Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 2002

# ECC Water Bypass in the Downcomer with DVI of APR1400 under LBLOCA

**Dong Won LEE and Hee Cheon NO**
Korea Advanced Institute of Science and Technology
Yusong-Gu 373-1, Daejon, Korea
Tel:+82-42-869-3857, Fax:+82-42-869-3895, Email:dwlee@nesun1.kaist.ac.kr

**Han Kon Kim and Seung Jong Oh**
Korea Energy Power Research Institute
Munji-Dong, Yusong-Gu 103-16, Daejon, Korea

## ABSTRACT

In the present study, several experiments related to the thermal-hydraulic phenomena in the downcomer with DVI under LBLOCA (Large Break Loss of Coolant Accident) were carried out using the experimental facility of plane-channel type scaled down as 1/7 ratio of prototype reactor (APR1400). Especially, phenomena such as ECC (Emergency Core Cooling) water entrainment and mixing in the downcomer were focused in the present study. Water film spreading is studied and compared with the full-scaled experiment and the experiment with a 1/7 scaled cylindrical-type test section to see the scaling effect and its curvature effect, respectively. It turns out that the curvature effect is negligible and the present modified linear scaling law is more appropriate than the linear scaling law. The water height in the downcomer and the amount of ECC water bypass by onset of sweep-out were measured from the visual observation of sweep-out in the downcomer. From this test, the onset of continuous sweep-out was used to analyze the water height in the downcomer. The amount of ECC water bypass by sweep-out was measured and compared with the UCB and KfK correlations. It is found that the best fit of the data from the present experiment lies between the predictions by the two correlations. ECC water mixing phenomena in downcomer were observed focusing on the ECC water film behavior. From the air and water mixing tests, it is concluded that ECC water bypass fraction is highly dependent on DVI position rather than gas flow rates and ECC water bypass fraction is less than 10 % of injection ECC water. From the steam and water mixing tests, it is concluded that ECC bypass fraction with steam injection is under 1.5 % and much less than that with an air injection because of the condensation in the downcomer.

## 1. INTRODUCTION

Among the advanced design features of Advanced Power Reactor 1400 MW (APR1400), the direct vessel injection (DVI) mode is adopted as a safety injection system (SIS) instead of a conventional cold leg injection (CLI) mode. Thermal-hydraulic phenomena such as ECC water mixing and its bypass in the downcomer with DVI are expected to be different from those with the existing CLI mode. Especially, when ECC water is injected through DVI in reflood phase, injected ECC water is mixed with the high-speed steam from the intact cold leg and ECC water can be bypassed to the broken cold leg. It is required to confirm the design validity of the DVI mode and to enhance understanding on thermal-hydraulic phenomena in the downcomer. In the present study, several experiments related to the thermal-hydraulic phenomena in the downcomer with DVI under LBLOCA (Large Break Loss of Coolant Accident) were carried out using the experimental facility of a plane-channel type scaled down to 1/7 length scale ratio of prototype reactor (APR1400). Especially, the phenomena such as ECC water entrainment and mixing in the downcomer were focused in the present study.

## 2. EXPERIMENTAL FACILITY

The size and structure of test section was determined with consideration of the calculated value of thermal-hydraulic conditions from the prototype reactor (APR1400) and also, information like the water film spreading width and thickness from the preceding experiment [1] was reflected on this design. This test section was made in the form of a plane channel It was scaled down to 1/7 length scale ratio of the prototype reactor (APR1400) as shown figure 1: the diameters of the DVI line and cold leg are 0.03 m and 0.109 m, respectively. The width and height of this test section were changed to be able to observe the entire water film width and to obtain the proper value of steam velocity. This size of test section was also limited by the commercial size of front material. The front face of the test section was made of transparent material to observe the mixing phenomena [2]. Two types of nozzle were used in the DVI line as shown in figure 2, which can make the water film narrow in order to investigate the effect of the amount of ECC water bypass by the water film width according to the water flow rate. This facility was designed and manufactured as shown in figure 3. The blower and steam generator were used to supply the air and steam up to 30 m/sec in the test section, respectively, and the water tank and water pump supply the water at up to 4 m/sec. To separate and measure each amount of water and steam in the mixture through the broken cold leg, the separator was manufactured. To obtain of superheated up to 50℃, the pre-heater was placed in front of the steam injection pipe. Temperature, pressure and flow sensors were installed at the inlet and outlets to measure the heat transfer between the superheated steam and subcooled water. And the video camera was used to observe and record the phenomena.

