed., MacMillan and Company Ltd., London, UK (1968).
15. J. L. Anderson and R. L. Benedetti, "Critical Flow Through Small Pipe Breaks," EPRI NP-4532, Idaho National Engineering Laboratory, May (1986).
16. T.S.Andreychek, et al, "Loss of RHRS cooling while the RCS is partially filled," WCAP-11916, July (1988).
17. Anderson, J. L. and Owca, W. A., "Data Report for the TPFL Tee/Critical Flow Experiments, " NUREG/CR-4164, EGG-2377, November (1985).
18. S.H.Lee, et al "Evaluation of Thermal Hydraulic Safety Analysis Computer Code System for CANDU Reactor," KINS/GR-057 (1993), KINS/GR-077 (1994), KINS/GR-100 (1995), KINS/GR-111 (1996).
19. Thermal Hydraulics Group "RELAP5/MOD3 Code Manual Volume 1 : Code Structure, System Models, and Solution Methods," Scientech, Inc. , NUREG/CR-5535 (1998).