Experimental Study for Multidimensional ECC Behaviors in Downcomer Annuli with Direct Vessel Injection Mode during the LBLOCA Reflood Phase

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For the assessment of the multidimensional safety analysis codes various investigations have been performed to provide detailed information for the ECC (Emergency Core Coolant) behavior in a downcomer annulus. In the present study, the multidimensional ECC bypass phenomena in the downcomer annuli of the UPTF (Upper Plenum Test Facility) and APR1400 (Advanced Power Reactor 1400) geometries are studied to fill in the lack of knowledge about the phenomena that could occur in the DVI (Direct Vessel Injection) system downcomer. The experiments for the direct ECC bypass have been conducted in the transparent downcomer models of the UPTF and APR1400 using air and water. The flow patterns and the bypass mechanisms of the ECC bypass were identified and the characteristics of it in both downcomers were compared with each other. Based on the visual observations, the cross flow between the downward liquid film and circumferential gas was found to be the most important flow pattern of the bypass phenomena. An analysis for the flow regime was conducted and the Wallis parameters were introduced as the significant non-dimensional parameters of the multidimensional two-phase flow phenomena.

KEYWORDS: APR1400, upper plenum test facility, direct vessel injection, large break loss of coolant accident, bypass, emergency core coolant

I. Introduction

Recently, a lot of experimental and numerical studies have been carried out to develop and validate the multidimensional safety analysis codes which can simulate the two phase flow phenomena of nuclear reactors more realistically during a LBLOCA (Large Break Loss of Coolant Accident). From the studies, it was found that multidimensional approaches are required for the modeling of the flow process in a PWR (Pressurized Water Reactor) downcomer due to the complexity and asymmetry of the flow within it.¹ For the validation and improvement of the safety codes, it is important to identify the bypass mechanism of the ECC (Emergency Core Coolant) and the flow regimes that exist in the downcomer during the accident since the closure laws of the present safety codes which are employed to describe the transfer of the mass, momentum and energy at the gas and liquid interface are based on a physical modeling and the flow patterns.

Various investigations have been performed in the past to obtain detailed information about the multidimensional ECC behaviors in the downcomer during the LOCA (Loss of Coolant Accident). Collier³ and Block and Rothe³ produced time dependent flow patterns from the analysis of the liquid fraction measurements in the Battelle-Columbus 2/15 scale model and CREARE 1/15 scale model respectively. In the full scale UPTF (Upper Plenum Test Facility) experiments reported by Weiss et al.,¹ the temperature measurements were used to obtain information about the liquid distribution and it was reported that heterogeneous phase distributions existed in the downcomer. Demster and Abouhadra⁴ studied the two-phase flow regimes prevailing in a transparent 1/10 scale model and mapped the flow patterns for a wide range of gas and water injection conditions. However, most of these studies except for the UPTF test were performed to investigate the ECC bypass phenomena in the downcomers with the CLI (Cold Leg Injection) mode of the ECCS (Emergency Core Cooling System).

The need for experimental studies regarding the multidimensional ECC behaviors in the downcomers with the DVI (Direct Vessel Injection) mode was raised from the licensing process of APR1400 (Advanced Power Reactor 1400).⁵ Safety analysis results for the APR1400 using the evaluation models and the best estimate codes under the same conditions revealed large differences in predicting the major parameters in the downcomer such as the ECC bypass rate, collapsed water level, and subcooling margin during the reflood phase of a LBLOCA. Due to these differences, experimental data to evaluate and verify the analysis tools as well as to understand the downcomer thermal hydraulics in the DVI system was required.⁶

The multidimensional phenomena in the DVI system during the reflood phase had been investigated in the UPTF Test 21-D experiment.⁷–⁹ From this full scale experiment, an insight was gained on the bypass phenomena occurring in the DVI mode. However, it was still difficult to interpret from the experiment what flow patterns existed and what the detailed mechanism of the ECC bypass was. Also owing to the geometrical differences between the UPTF and APR1400, the experimental data could not be directly applied to the safety analysis of the APR1400.⁵

