Mechanism of Falling Water Limitation under Counter-current Flow through a Vertical Flow Path*

By Yukio SUDO** and Akira OHNUKI***

The present study investigates the mechanism of falling water limitation under a counter-current flow through a vertical flow path with the experiment of an air/water two-phase flow. The effects of flow path diameter D and length L which are major parameters for the problem are investigated systematically in the experiment. A comparison of the experimental results and the theoretical results reveals that the mechanism is different between a short flow path and a long flow path. The boundary between the short and the long flow paths is located at about $L/D = 2$. For the short flow path, a larger ratio of L/D gives a larger dimensionless superficial liquid velocity j_l^* at the same dimensionless superficial gas velocity j_g^* . For the long flow path, a larger L/D conversely gives a smaller j_l^* at the same j_g^* though the effect of D itself is rather small.

Keywords : Multiphase Flow, Loss-of-Coolant Accident, Safety Analysis, Refill, Reflood, Counter-current Flow Limitation, Single Vertical Flow Path, Parameter Effects

1. Introduction

In the safety analysis of a postulated light water reactor loss-of-coolant accident (LWR-LOCA), it has become more important to understand the phenomena of a two-phase flow as major efforts are directed to best-estimate calculations for LWR-LOCAs in recent years. As one of the important phenomena of two-phase flow related to LWR-LOCAs, there is a limit of falling water under a vertical counter-current flow.⁽¹⁾ This phenomenon is classified into two major items, (i) suppression of flow rate at which water accumulated once in the upper plenum falls into the core through holes both at the upper core support plate and the end box tie plate, which are located at the interface between the upper plenum and the core, during a reflood phase in the LWR-LOCA; and (ii) suppression of emergency core cooling water delivery into the downcomer during a refill phase in the pressurized water reactor (PWR) LOCA. The estimate for the flow rate of falling water is important in both cases because falling water contributes directly to the core cooling in the LWR-LOCA.

On these problems, many investigators have carried out fundamental experiments with a vertical tube or perforated plate simulating the end box tie plate and an annular tube or rectangular channel simulating a PWR downcomer, along with the analysis. One of typical correlations proposed for experimental results is the following correlation which Wallis, et al. proposed for the dimensionless superficial gas and

liquid velocities, j_g^* and j_l^* ,⁽²⁾

$$j_g^{*1/2} + m j_l^{*1/2} = C \dots\dots\dots (1)$$

where m and C are constants. This is called j^* model. Furthermore, K^* model based on Kutateladze number⁽³⁾ and H^* model⁽⁴⁾ have been proposed other than j^* model. It should be noted here that these models have the same form as Eq. (1) and the constants, m and C are determined under the assumption of linear relationship on each plane of $j_g^{*1/2} - j_l^{*1/2}$, $K_g^{*1/2} - K_l^{*1/2}$ and $H_g^{*1/2} - H_l^{*1/2}$, respectively. The important fact is that the effects of major parameters related to the configuration of flow path, i.e. flow path diameter D and length L have not been investigated systematically in the experiments notwithstanding that m and C in Eq. (1) are not constant but depend strongly on the flow path configuration. On the other hand, analytical studies have proposed the following predictions for the limit of falling water flow rate against an upward gas flow:

(1) The relationship of j_g^* vs j_l^* is given by an envelope with respect to void fraction α of the momentum equation which is obtained from the momentum balance between gas and liquid in the flow path;⁽²⁾

(2) the relationship of j_g^* vs j_l^* is given by a simultaneous equations composed of a continuity equation in which the critical relative velocity between liquid and gas phases is considered and the momentum equation described above;⁽⁴⁾ and

(3) the flow rate of falling water is given by the condition that a falling water flow rate Q_l included in the momentum equation for the whole length of flow path takes the maximum with respect to void fraction α .

Any model described above has not yet fully clarified the mechanism of falling water limitation under a counter-current flow.

This study, therefore, investigates experimentally the effects of predominant parameters on the falling water limitation for an air/water two-phase counter-current flow in a vertical flow path and compares the correlation obtained from the analysis

* Received June 28, 1982

** Senior Engineer,
Japan Atomic Energy Research Institute
Tokai-Mura, Ibaraki-Ken 319-11

*** Engineer
Japan Atomic Energy Research Institute
Tokai-Mura, Ibaraki-Ken 319-11

with the experimental results including the existing experimental results.