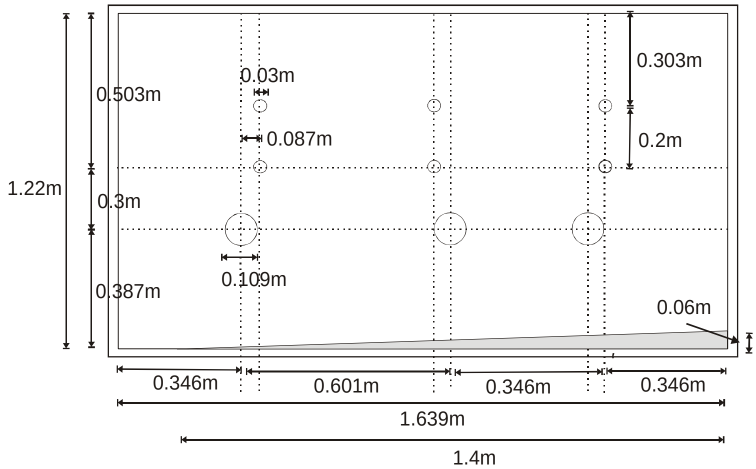


Figure 1. Schematic of test section

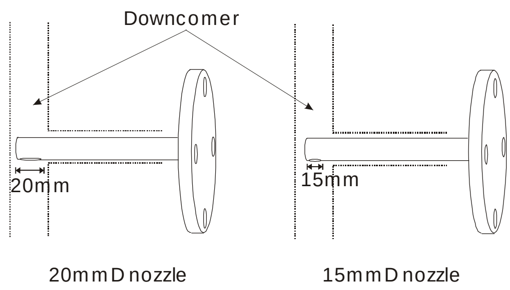


Figure 2. Schematic of nozzles

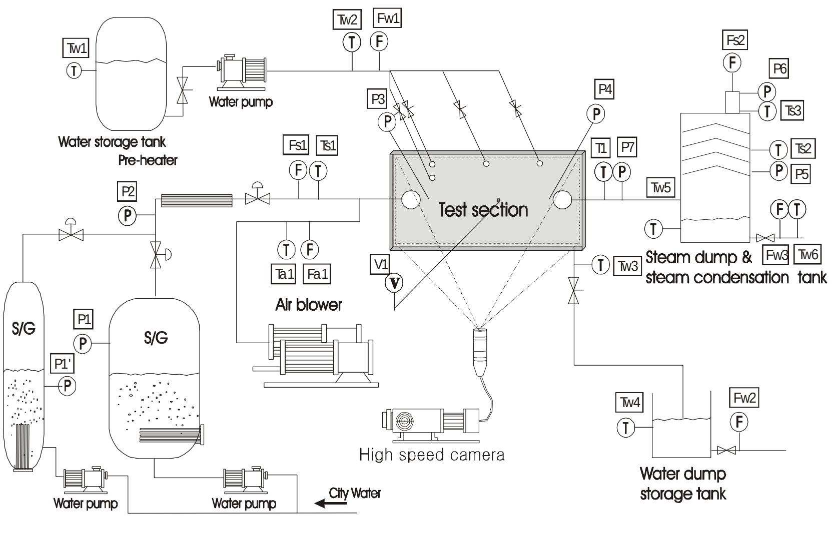


Figure 3. Schematic of experimental facility

## 3. EXPERIMENTAL RESULTS

With this experimental facility, 3 sub-experiments were carried out: (1) The experiment for the water film spreading is performed to verify the curvature effect and scaling law, (2) the onset of sweep-out and the amount of ECC water bypass by sweep-out are also investigated for ECC direct bypass to the broken cold leg, and (3) ECC water mixing phenomena in downcomer are observed focusing on the ECC water film behavior and ECC water direct bypass.