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This paper describes the hydraulic behavior of the ECC and the mechanism of the ECC bypass in the DVI system downcomer. The typical flow patterns that could exist in the downcomers during the reflood phase of a LBLOCA were illustrated based on the visual observation. To investigate the effect of the downcomer geometry and its scale, a series of experiments have been performed in 1/7.3 and 1/4 scaled UPTF and 1/7 and 1/5 scaled APR1400 downcomers in air and water flow conditions. And the differences of the bypass characteristics between these two geometries were discussed. From the observation results, an analysis for the dominating flow pattern was conducted to understand the bypass mechanism. As a result of the analysis the Wallis parameters were derived as the significant non-dimensional parameters of the multidimensional ECC bypass phenomena and the experimental results that were obtained in the various scaled models were analyzed with the dimensionless parameters.

II. Test Facility

In the PWRs with a DVI mode, the steam produced in the reactor core flows to the downcomer via three intact cold legs during the reflood phase of a LBLOCA. It flows circumferentially along the downcomer to the break and causes the bypass of the ECC in the downcomer. There are two ECC bypass mechanism in the DVI system downcomer during the reflood phase of the LBLOCA. One is the sweep-out which is the bypass from the top region of accumulated water in the downcomer and the other is the direct ECC bypass which is induced by the interaction between the transverse gas and downward liquid film. The sweep-out mechanism in the DVI system downcomer was studied by MPR associates,7) Yoon and Suh10) and Lee et al.11) In the present study, we focused on the direct ECC bypass only and the experiments were conducted excluding the sweep-out phenomena. For this, the downcomer water level is maintained sufficiently lower than the cold leg elevation to exclude the effect of the sweep-out during the experiments. To investigate the direct ECC bypass phenomena in the downcomer, the DIVA (Direct Vessel Injection Visualization and Analysis) test facility was constructed. The facility was designed for an operation with air–water as the working fluids.

1. Scaling Methodology

An appropriate scaling methodology has to be applied to a scaled test facility for the reproduction of the interested phenomena of the prototype. In the present study the modified linear scaling12) was applied for the design of the test facility and the derivation of the experimental conditions. The results of the scaling analysis showed that it has the same geometrical scaling criterion as the linear scaling, but it has time and velocity scales which are reduced by the square root of the length scale to preserve the gravity effect. The major scaling ratios are summarized in Table 1.

| Parameter      | Modified linear scaling |
|----------------|-------------------------|
| Length ratio, $l_R$ | $l_R$ |
| Area ratio, $a_R$ | $l_R^2$ |
| Volume ratio, $V_R$ | $l_R^3$ |
| Time ratio, $t_R$ | $l_R^{1/2}$ |
| Velocity ratio, $v_R$ | $l_R^{1/2}$ |
| Flow rate ratio, $n_R$ | $l_R^{1/2}$ |
| Pressure drop ratio, $\Delta p_R$ | $l_R$ |
| Gravity ratio, $g_R$ | 1 |
| Pressure ratio, $p_R$ | 1 |
| Temperature ratio, $T_R$ | 1 |
| Void ratio, $\alpha_R$ | 1 |
| Slip ratio, $S_R$ | 1 |
| Aspect ratio, $l_R/D_R$ | 1 |

Fig. 1. The test sections are indicated in detail in Figs. 2 and 3. The DIVA test facility consists of the air supply system, the ECC injection system, the test sections, the air–water separator, the collection tank for the ECC bypass flow and the drain system of the test section. Air flow is supplied by three rotary type roots blowers and delivered to the test section through three intact cold legs. ECC water is delivered to each DVI nozzle by vertical type pumps. The APR1400 test sections of the DIVA test facility are 1/5 and 1/7 linear scaled models simulating the downcomer of the 2HL×4CL arranged loop of ARP1400 and the UPTF test section is a 1/7.3 model simulating the downcomer of the 4HL×4CL arranged loop of the UPTF. Additionally, the UPTF test section of the MIDAS (Multi-Dimensional Investigation in Downcomer Annulus Simulation) test facility which was primarily designed for a steam–water experiment was also used for the present experiments.13) It was a 1/4 model of the UPTF downcomer. The reactor core is not simulated since the objective of this study is to investigate the ECC bypass phenomena in the downcomer region only. Hot leg nozzles are installed in the test section but they only play the role of flow blockages inside the downcomer as shown in Figs. 2 and 3. The divergent nozzles of the cold legs and hot legs in the actual plants were not simulated and straight nozzles were equipped in the present test facility. The delivered air and water is interacted in the test section and some portion of the two phase mixture is discharged to the air–water separator via the broken cold leg. In the air–water separator, the bypassed two-phase mixture is separated. The separated ECC flows downward and accumulates in the ECC collection tank and the air is vented to the atmosphere through an upper pipe of the separator. At the drain system of the test section, a control valve is installed and thereby the water level in the downcomer can be controlled at a target value. In the present study, the downcomer water level was maintained at 1.0 m from the bottom of the cold
leg to exclude the effect of the sweep-out.