[Nomenclature]

A : flow area, C : constant, D : flow path diameter, f : friction factor, g : acceleration of gravity, H : water level in the upper plenum, ℓ : turbulent mixing length, L : flow path length, L^* : critical length, m : constant, P : pressure, Q : volumetric flow rate, R : radial distance, Re : Reynolds number, v : velocity, V : superficial velocity, z : vertical distance, α : void fraction, γ : specific weight, μ : dynamic viscosity, λ : friction factor due to contraction, τ : shear stress. (Subscripts) g : gas phase, ℓ : liquid phase, l : cross section l, 0 : cross section 0, i : interface between gas and liquid phases. (Dimensionless number) j_k^* , γ_k^* , v_k^* ($k = \ell, g$), ρ^* , γ^* , ℓ^* , μ_ℓ^* : dimensionless numbers of V_k , γ_k , v_k ($k = \ell, g$), ρ , γ , ℓ and μ_ℓ , respectively, defined by Eqs. (2) and (7).

2. Experiments

2.1 Schematic of experimental rig.

Experimental rig is designed so as to investigate the effects of predominant parameter systematically which influences the limit of falling water in a vertical tube with use of air/water two phase flow. Figure 1 shows a schematic of experimental rig.

Fig. 1 Schematic of test rig

The experimental rig except the sources of air and water is composed of a test tube (inner diameter D and length L), an upper plenum above the flow path (that is, test tube) and a lower plenum under the flow path. The experimental rig is made of acrylic resin which permits observation of the flow pattern. There are two spaces just above and below the flow path where pressure taps are attached. The inner diameters of these spaces are denoted by D_1 and D_0 , respectively as shown in Fig. 1. D_1 and D_0 are 90 mm and are constant in this experiment. The upper plenum is a cylinder of 200 mm I.D. and 500 mm in height. A water injection pipe of 18 mm I.D. is attached at the top of the upper plenum. The top of the upper plenum is open to the atmosphere through a pipe of 100 mm I.D. The

lower plenum is of rectangular shape of 183 mm $\times$ 183 mm and 1000 mm in height and the air injection pipe of 25 mm I.D. is attached at the side wall of the lower plenum. Air injected by a compressor goes into the lower plenum through a flow regulation valve and a rotor meter.

To measure water levels both in the upper plenum and in the lower plenum, the level meters of glass tube are set in the upper and lower plena. All experiments were carried out under the atmospheric pressure and room temperature.

Table 1 shows the experimental conditions, the inner diameter D of the flow path, the flow path length L, the inner diameter D_0 (or D_{0eq}) of the spaces just above and below the flow path and the water level H in the upper plenum. The conditions of the earlier tests discussed in the present study are also listed in Table 1.

No	D(mm)	L(mm)	H(mm)	Do or Doe(mm)	Comment
1	12	20	300	90	Present Test
2	18	3	300	90	
3	18	18	300	90	
4	18	20	300	90	
5	18	90	300	90	
6	18	180	300	90	
7	25	3	300	90	
8	25	5	300	90	
9	25	20	300	90	
10	25	50	300	90	
11	25	125	300	90	
12	25	250	300	90	

No	D(mm)	L(mm)	H(mm)	Do or Doe(mm)	Comment
13	25	250	150	90	Present Test
14	25	250	50	90	
15	25.4	12.7	0	146	
16	30.5	12.7	0	146	
17	30.5	30.5	0	146	
18	30.5	61	0	146	
19	30.5	122	0	146	
20	30.5	254	0	146	
21	38.1	12.7	0	146	
22	50.8	1520	-	330.2	(9)
23	10.5	20	267	36.1	(3)
24	10.5	20	267	28.0	

Table 1 Matrix of tests investigated in this study

2.2 Experimental procedure

To obtain an initial holdup of water in the upper plenum, air was first supplied at a continuous high flow rate into the lower plenum, and water was injected into the upper plenum until the water reached a specified level in the upper plenum. After that, the flow rate of air injected into the lower plenum was regulated to a specific volumetric flow rate Q_g , and the flow rate of water injected into the upper plenum was also regulated so that the water level H in the upper plenum was kept at the specified value. The water level H in the upper plenum was kept constant during a test. After it was confirmed by measuring the rising velocity of water level in the lower plenum that the falling water flow rate into the lower plenum was steady, the volumetric flow rate of falling water Q_ℓ was calculated from the rising velocity of water level in the lower plenum under a constant flow rate Q_g of air.

After Q_ℓ was measured under a specified air flow rate Q_g , the water in the lower plenum was drained. The procedure mentioned

above was repeated to obtain Q_L under another specified air flow rate. The observation of flow pattern was also done at the same time.