### *3.1 Water Film Spreading Test*

As the water film spreading width is closely related to the amount of ECC water direct bypass to the broken cold leg, the investigation of water film spreading is important to analyze the ECC water bypass and mixing. Therefore, water film spreading tests were carried out and their results were compared with the preceding experimental results and KAERI experiment to verify the curvature effect and the scaling law used in this study. The water film spreading test was performed as follows; water was injected into the downcomer through DVI by pump without the injection of air or steam and the water film width was measured at the position of 10, 40, and 61 cm below the DVI nozzle at the same time. Figure 4 shows a photo of the water film spreading test at 1.0 kg/sec of water mass flow rate. In order to verify the effect of the water film width on the ECC water bypass fraction, the nozzles were used in this experiment, which can reduce the water film width. Figure 5 shows the result of the water film spreading test including the nozzle test. As shown in this figure, the water film spreading width increases as the water flow rate goes up. It is confirmed that the water film width can be much more narrow with a nozzle. This reduction of water film width can affect the amount of ECC water bypass as mentioned in detail later.

From the comparison with KAERI experimental results which was performed with the cylindrical test section with the same 1/7 scale relative to prototype reactor (APR1400) [1], the width of the water film in this experiment is similar to that of KAERI test results as shown in figure 6 even with the different geometry. Therefore, it is concluded that the curvature effect can be ignored in this experiment. Additionally, the full-scaled flat-type experiment [3] was compared with the results from the present tests to verify the scaling law used in this study. This preceding experiment was performed using a full scale facility, which had 20 cm diameter of DVI nozzle. Two scaling laws, a linear scaling law and a modified linear scaling law, were used in this study. The velocity is conserved in the linear scaling law, but the velocity is reduced about 0.98 m/sec in the modified linear scaling law, which was suggested by KAERI [4]. As shown in figure 7, the suggested modified linear scaling law is more reasonable than the existing linear scaling law in this experiment. From this result, the steam or air and water flow rates were determined using this modified linear scaling law.

Figure 4. Experimental photo of water film width (Water mass flow rate = 1.0 kg/sec)

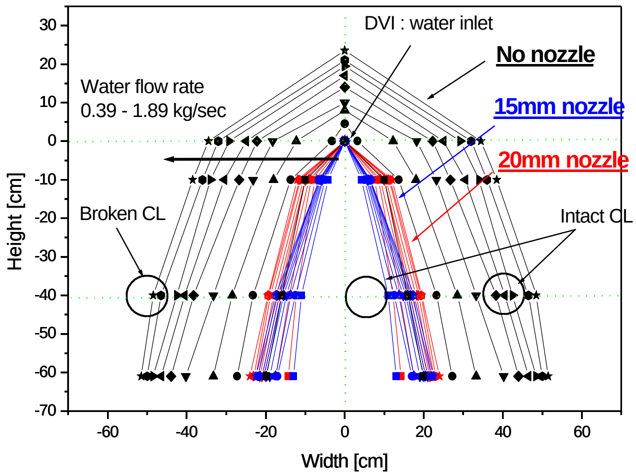


Figure 5. Experimental results of water film spreading width with/without nozzle

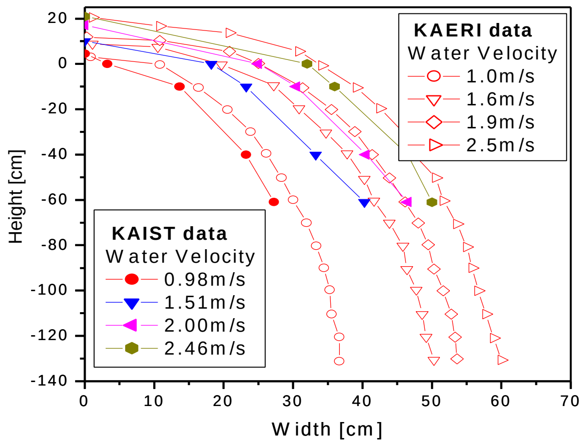


Figure 6. Comparison with results from KAERI experiment with the 1/7 scaled annulus downcomer