Major measuring parameters are the air injection flow rates, water injection flow rates, air and water temperatures and pressures, ECC bypass rate, ECC penetration rate and the downcomer water level. The instrumentations and uncertainties of the measuring parameters are summarized.
in Table 2. From these measurements, we calculated the bypass fraction which definition is the fraction of the input water that is directly bypassed out and analyzed the experimental data with the parameter.

The flow conditions of the present experiments were derived from the preliminary analysis results of the APR1400 using the TRAC code and the experimental conditions of the UPTF Test 21-D by applying the modified linear scaling. The safety injection system of the APR1400 comprises of four mechanically independent but two electrically separated trains. By assuming the failure of an electrical train of the ECCS, the present tests for the APR1400 were carried out with two activating DVI nozzles and the ECC water was injected through the nearest (broken side DVI: DVI4) and the farthest (intact side DVI: DVI2) nozzles from the broken cold leg.

### III. ECC Bypass Mechanism in the DVI System Downcomer during the Reflood Phase

#### 1. Direct ECC Bypass in the UPTF Downcomer

Figure 4 shows the typical hydraulic phenomena in the 1/7.3 scale UPTF downcomer for the 10 m/s gas velocity condition at each intact cold leg and 40% of the ECC bypass fraction condition. The observed flow patterns are illustrated in Fig. 5 by unwrapping the downcomer. As indicated in Fig. 3, the UPTF downcomer has two DVI nozzles located at the center of the adjacent two cold legs. From this geometrical configuration, the downward ECC film is greatly affected by the impinging jet of air on the core barrel wall. In the case of the broken side DVI nozzle (DVI1), the main flow direction of the liquid film is inclined to the broken cold leg due to the interfacial shear stress between the liquid film and the transverse air flow coming from Cold leg-1 as shown in Fig. 4. At the vicinity of the broken cold leg, the gas flowing out to the break with an orthogonal direction of the core barrel entrains the liquid from the liquid film as shown in Fig. 6. Thus the direct bypass of the ECC originates from two processes; the ECC is delivered from the injection location to the vicinity of the broken cold leg by the circumferential gas flow and then it is bypassed out by the off-take of the perpendicular directional gas flow. At the lower boundaries of the inclined liquid film, a droplet entrainment takes place. However, most of the droplets are de-entrained again at both the inner and outer walls and flow downward reform-

| Parameter           | Instrument       | Uncertainty |
|---------------------|------------------|-------------|
| Air flow rate (kg/s)| Vortex flow meter| 1.1%        |
| Water flow rate (kg/s)| Turbine flow meter| 0.3%    |
| Bypass rate (kg/s)   | Differential pressure transmitter | 4%       |
| Penetration rate (kg/s)| Coriolis meter       | 2.5%        |
| Pressure (Pa)        | Pressure transmitter| 0.2%    |
| Temperature (°C)     | PT-100Ω RTD       | 1.0°C       |
ing as a water film. As shown in Fig. 5, this region between Cold leg-1 and the broken cold leg is dominated by the cross flow conditions in the form of a film shear flow and is similar to a film flow or annular flow pattern of the flow regime map in the present safety analysis code.