2.3 Expression of experimental results

To show the relationship between Q_L and Q_g obtained for the given configuration of flow path (L and D) and water level H in the upper plenum, j_g^{*2} is adopted for the ordinate and j_L^{*2} for the abscissa based on the Wallis expression. j_g^* and j_L^* are expressed as follows:

$$j_g^* = V_g \gamma_i^{1/2} / \{gD(\gamma_i - \gamma_o)\}^{1/2},$$

$$\text{where } V_k = Q_k / \frac{\pi}{4} D^2 \quad (k=g, l) \quad (2)$$

3. Theory

3.1 Relationship among j_g^* , j_L^* and α in vertical flow path of constant flow area

For a steady-state counter-current flow of upward air and downward water in a vertical flow path of constant flow area, the relationship among j_g^* , j_L^* and α is introduced under the following assumptions:

- (1) completely separated annular flow,
- (2) air flow is turbulent and water flow is laminar, and
- (3) steady flow.

From the force balance between the two control surfaces separated by distance dZ as shown in Fig. 2, shear stress is expressed for each phase as follows:

$$\tau_o = -\frac{1}{2} \left(\frac{dP}{dZ} + \gamma_o \right) \quad (0 \leq r \leq r_i) \quad (3)$$

$$\tau_i = -\frac{r}{2} \frac{dP}{dZ} - \frac{1}{2} \left\{ \gamma_i r - (\gamma_i - \gamma_o) \frac{r_i^2}{r} \right\} \quad (r_i \leq r \leq \frac{D}{2}) \quad (4)$$

Fig. 2 Model for obtaining the relationship among j_g^* , j_L^* and α

The shear stress for the turbulent air flow is expressed as follows by use of mixing length l_g and similarly for the laminar water flow:

$$\tau_o = \frac{\gamma_o}{g} l_g^2 \left(\frac{dv_o}{dr} \right)^2 \quad (5)$$

$$\tau_i = -\mu_i \frac{dv_i}{dr} \quad (6)$$

The above equations are rewritten by introduction of the following dimensionless numbers:

$$\left. \begin{aligned} \gamma_k &= \gamma_i^* (\gamma_i - \gamma_o), \\ v_k &= v_i^* (gD(\gamma_i - \gamma_o))^{1/2} / \gamma_i^{1/2}, \quad (k=g, l) \\ r &= r^* \left(\frac{D}{2} \right), \quad \frac{dP}{dZ} = P^* (\gamma_i - \gamma_o), \\ l_g &= l_g^* \left(\frac{D}{2} \right), \quad \alpha = \left(\frac{2r_i}{D} \right)^2, \\ \mu_i &= \mu_i^* D \left\{ D(\gamma_i - \gamma_o) \frac{\gamma_i}{g} \right\}^{1/2} \end{aligned} \right\} \quad (7)$$

By combining Eq. (3) with Eq. (5) and Eq. (4) with Eq. (6), the following are obtained.

$$\frac{dv_o^*}{dr^*} = -\{-(P^* + \gamma_o^*)\}^{1/2} r^{*1/2} / 2l_g^* \quad (8)$$

$$\frac{dv_i^*}{dr^*} = \frac{(P^* + \gamma_i)}{8\mu_i^*} r^* - \left(\frac{\alpha}{8\mu_i^*} \right) \frac{1}{r^*} \quad (9)$$

Equations (8) and (9) are integrated with the following boundary conditions:

$$v_L^* = 0 \quad \text{at } r^* = 1 \quad (r = D/2),$$

$$v_g^* = v^* \quad \text{at } r^* = \sqrt{\alpha} \quad (r = r_i)$$

The results are as follows:

$$v_i^* = -\frac{(P^* + \gamma_i^*)}{16\mu_i^*} (1 - r^{*2}) - \frac{\alpha}{8\mu_i^*} \ln r^* \quad (10)$$

$$v_o^* = \{-(P^* + \gamma_o^*)\}^{1/2} (\alpha^{3/4} - r^{*3/2}) / 3l_g^* + v_{oi}^* \quad (11)$$

By assuming a slip at the interface between the two phases, that is, $v_{gi}^* = -v_{Li}^* (\gamma_g / \gamma_L)^{1/2}$ at $r^* = \sqrt{\alpha}$, v_{gi}^* is reduced as follows from Eq. (10).

$$v_{oi}^* = (\gamma_o / \gamma_i)^{1/2} \{ (P^* + \gamma_i^*) (1 - \alpha) + \alpha \ln \alpha \} / 16\mu_i^* \quad (12)$$

The relations between j_g^* and v_g^* and between j_L^* and v_L^* are as follows,

$$j_g^* = 2 \int_0^{\sqrt{\alpha}} v_g^* r^* dr^* \quad \text{and} \quad j_L^* = 2 \int_{\sqrt{\alpha}}^1 v_L^* r^* dr^*.$$