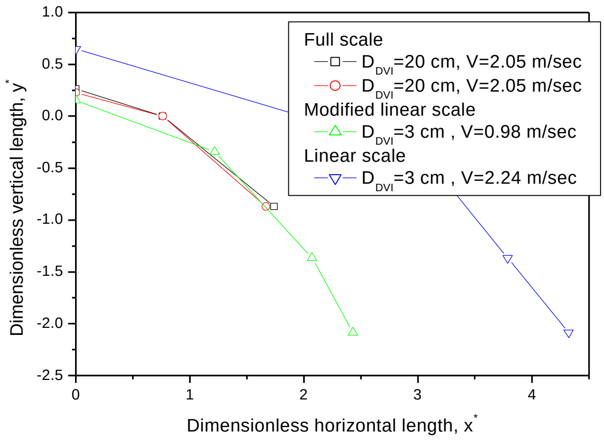


Figure 7. Comparison with results from full-scaled flat-type water-scaling experiment

### *3.2 Sweep-out Test*

ECC water accumulated in the downcomer is fluctuated by high-speed steam from the intact cold leg. Liquid droplets are produced on the surface of fluctuated ECC water and these droplets are bypassed to the broken cold leg by high-speed steam. Also, a part of the ECC water is bypassed in the form of liquid slug to the broken cold leg. Such a bypass phenomenon is called sweep-out. Figure 8 shows a photo of sweep-out at 0.30 kg/sec of air flow rate. It is considered that sweep-out is an important factor to determine the amount of the ECC water bypass and the water level in the downcomer. In this study, sweep-out was investigated with the focus of the following two items; (a) height of ECC water in the downcomer and (b) the amount of ECC water bypass by sweep-out.

Onset of sweep-out was tested experimentally and analyzed using the Crowley & Rothe correlation (1) [5]. Generally, onset is defined as a starting point of sweep-out, at which a very small amount of sweep-out is started. However, this happened intermittently and, in turn, the onset of sweep-out was subjectively determined. Therefore, the concept of onset of continuous sweep-out was introduced and used in this study, which was determined when sweep-out happened continuously. The concept of the onset of continuous sweep-out is more objective and gives less uncertainty to predict the onset. Also, the onset of continuous sweep-out is independent of the geometrical length between the broken cold leg and the intact cold legs as shown in figures 9 and 10. They show the onsets of intermittent and continuous sweep-out according to each intact cold leg position. Figure 11 shows the test results using the onset of continuous sweep-out with air and steam. As shown in this figure, A value in the Crowley and Rothe correlation is 1.63 and 2.38 with air and steam injection, respectively:

$$Fr_g\left[\frac{r_g}{\Delta r}\right]^{0.5} = A\left[\frac{h_b}{d}\right]^{2.5} \qquad (1)$$

The amount of ECC bypass by sweep-out is described with flow quality in the broken cold leg, which is expressed by the following equation:

$$x_{flow} = \frac{m_g}{m_f + m_g} \qquad (2)$$

Figures 12 and 13 show the experimental results of ECC water bypass by sweep-out according to the water height in the downcomer and gas flow rates. As shown in these figures, the bypass amount is highly dependent on the water height rather than the gas flow rate. As the level in the downcomer, $h$, becomes small, i.e., the water height closer to the broken cold let, much more of the ECC fluid is bypassed to the broken cold leg. Also, these results are compared with the existing experimental results and correlations such as UCB and KfK [5] in figure 13. It is concluded that the best fit of the data from the present experiment lies between the predictions by the two correlations.