As shown in Fig. 5, all of the ECC from the intact side DVI (DVI2) was delivered to the lower downcomer under this flow condition. The air injected through Cold leg-2 and Cold leg-3 impinges on the downcomer barrel and it creates stagnation regions of the impinging jet, where the static pressure is raised as the impinging fluid is decelerated against the surface. No ECC, therefore, was observed in these stagnation regions of an air impinging jet as shown in Fig. 4. At the center of Cold leg-2 and Cold leg-3, the two stagnation regions collide and the gas cannot flow laterally but either upward or downward. Then most of the ECC from the intact side DVI nozzle penetrates to the lower downcomer entrained by the downward gas flow. Some of the ECC is held up in the upper downcomer region because of the upward gas flow and it flows laterally along the narrow spaces between the upper end of the downcomer and the stagnation regions. As the ECC recedes from the stagnation regions, it begins to flow downward by gravitational force. And then it collides with the hot legs and loses its circumferential momentum.

2. Direct ECC Bypass in the APR1400

Typical hydraulic phenomena of the direct ECC bypass in the APR1400 downcomer are presented in Fig. 7 by dividing it into 4 regions for the 15 m/s gas velocity condition at each intact cold leg in the 1/5 APR1400 downcomer. Under this flow condition, about 30% of the ECC is bypassed out to the broken cold leg. Fig. 7(a) shows the direct ECC bypass phenomena in Region-1 between the broken cold leg and Cold leg-1. Air injected through Cold leg-1 flows circumferentially to the break and it causes the downward liquid film to shift to the broken cold leg. Thus the majority of the ECC
coming into this region cannot penetrate to the lower downcomer. The ECC penetration of the broken side DVI nozzle was observed in Region-2 as shown in Fig. 7(b), where the local gas velocity is lower than that of Region-1. Similar to the bypass processes in the UPTF downcomer, the downward liquid film is delivered to the off-take region near the broken cold leg by the circumferential gas flow and then it is bypassed out by the perpendicular flowing gas.

In Region-3 and Region-4, a stagnation region of the air impinging jet from Cold leg-2 was observed as shown in Figs. 7(c) and (d). The downward liquid is held up above the stagnation region in front of Cold leg-2 and the ECC and air are rapidly mixed by the break-up of the liquid film. The two-phase mixture flows circumferentially but almost all of the ECC penetrates into the lower downcomer since the interfacial shear stress cannot exceed the gravitational force under this gas injection condition.

The observation results in the UPTF and APR1400 test sections showed that two important processes existed in the DVI system downcomers; the delivery of the liquid film to the off-take region and the off-take at the vicinity of the broken cold leg. In a low gas velocity condition lower than 5 m/s, the downward liquid film is not delivered to the break since the interfacial shear stress is markedly smaller than the gravity force. Thus the off-take is the only bypass process in this condition. As the gas velocity increases, the effect of the interfacial shear stress increases and the liquid film begins to be shifted to the broken cold leg. Some portion of the inclined liquid film enters the off-take region since all of the entered ECC is observed to be bypassed out to the broken cold leg in a gas velocity condition higher than 10 m/s. Therefore, the ECC bypass is greatly affected by the portion of the ECC delivered from the injection location to the off-take region. It should be noted that the gas velocity condition of the reflood phase is 10–25 m/s at each intact cold leg. In these flow conditions, the delivery of the liquid film to the off-take region is found to be the most important process of the direct ECC bypass.

Subsequently the analysis for the relevant flow pattern, the film flow which is associated with the cross flow between the circumferential gas flow and the downward liquid film was carried out to interpret the bypass mechanism and the characteristics of the flow pattern.
IV. Analysis for the Film Flow in the Downcomer Annulus

Various investigations have been performed to understand the film flow or annular flow in the co-current flow and counter-current flow conditions. However, the analysis for the film flow associated with the cross flow has not been carried out which is the dominant flow pattern of the multidimensional ECC bypass phenomena. To understand the mechanism and derive the important dimensionless parameters of the phenomena, an analysis for the flow pattern was introduced in the present study.

The control volume of the film flow in the downcomer annulus is indicated in Fig. 9 and the force balances acting on each phase are illustrated in the figure. The lumped parameter approach of the present study is similar to the analysis of the countercurrent annular flow which was suggested by Wallis, but it was extended to the film flow in the cross flow conditions.

Following assumptions are applied to the present analysis.