Therefore, j_g^* and j_L^* are expressed as follows from Eqs. (10), (11) and (12).

$$\begin{aligned} j_o^* &= \frac{\{-(P^* + \gamma_o^*)\}^{1/2}}{7l_g^*} \alpha^{7/4} \\ &+ \frac{(\gamma_o / \gamma_i)^{1/2}}{16\mu_i^*} \alpha \{ (P^* + \gamma_i^*) (1 - \alpha) + \alpha \ln \alpha \} \\ j_i^* &= -\frac{(P^* + \gamma_i^*)}{32\mu_i^*} (1 - \alpha)^2 \\ &+ \frac{\alpha}{16\mu_i^*} (1 - \alpha + \alpha \ln \alpha) \end{aligned} \quad (13)$$

Elimination of P^* from Eqs. (13) and (14) gives the following relationship among j_g^* , j_L^* and α under the assumption of $l_g^* = \sqrt{\alpha} / 7$. (6)

$$\begin{aligned} j_o^* &= \alpha^{3/4} \left[1 - 2 \left\{ \frac{\alpha}{1 - \alpha} + \left(\frac{\alpha}{1 - \alpha} \right)^2 \ln \alpha \right. \right. \\ &\quad \left. \left. - \frac{16\mu_i^*}{(1 - \alpha)^2} j_i^* \right\} \right]^{1/2} - 2 \left(\frac{\alpha}{1 - \alpha} \right) \left(\frac{\gamma_o}{\gamma_i} \right)^{1/2} j_i^* \\ &+ \frac{\alpha^2}{16\mu_i^*} \left(\frac{\gamma_o}{\gamma_i} \right)^{1/2} \left\{ 2 + \frac{1 + \alpha}{1 - \alpha} \ln \alpha \right\} \end{aligned} \quad (15)$$

where $j_g^* > 0$ and $j_L^* < 0$.

3.2 Differential pressure balance between two phases for separated flow

(A) In case of short flow path

When the differential pressures over the short flow path are balanced between two phases of gas and liquid in a completely separated flow, another relationship among j_g^* , j_L^* and α is obtained under the following assumptions:

- (1) The effect of change in flow area just after the exit of upward air flow is neglected.
- (2) The effect of change in flow area just

after the exit of downward water flow is also neglected.

(3) The effect of contraction of inlet flow area for each phase (upper end plane of flow path for water and lower end plane of flow path for air) is considered.

(4) The flows of air and water are turbulent and laminar in the flow path, respectively.

It is considered here that the effect of pressure drop due to contraction of both air and water flows is the predominant feature for the short flow path and that the differential pressures for both phases in the completely separated two phase flow are balanced between inlet and outlet of flow path.

In each phase of air and water in the model shown in Fig. 3, the following relations of differential pressures, P_0-P_1 , between inlet and outlet of flow path are obtained.

liquid phase: $P_0-P_1=\gamma_l L$

$$-\frac{\gamma_l}{2g} \left[1 + f_l(L/D) / \sqrt{1-\alpha} + \lambda_l - \left(\frac{A_{l1}}{A_{l0}} \right)^2 \right] V_l^2 \quad (16)$$

$$\text{gas phase: } P_0-P_1 = \frac{\gamma_g}{2g} V_g^2 \left[1 - \left(\frac{A_{g0}}{A_{g1}} \right)^2 + \lambda_g + f_g \left(\frac{L}{D} \right) / \sqrt{\alpha} \right] \quad (17)$$

Fig. 3 Model for balance between gas and liquid differential pressures for a short flow path

where V_g is average gas velocity, V_l average liquid velocity, A_l flow area of liquid phase, A_g flow area of gas phase, f_g frictional loss coefficient of gas phase, f_l friction loss coefficient of liquid phase, λ_g friction factor due to contraction of gas phase and λ_l friction coefficient by contraction of liquid phase. Subscripts 0 and 1 show values at the 0 cross section and the 1 cross section, respectively. The following are assumed for contraction of both gas and liquid flows.

$$\lambda_l = \left(\frac{A_{l2}}{A_{l1}} \right)^2 \left(\frac{A_{l1}}{A_l} - 1 \right)$$

$$\lambda_g = \left(\frac{A_{g2}}{A_{g0}} \right)^2 \left(\frac{A_{g0}}{A_g} - 1 \right)$$

Therefore, Eqs. (16) and (17) are rewritten as follows by use of Eq. (2).