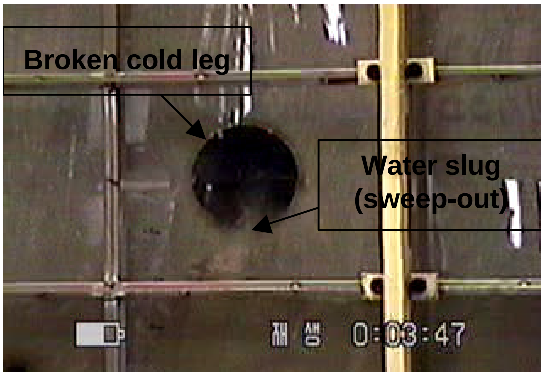


Figure 8. Experimental photo of sweep-out (Air flow rate = 0.30 kg/sec)

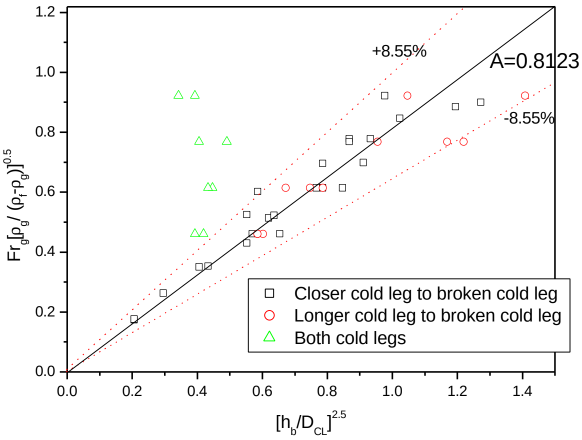


Figure 9. Onset of intermittent sweep-out

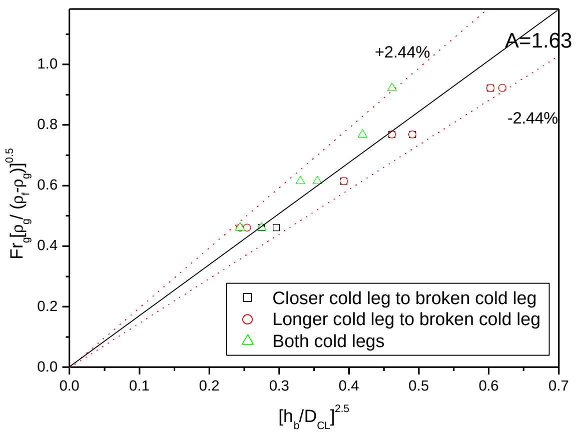


Figure 10. Onset of continuous sweep-out

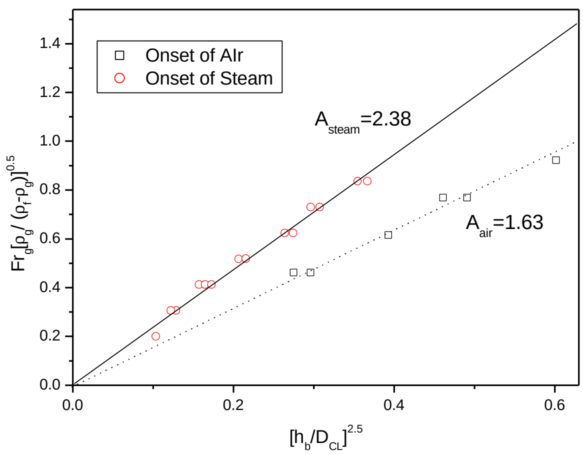


Figure 11. Result of onset of sweep-out with air and steam

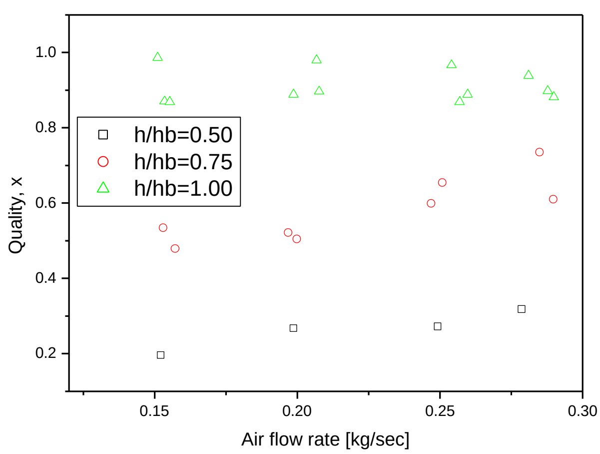


Figure 12. The amount of ECC water bypass by sweep-out vs gas mass flow rate

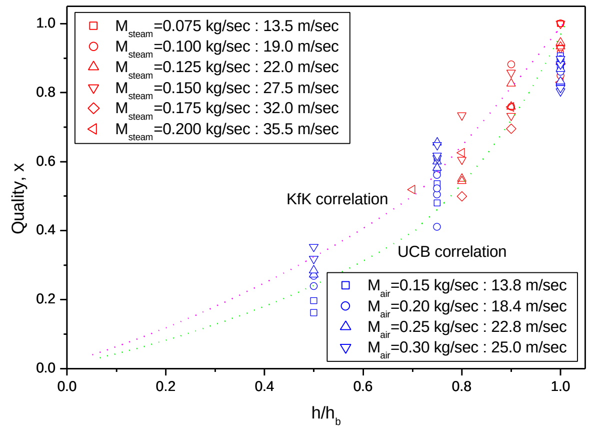


Figure 13. Amount of ECC water bypass by sweep-out with UCB and KfK correlations

### *3.3 ECC Water Bypass Test*

When ECC water is injected through DVI in the reflood phase, the injected ECC water is mixed with the high-speed steam from the intact cold leg and ECC water was bypassed to the broken cold leg. Figure 14 shows an experimental photo of ECC water mixing with the high-speed steam. As shown in this figure, ECC water from each DVI nozzle was mixed with steam and a part of ECC water was bypassed to the broken cold leg with steam not condensed in the downcomer. To investigate these ECC water mixing phenomena, the following tests were carried out according to the test matrix as shown in table 1: air/water mixing test was firstly performed to investigate such parametric effects without condensation as DVI position, cold leg position, air flow rate, water flow rate etc. and then, steam/water mixing test was carried out to investigate ECC water bypass. In the present study, the air/steam and water flow rate was used up to 0.224 and 1.71 kg/sec, respectively. To investigate the DVI position effect, water was injected each DVI line and all DVI lines. Additionally, to investigate the effect of water film width, two types of nozzle were used.