1. The radial direction behaviors of the gas and liquid are neglected.
2. The axial directional gas velocity is neglected since the lateral gas flow is dominant during the direct ECC bypass.
3. The lumped parameter approach is applied therefore the liquid velocity perpendicular to the cross section is assumed to be uniform.
4. The curvature effect is neglected and thus the Cartesian coordinate is used.
5. The pressure is the same in the liquid and gas phase.

In the control volume, the $x$-directional force balances of each phase are as follows.

For the gas flow,

$$- (P_2 - P_1) D_2 H - 2 \int_{A} \tau_{i,x} dA = 0 \quad (1)$$

and for the liquid flow

$$- (P_2 - P_1) D_1 H + 2 \int_{A} \tau_{i,x} dA - 2 \int_{A} \tau_{w,x} dA = \rho_f \mu_{f_2}^2 D_1 H - \rho_f \mu_{f_1}^2 D_1 H. \quad (2)$$

From these equations, the pressure loss term can be eliminated by the assumption (5):

$$\frac{2 \int_{A} \tau_{w,x} dA}{(1 - \alpha)} - \frac{2 \int_{A} \tau_{i,x} dA}{\alpha(1 - \alpha)} = - \rho_f \mu_{f_2}^2 D_1 H. \quad (3)$$

As above, the $y$-directional force balances can be expressed as follows:

$$\frac{2 \int_{A} \tau_{w,y} dA}{(1 - \alpha)} + \frac{2 \int_{A} \tau_{i,y} dA}{\alpha(1 - \alpha)} - (\rho_f - \rho_g) g D WH \quad (4)$$

For the wall and interfacial shear stress we will introduce the following constitutive relations:

![Fig. 8 Phase distribution and flow patterns in the APR1400 downcomer](image1)

![Fig. 9 Control volume of the cross flow](image2)
Experimental Results for the Direct ECC Bypass

The experiments, the single DVI nozzle injection tests of the bro-

ing air and water and the test results are presented in

performed in the 1/7.3 and 1/4 scale UPTF test sections us-

in the domain of the Wallis parameter.

parameters for the multidimensional ECC bypass phenomena.

The assumption (3) that the liquid velocity is uniform along

the cross section gives the following relationships:

\[ u_f = u_f(x), \quad v_f = v_f(y). \]  

(7)

By considering the mass conservation in the control volume with an infinitesimal width, following equation can be obtained:

\[ \rho_f(v_f1 - v_f2)dxD_1 = \rho_f[u_f(x + dx) - u_f(x)]HD_1. \]  

(8)

As shown in this analysis, the Wallis parameters that mean the ratios between the inertia force and the gravitation-

al force of each phase are the important non-dimensional par-

ameters for the multidimensional ECC bypass phenomena.

These dimensionless parameters had been used for the data analysis of the UPTF test regarding the entrainment from

the downcomer water level during the reflood phase.\(^7\) From

these results it was confirmed that the data of the ECC by-

pass obtained from various test facilities can be analyzed

in the domain of the Wallis parameter.

V. Experimental Results for the Direct ECC Bypass

in the UPTF and APR1400 Downcomer

Separate effect tests for the direct ECC bypass have been

performed in the 1/7.3 and 1/4 scale UPTF test sections us-

ing air and water and the test results are presented in Fig. 10

using the gas Wallis parameter at the broken cold leg. In these

experiments, the single DVI nozzle injection tests of the bro-

If the boundary conditions of the control volumes, \( u_f(0) = 0, \quad u_f(W) = u_{f2} \), are applied, then the \( x \)-directional liquid velocity is expressed as a function of the space:

\[ u_f(x) = \frac{(v_f1 - v_f2)}{H} x = \frac{u_{f2}x}{W}. \]  

(9)

By applying a similar approach to the control volume with an infinitesimal height the \( y \)-directional liquid velocity can be expressed as follows:

\[ v_f(y) = v_f2 + \frac{u_{f2}y}{W}. \]  

(10)

The velocity functions are substituted with the liquid veloci-

eties in Eqs. (5) and (6). By substituting the wall and interfa-

cial shear stress terms into Eqs. (3) and (4) and dividing all the terms by the gravitational term of Eq. (4), the Wallis

parameters of each phase of which the definition is Eq. (11) are derived as the non-dimensional variables of the gas and liquid velocity and finally, the non-dimensional-

ized equations of the film flow in the downcomer annulus are written as Eqs. (12) and (13):

As shown in this analysis, the Wallis parameters that mean the ratios between the inertia force and the gravitation-

al force of each phase are the important non-dimensional par-

ameters for the multidimensional ECC bypass phenomena.