$$\begin{aligned} (P_0-P_1)/\gamma_l L = & 1 - \left[1 + f_l \left(\frac{L}{D} \right) / \sqrt{1-\alpha} \right. \\ & + \left. \left\{ \frac{1-\alpha}{(D_1/D)^2-\alpha} \right\}^2 \left\{ \frac{(D_1/D)^2-\alpha}{1-\alpha} - 2 \right\} \right] \\ & \times \left(\frac{D}{2L} \right) \left(\frac{\gamma_l-\gamma_g}{\gamma_l} \right) j_l^2 / (1-\alpha)^2 \quad (18) \end{aligned}$$

$$\begin{aligned} (P_0-P_1)/\gamma_l L = & \left[1 + f_g \left(\frac{L}{D} \right) / \sqrt{\alpha} \right. \\ & + \left. \left\{ \frac{\alpha}{(D_0/D)^2-(1-\alpha)} \right\}^2 \times \left\{ \frac{(D_0/D)^2-(1-\alpha)}{\alpha} - 2 \right\} \right] \end{aligned}$$

$$\times \left(\frac{D}{2L} \right) \left(\frac{\gamma_l-\gamma_g}{\gamma_l} \right) j_g^2 \quad (19)$$

Elimination of P_0-P_1 from the above two equations gives

$$\begin{aligned} \frac{j_l^2}{\alpha^2} \left[1 + \frac{f_g(L/D)}{\sqrt{\alpha}} + \left\{ \frac{\alpha}{(D_0/D)^2-(1-\alpha)} \right\}^2 \right. \\ \times \left. \left\{ \frac{(D_0/D)^2-(1-\alpha)}{\alpha} - 2 \right\} \right] \\ + \frac{j_g^2}{(1-\alpha)^2} \left[1 + \frac{f_l(L/D)}{\sqrt{1-\alpha}} \right. \\ + \left. \left\{ \frac{1-\alpha}{(D_1/D)^2-\alpha} \right\}^2 \left\{ \frac{(D_1/D)^2-\alpha}{1-\alpha} - 2 \right\} \right] \\ = \frac{2L}{D} \left(\frac{\gamma_l}{\gamma_l-\gamma_g} \right) \quad (20) \end{aligned}$$

(B) In case of long flow path

For the long flow path, the balance of differential pressures of the two phases is assumed near the top end and bottom end of the flow path, respectively, rather than for the whole flow path. Therefore, the differential pressure of each phase is, first, assumed to be balanced within the distance L^* near the top end of flow path as shown in Fig. 4.

The following assumptions are applied in this case as well as in the case of short flow path:

- (1) Flow area change just after the exit of upward air flow is neglected;
- (2) air and water flows are turbulent and laminar, respectively; and
- (3) effect of contraction is taken into account at the top end of flow path for downward water flow.

Fig. 4 Model for balance between gas and liquid differential pressures for a long flow path

For the differential pressure $P-P_1$ shown in Fig. 4, the following are obtained under the above assumptions:

$$\begin{aligned} (\text{Liquid phase}) \quad P-P_1 = & \gamma_l L^* - \frac{\gamma_l}{2g} V_l^2 \left[1 + f_l \left(\frac{L^*}{D} \right) / \sqrt{1-\alpha} \right. \\ & + \left. \lambda_l - \left(\frac{A_{l1}}{A_{l0}} \right)^2 \right] \end{aligned}$$

$$(\text{Gas phase}) \quad P-P_1 = \frac{\gamma_g}{2g} V_g^2 \cdot f_g \left(\frac{L^*}{D} \right) / \sqrt{\alpha}$$

Elimination of $P-P_1$ from these two equations gives

$$\begin{aligned} \frac{j_l^2}{\alpha^2} f_g \left(\frac{L^*}{D} \right) / \sqrt{\alpha} + \frac{j_l^2}{(1-\alpha)^2} \left[1 + \left\{ \frac{1-\alpha}{(D_1/D)^2-\alpha} \right\}^2 \right. \\ \times \left. \left\{ \frac{(D_1/D)^2-\alpha}{1-\alpha} - 2 \right\} + f_l \left(\frac{L^*}{D} \right) / \sqrt{1-\alpha} \right] \\ = \frac{2L^*}{D} \left(\frac{\gamma_l}{\gamma_l-\gamma_g} \right) \quad (21) \end{aligned}$$

On the other hand, the following

relationship is obtained for the bottom region of flow path in the same manner when it is assumed that the differential pressures for both phases are balanced within the distance L^* near the bottom end of flow path:

$$\begin{aligned} & \frac{j_g^{*2}}{a^2} \left[1 + f_g \left(\frac{L^*}{D} \right) / \sqrt{a} \right. \\ & \quad + \left\{ \frac{a}{(D_0/D)^2 - (1-a)} \right\}^2 \left\{ \frac{(D_0/D)^2 - (1-a)}{a} - 2 \right\} \Big] \\ & \quad + \frac{j_l^{*2}}{(1-a)^2} f_l \left(\frac{L^*}{D} \right) / \sqrt{1-a} \\ & = \frac{2L^*}{D} \left(\frac{\gamma_l}{\gamma_l - \gamma_g} \right) \dots \dots \dots (22) \end{aligned}$$

The sum of Eqs. (21) and (22) gives, of course, Eq. (20) in case of $L = L^* + L^{*1}$.