Air and water mixing test was carried out to investigate the ECC water bypass to the broken cold leg without and steam condensation. The effects of DVI position and nozzle on the ECC water bypass fraction were investigated experimentally. Figure 15 shows the ECC water bypass fraction according to the air flow rate and DVI position. Each DVI represented the distance from the broken cold leg as shown in figure 14. From this result, ECC water bypass fraction is highly dependent on DVI position rather than gas flow rate and the total amount of ECC water bypass is less than 10 % of injection ECC water. Figure 16 shows the ECC water bypass fraction for different DVI nozzle diamters. As mentioned before, the nozzle plays a role in reducing the water film width and it can also affect the ECC water bypass as shown in this figure.

For the steam and water mixing test, the steam and water were injected up to 0.22 and 1.71 kg/sec, respectively. The errors of the amount of ECC water bypass were analyzed by mass and energy balance and these errors were about ± 10 %, ± 12 %, respectively. Figures 17 and 18 show the ECC water bypass fraction with steam flow rates injected from the intact cold leg and steam flow rates vented to the inlet of the broken cold leg, respectively. From this result, ECC water bypass fraction with steam injection was under 1.5 % and much less than that with air injection because of the condensation in the downcomer. As shown in these figures, as the water mass flow increases, the ECC water bypass fraction and the amount of vent steam decrease because of steam condensation. In figure 19, the effective superficial velocity which represents the Wallis number (3) is introduced to compare the ECC bypass fraction with air and steam injection. As shown in this figure, ECC water bypass fraction with steam seems to be much less than that with air injection.

$$j^{*}_{g,eff} = \frac{M_{g,eff}}{r_g A_{flow}} \left[ \frac{r_g}{\left( r_f - r_g \right) g D_{CL}} \right]^{1/2} \qquad (3)$$