These dimensionless parameters had been used for the data analysis of the UPTF test regarding the entrainment from

the downcomer water level during the reflood phase.\(^7\) From

these results it was confirmed that the data of the ECC by-

pass obtained from various test facilities can be analyzed

in the domain of the Wallis parameter.
broken side and the intact side were carried out independently to investigate the contribution of each DVI nozzle to the total bypass fraction. As shown in Fig. 10, the bypass fraction of the broken side DVI nozzle rapidly increases with the gas velocity. However, almost all of the ECC injected into the intact side DVI nozzle penetrates to the lower downcomer even though all of the ECC from the broken side DVI bypasses to the break. The bypass fraction of the simultaneous injection case of both DVI nozzles (DVI1&2), therefore, increases drastically in the low gas velocity condition \( f_{g} < 2 \) and then, it is held constant at approximately 50% although the gas velocity increases. From these characteristics of the direct ECC bypass, transition points where the slopes of the bypass curves rapidly change, were observed in the simultaneous injection case (nearby \( f_{g} = 2 \)).

A series of separate effect tests for the direct ECC bypass has been performed in the 1/7 and 1/5 scale APR1400 downcomer geometries and the experimental results are presented in Fig. 11. Especially our analysis was focused on the qualitative difference of the bypass characteristics between the UPTF and APR1400 downcomer since the quantitative comparison of the bypass fraction is not meaningful because of the difference in the dimensionless liquid injection flow rate between the two experiments. The bypass fraction curve of the broken side DVI has relatively lower inclination in the APR1400 downcomer. However, that of the intact side DVI nozzle shows an opposite trend and it was found that the characteristics of the bypass curves rapidly change, were observed in the simultaneous injection case (nearby \( f_{g} = 2 \)).

VI. Conclusion

In the present study, an experimental investigation on the direct bypass has been performed, which occurs in the DVI (Direct Vessel Injection) system downcomer during the reflood phase of a LBLCOA (Large Break Loss of Coolant Accident). The heterogeneous phase distributions of the two-phase flow were illustrated and the bypass characteristics were described in the APR1400 and UPTF (Upper Plenum Test Facility) downcomer. From the visual observations, the film flow associated with the cross flow between the circumferential gas and the downward liquid is found to be the major flow pattern during the direct ECC (Emergency Core Coolant) bypass. An analysis for the flow pattern was attempted using phasic momentum equations and it is revealed that the Wallis parameters are significant dimensionless parameters of the multidimensional ECC bypass phenomena. A series of the experiments for the direct ECC bypass were carried out in the various scaled models and it was found that the characteristics of the bypass curves are highly dependent on the geometrical configuration such as the length of the upper downcomer from the cold leg and the elevation of the DVI nozzle.

However, current experiments were carried out in the air
and water condition and the effects of phase change were not investigated. Since the condensation reduces the steam flow to the broken cold leg, the reduction of the steam should be considered to compare the current experimental data with steam–water test results. Also it should be noted that local phenomena such as the break-up of the liquid film induced by the jet impingement of gas can be affected by the steam condensation.

Even though this experimental study did not consider the effects of phase change thereby it has a limitation to its applicability, it is believed that the results obtained by such a study are useful for the improvement or assessment of the multidimensional safety analysis codes and the development of relevant thermal hydraulic models by furnishing detailed information for the multidimensional behaviors of the ECC.