Elimination of void fraction α from each set of Eqs. (20) and (15), Eqs. (21) and (15) and Eqs. (22) and (15) gives the relationship between j_g^* and j_l^* for the case of short flow path, top region of long flow path and bottom region of long flow path, respectively. The iterative calculation was performed under two sets of $f_g = 0.05$ and 0.005 with $f_l = 64/Re_l$. In the following, calculated results are presented for the case of $f_g = 0.05$ because the difference between $f_g = 0.05$ and 0.005 is negligible, and j_l^* is taken positive for the downward water flow.

4. Discussion

4.1 Effects of configuration of flow path

(A) Effect of flow path length L

Figures 5 through 9 present the comparison between experimental and theoretical results to show the effect of flow path length L . Experimental results shown in Figs. 5 through 8 were obtained in the present experiment, and those in Fig. 9 by Liu, et al.(8). As shown in Table 1, the differences in test conditions between those two tests are as follows: Water level in the upper plenum, H is 300 mm for the present experiment and about 0 mm for Liu, et al., and diameter of spaces just above and below flow path, D_0 is 90 mm for the present experiment and 146 mm for Liu, et al. Figure 5 shows the effect of L for short flow paths ($L \leq 50$ mm) in the case of $D = 25$ mm. It is noticed that j_l^* becomes larger with an increasing L at the same j_g^* , and the theoretical results obtained for the short flow path by simultaneous equations (15) and (20) have the same tendency as the experimental results though the difference between the two is rather large in the case of $L = 3$ and 5 mm.

Figure 6 shows the experimental results for the long flow path. Though the results of $L = 20$ mm are almost the same as those of $L = 50$ mm, it is clear in Fig. 6 that j_l^* becomes smaller with an increasing L for more than 50 mm at the same j_g^* . This is a tendency obviously inverse to the case of short flow path shown in Fig. 5. This difference in tendency between the short and long flow paths suggests that the mechanism of falling water limitation is different between the short and long flow paths. Figure 6 also shows the theoretical results of simultaneous equations (15) and (21) with $L^* = 3D$ and $L^* = D/2$. The theoretical results with $L^* = 3D$ and $D/2$ agree well with

Fig. 5 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (I) - short flow path for $D = 25$ mm

Fig. 6 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (II) - long flow path for $D = 25$ mm

the experimental results for $L = 125$ mm and 250 mm, respectively.

Shown in Figs. 7 and 8 is the comparison between the results of the experiment and theory for the short and long flow paths, respectively in case of $D = 18$ mm. In the two figures, the same tendency as the case of $D = 25$ mm is observed that j_l^* becomes larger with an increasing L at the same j_g^* for the short flow path and that j_l^* becomes smaller with an increasing L for the long flow path. Theoretical results obtained from Eqs. (15) and (20) for the short flow path and from Eqs. (15) and (21) with $L^* = D/2$ for the long flow path agree well with the experimental results. As for the theory of long flow path, Eq. (21) is here adopted instead of Eq. (22). The selection of Eq. (22) is not proper because a dry region is always observed on the inner wall at the lower part of flow path in the experiment for $j_l^{*1/2}$ below 0.15 and because the discrepancy between the experimental and theoretical results is much larger with the set of Eqs. (15) and (22) than with that of Eqs. (15) and (21). Therefore, the combination of Eqs. (15) and (21) is adopted for the theory of long flow path from now on. In Figs. 6 and 8, hatched regions are the unstable regions for $j_g^{*1/2}$ less than 0.3, in which measurement

of Q_L is difficult because Q_L is not constant and the flow is extremely unstable. This unstable phenomenon was observed for $L = 125$ and 250 mm in the case of $D = 25$ mm and for $L = 90$ and 180 mm in the case of $D = 18$ mm.

Figure 9 shows the comparison between present theoretical results and the results of experiment carried out by Liu, et al., which show the effect of flow path length L . Figure 9 shows that the theoretical results for the short flow path give good predictions of the experimental results for comparatively short flow paths, $L = 12.7$ and 61 mm and the theoretical results obtained by Eqs. (15) and (21) with $L^* = 3D$ do for the long flow path.