Figure 14. Experimental photo of ECC water bypass by ECC water mixing with steam

Table 1. Test matrix by used scaling law

| Unit (kg/sec) | Linear scaling law | **Modified linear scaling law** |
|---|---|---|
| Steam mass flow (2 intact cold legs) | ~ 1.567 | **~ 0.224** |
| Water mass flow (3 DVIs) | ~ 11.987 | **~ 1.71** |
| DVI position | **DVI 11, DVI 12, DVI 13** | |
| Nozzles | **15 mm D** | **20 mm D** |

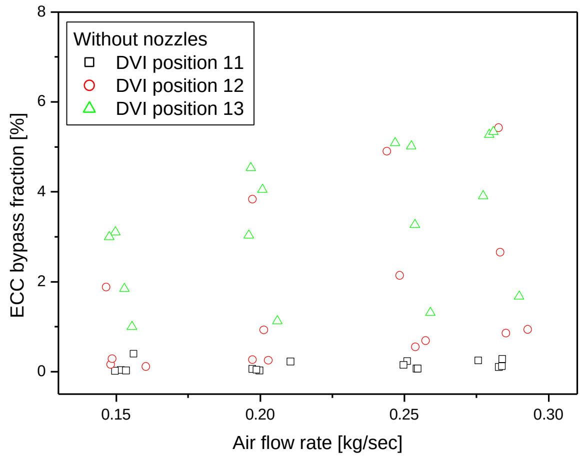


Figure 15. ECC water bypass by ECC water mixing according to DVI position

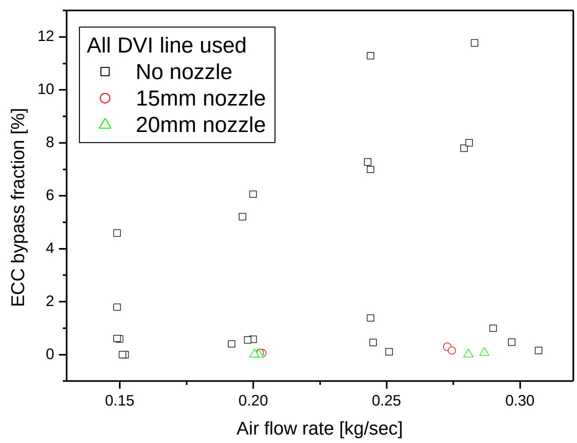


Figure 16. ECC water bypass by ECC water mixing according to the existence of nozzle

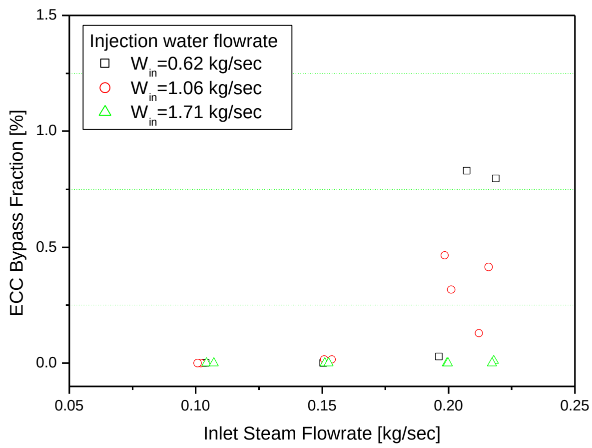


Figure 17. ECC water bypass by ECC water mixing with steam flow rates injected from the intact cold leg

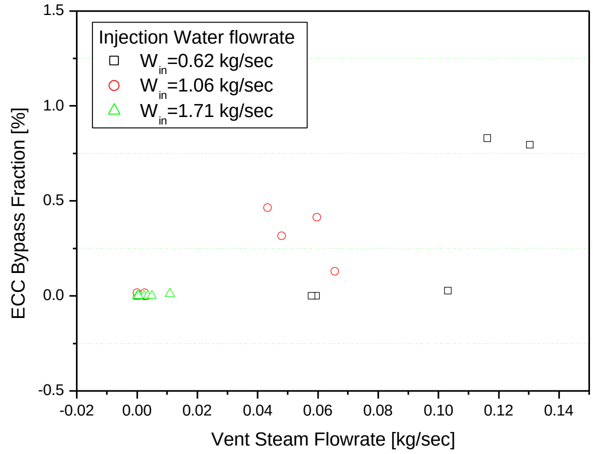


Figure 18. ECC water bypass by ECC water mixing with steam flow rates vented to the inlet of the broken cold leg