Nomenclature

\[ \begin{align*}
A & : \text{Area (m}^2\text{)} \\
D & : \text{Depth of control volume (m)} \\
f & : \text{Interfacial friction factor} \\
g & : \text{Constant of gravitation (m/s}^2\text{)} \\
H & : \text{Height of control volume (m)} \\
J_g & : \text{Wallis parameter} \\
L & : \text{Length Ratio} \\
L & : \text{Length (m)} \\
P & : \text{Pressure (Pa)} \\
w & : \text{X-directional velocity (m/s)} \\
v & : \text{Y-directional velocity (m/s)} \\
W & : \text{Width of control volume (m)}
\end{align*} \]

(Greek Symbols)

\[ \begin{align*}
\alpha & : \text{Void fraction} \\
\nu & : \text{Density of fluid (kg/m}^3\text{)} \\
r & : \text{Shear stress (Pa)}
\end{align*} \]

(Subscripts)

\[ \begin{align*}
f & : \text{Liquid} \\
g & : \text{Gas} \\
i & : \text{Interface} \\
m & : \text{Direction (x or y)} \\
\text{model} & : \text{Model} \\
\text{proto} & : \text{Prototype} \\
w & : \text{Wall}
\end{align*} \]

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References

1) P. A. Weiss, H. Wazinger, R. Hertlein, “UPTF experiment: a synopsis of full scale test results,” Nucl. Eng. Des., 122, 219 (1990).
2) R. P. Collier, “Downcomer flow topology results at 2/15 scale,” Proc. 7th Water Reactor Safety Research Information Meeting, Gaithersburg, USA, Nov. 5–9, 1979, (1979).
3) J. A. Block, P. H. Rothe, “ECC bypass research: downcomer flow topography and recent research results,” Proc. 6th Water Reactor Safety Research Information Meeting, Gaithersburg, USA, Nov. 6–9, 1978, (1978).
4) W. M. Dempster, D. S. Abouhadra, “Multidimensional two-phase flow regime distribution in a PWR downcomer during an LBLOCA refill phase,” Nucl. Eng. Des., 149, 153 (1994).
5) C.-H. Song, et al., “Multi-dimensional Thermal Hydraulic Phenomena in Advanced Nuclear Reactor Systems: Current Status and Perspectives of R&D Program in KAERI,” Proc. NURETH-10, Seoul, Korea, Oct. 5–9, 2003, (2003).
6) K. H. Bae, et al., “Pre-test analysis for the KNGR LBLOCA DVI performance test using a best estimate code MARS,” Proc. NTHAS2, Fukuoka, Japan, Oct. 15–18, 2000, (2000).
7) MPR Associates, Summary of Results from the UPTF Downcomer Injection/Vent Valve Separate Effects Tests: Comparison to Previous Scaled Tests, and Application to Babcock & Wilcox Pressurized Water Reactors, MPR-1392, (1992).
8) P. S. Damerell, J. W. Simons, 2D/3D Program Work Summary Report, NUREG/IA-0126, (1993).
9) P. S. Damerell, J. W. Simons, Reactor Safety Issues Resolved by the 2D/3D Program, NUREG/IA-0127, (1993).
10) S. H. Yoon, K. Y. Suh, “Investigation of sweep-out mechanism and critical void height in annular downcomer,” J. Nucl. Sci. Technol., 40, 834 (2003).
11) D. W. Lee, et al., “An experimental study of thermal-hydraulic phenomena in the downcomer with a direct vessel injection system of APR1400 during the LBLOCA reflood phase,” J. Nucl. Sci. Technol., 41, 440 (2004).
12) B. J. Yun, et al., “Scaling for the ECC bypass phenomena during the LBLOCA reflood phase,” Nucl. Eng. Des., 231, 315 (2004).
13) T. S. Kwon, et al., “Multidimensional mixing behavior of steam–water flow in a downcomer annulus during LBLOCA reflood phase with a direct vessel injection mode,” Nucl. Technol., 143, 57 (2003).
14) H. K. Kim, Test Matrix for the KNGR DVI Performance, Internal Document of Korea Electric Power Research Institute, NKD/BD-01100M, (2001).
15) G. B. Wallis, “Annular two-phase flow, Part I: Simple theory,” J. Basic Eng., 92D: 59, 73 (1970).
16) B. J. Yun, et al., “Air-water test on the direct ECC bypass during LBLOCA reflood phase with DVI: UPTF Test 21-D counterpart test,” J. Korean Nucl. Soc., 33, 315 (2001).