Figure 10 presents the experimental results for the long flow path, $L = 1520$ mm obtained by Wallis, et al.⁽⁹⁾ The test conditions of D , D_0 and L are much different from those of tests discussed in Figs. 5 to 9. The theoretical results by Eqs. (15) and (21) with $L^* = 3D$ and $D/2$ agree well with the experimental results for $D = 50.8$ and $D_0 = 330.2$ mm.

Fig. 7 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (III) - short flow path for $D = 18$ mm

Fig. 8 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (IV) - long flow path for $D = 18$ mm

Fig. 9 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (V) - for $D = 30.5$ mm

Fig. 10 Effect of flow path length on the relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$ (VI) - long flow path for $D = 50.8$ mm

(B) Effect of flow path diameter D

Figures 11 to 13 show the effects of D . Comparisons between the experimental and theoretical results on the effect of D are shown in Figs. 11 ($D = 12, 18$ and 25 mm) and 12 ($D = 25.4, 30.5$ and 38.1 mm) for the short flow paths of $L \leq 20$ mm and in Fig. 13 ($D = 18$ and 25 mm) for the long flow paths of $L \geq 90$ mm.

Figure 11 shows that the effect of difference in diameter between $D = 18$ and 25 mm is not significant in the case of very short flow path, $L = 3$ mm but is significant in the case of long flow path, $L = 20$ mm for $j_g^{*1/2} < 0.6$, the tendency being that a smaller D yields a larger j_l^* at the same j_g^* . On the other hand, the theoretical results give an overestimate of the effect of D compared to the experimental results, though the theoretical results show the same tendency as the experiments that the smaller D , the larger is j_l^* at the same j_g^* . However, it should be noted that both experimental and theoretical results indicate the same tendency in the effect of D that a small D yields a larger j_l^* at the same j_g^* for the short flow path.

Fig. 11 Effect of flow path diameter on relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$
(I) - short flow path for $L = 3$ and 20 mm

Figure 12 shows the comparison of the experimental and the theoretical results for the test conditions of Liu, et al. The features of this experiment are that the flow path length L is 12.7 mm, which comes between $L = 3$ mm and 20 mm of which results are shown in Fig. 11, and water level H in the upper plenum is almost 0 mm with $D_0 = 146$ mm. Though the theoretical results do not always agree well with the experimental results, the effects of D are clearly recognized both in the experimental and theoretical results such that a smaller D yields a larger j_l^* at the same j_g^* as stated above. It should be noted at the same time that magnitude of the effect of D is almost the same between the theory and the experiment. Besides, it should be noted in Fig. 11 that the experimental results as well as the theoretical results show an evident tendency that a larger L gives a larger j_l^* at the same D and j_g^* , which is clearly observed for $L = 3$ mm and 20 mm.

Fig. 12 Effect of flow path diameter on relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$
(II) - short flow path for $L = 12.7$ mm (8)

The effects of D and L for the short flow path are recognized easily on the right hand side of Eq. (20) in the theory. In Eq. (20), the larger L/D , that is, the larger L and/or the smaller D gives the larger j_l^* at the same j_g^* . On the other hand, the effects of L and D are not included directly in Eq. (15).

Figure 13 presents the effect of flow path diameter D for the long flow path. The effect of D can not be directly investigated because the flow paths are not the same for both $D = 18$ and 25 mm in the figure but can be investigated as follows because the effect of the flow path length itself is rather small for the long path as seen in the figure. The experimental results for $D = 18$ and $L = 125$ mm should be between $L = 90$ and 180 mm with $D = 18$ mm and they can be compared with the results for $D = 25$ and $L = 125$ mm with respect to the effect of D . The comparison of the two reveals no significant difference. In the same manner, the comparison of the cases of $D = 18$ and 25 mm with $L = 180$ mm reveals no significant difference. For reference, the theoretical results with $L^* = D/2$ are illustrated in the figure, showing a good coincidence with the experimental results.

Fig. 13 Effect of flow path diameter on relationship of $j_g^{*1/2}$ vs $j_l^{*1/2}$
(III) - long flow path

From the above discussion about the effects of configuration of flow path, L and D on the falling water limitation, it is pointed out that the larger L gives the larger j_l^* for the short flow path and the smaller j_l^* for the long flow path at the same j_g^* . It is understood from Figs. 5 to 9 that the boundary between the short and long flow path is located at about $L/D = 2$. The theory well predicts this tendency of experimental results as the effects of L/D on the right hand side of Eq. (20), with respect to the effects of L and D for the short flow path. As for the theory for the long flow path, the set of Eqs. (15) and (21) was adopted in the present study because a dry region was observed on the inner wall at the lower part of flow path. The set of Eqs. (15) and (21) with $L^* = D/2$ to $3D$ gives good predictions of the experimental results for the long flow path. The effect of D is rather small for the long flow path in the experiment.

4.2 Effect of water level H in upper plenum

Water level H in the upper plenum is another major parameter which is considered to have greater effects on the limit of

falling water other than the configuration of flow path. It has been reported that water level H in the upper plenum has no significant effects for the thin perforated plates between $H = 267$ and 445 mm by Hsieh, et al.⁽³⁾ and between $H = 50$ and 1600 mm by Naitoh, et al.⁽⁵⁾

Figure 14 presents the effect of H for a vertical flow path with $D = 25$ mm, $D_0 = 90$ mm and $L = 250$ mm, by investigation of $H = 50, 150$ and 300 mm. No significant effects of H are observed in Fig. 14 as stated above for the perforated plates. The tendency of experimental results is well predictable by the theory for the long flow path with $L^* = D/2$.

Fig. 14 Effect of upper plenum water accumulation on relationship of $j_g^{*1/2}$ vs $j_\ell^{*1/2}$ for $D = 25$ mm

As one of the reasons why the water level H in the upper plenum has no significant effects, it can be considered that the pressure of gas phase changes with a change in water level in the upper plenum so that the change in water level does not cause any change in the differential pressure balance over the whole flow path for the short flow path, and in the differential pressure balance near the top end of flow path for the long flow path, even if the water level in the upper plenum changes. Therefore, the fact that a change in water level in the upper plenum gives no significant effects can be pointed out as one of the evidences for the validity of the model developed in the present study.

4.3 Investigation on application of present model to perforated plate

Many experimental results have been reported until now on the falling water limitation with a thin perforated plate of L less than 20 mm. Figure 15 presents the comparison of theory developed in the present study and the results of experiment by Hsieh, et al. of which test conditions are clearly given in the literature⁽³⁾, in order to investigate the applicability of the present model to the perforated plates. The equivalent diameter D_{0eq} which is given below is adopted here as the diameters D_0 and D_1 of spaces just above and below the test section for a perforated plate: $\pi D_{0eq}^2/4 = \text{total flow area of space}/\text{number of flow paths}$. In the figure, "A" indicates the case of five holes and "B" the case of three holes. Figure 15 shows clearly that the theoretical results for short flow

path based on the equivalent diameter D_{0eq} are in good coincidence with the experimental results.

Fig. 15 Illustration of applicability of present theory to the multifold flow paths⁽³⁾

5. Conclusions

On the limit of falling water in a vertical counter-current flow, the following are made clear from the experimental and theoretical investigations on the air/water two-phase flow in a vertical flow path.

(I) The effects of predominant parameters are made clear experimentally. That is, under the effect of flow path length, (i) a longer flow path gives a larger j_ℓ^* at the same j_g^* for the short flow path; and (ii) vice versa for the long flow path. The boundary of the short and long flow paths lies at about $L/D = 2$. (iii) With respect to the effect of flow path diameter, the smaller flow path diameter gives the larger j_ℓ^* at the same j_g^* for the short flow path but no significant effect is observed for the long flow path. (iv) The effect of water level in the upper plenum is negligible also for a vertical flow path as reported for perforated plates.

(II) As one expressing the mechanism of falling water limitation in a vertical flow path, the present study proposed a model in which the mechanism is different between the short flow path and long flow path. The model is in good coincidence with the experimental results and it is applicable to perforated plates for the prediction with the short flow path.

References

- (1) Sudo, Y., Remarks of Two-phase Flow Dynamics related to the LOCA, J. At. Energy Soci. Japan. (in Japanese) 23-7 (1981).
- (2) Wallis, G.B., "One-dimensional Two-Phase Flow", McGraw-Hill (1969).
- (3) Hsieh, C., et al., NUREG/CR-1808, (1980).
- (4) Sun, K.H., Flooding Correlation for BWR Bundle Upper Tie Plates and Bottom Side-Entry Orifices, 2nd Multi-Phase Flow and Heat Transfer Symposium, Miami (1979).
- (5) Naitoh, M., et al., J. Nucl. Sci. Technol. 15-11 (1978).
- (6) Wallis, G.B., "One-dimensional Two-Phase Flow", p.344, McGraw Hill (1969).
- (7) Ueda, T., "Kieki-Nisoryudo — Nagare to Netsudentatsu", (in Japanese), p.85 Yokendo, (1981).
- (8) Liu, C.P., et al., EPRI-2262, (1982).
- (9) Wallis, G.B., et al., EPRI-786, (1978).