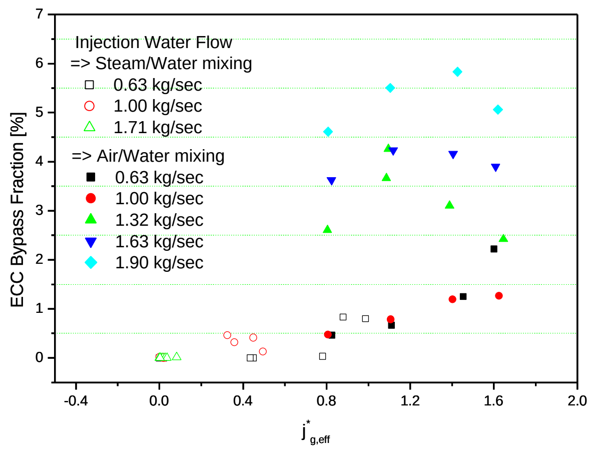


Figure 19. ECC water bypass fraction with air and steam injection

## 4. CONCLUSIONS

In the present study, several experiments related to the thermal-hydraulic phenomena in the downcomer with DVI under LBLOCA were carried out using the experimental facility of a plane-channel type scaled down as 1/7 ratio of prototype reactor (APR1400). The phenomena such as ECC water entrainment and mixing in the downcomer were the focus in the present study.

The experiment for water film spreading was performed to verify the curvature effect and scaling law and it is concluded that the curvature effect can be ignored and the modified linear scaling law is more suitable than the linear scaling law when compared with the 1/7 scale cylindrical-type facility and the full-scaled flat-type experiment.

The onset of sweep-out and the amount of ECC water bypass by sweep-out were investigated for ECC direct bypass to the broken cold leg. The onset of continuous sweep-out was used to analyze the water height in the downcomer. The A value in Crowley and Rothe correlation was found to be 1.63 and 2.38 with the air and steam, respectively. The amount of ECC water bypass by sweep-out was measured and compared with the UCB and KfK correlations. It turns out that the best fit of the data from the present experiment lies between the predictions by the two correlations.

The air and water mixing tests are carried out to investigate the effect of condensation on the ECC water bypass. It is concluded that ECC water bypass fraction is highly dependent on DVI position rather than gas flow rate. Also, the ECC water bypass fraction is shown to be less than 10 % of injection ECC water. From the steam and water mixing tests, it is concluded that ECC bypass fraction with steam injection is under 1.5 % and much less than that with air injection because of the condensation in the downcomer.

## ACKNOWLEDGEMENT

This work has been supported by Korea Energy Power Research Institute (KEPRI) through research contract. Special thanks are given to Dr. S. J. Oh, and Dr. H. K. Kim.

## NOMENCLATURE

$A_{flow}$ : Flow area of steam
$D_{CL}$ : Cold leg diameter
$h$ : Distance from center of cold leg to the height of water in the downcomer
$h_b$ : Distance from center of cold leg to the height of water for onset of sweep-out in the downcomer
$Fr$ : Froude number
$j^*_{g,eff}$ : Effective superficial velocity of gas
$L$ ($y^* = \frac{y}{L}$) : Scaling length from cold leg to DVI line
$L_{DC}$ : Length from cold leg to water height in downcomer ($\approx D_{CL}$)
$m_f$ : Liquid mass flow rate
$m_g$ : Gas mass flow rate
$M_{g,eff}$ : Total steam flow rate

$W \ (x^* = \frac{x}{W})$ : Scaling length of downcomer circumference

$x_{flow}$ : Flow quality

$r_f$ : Density of fluid (water)

$r_g$ : Density of gas

$\Delta r$ : Density difference ( $r_f - r_g$ )

## REFERENCES


1. B.J. Yoon, T.S. Kwon and C.H. Song, “Experimental study on water film spreading at reflood phase in the downcomer with DVI of APR1400 under LBLOCA , KNS Autumn Meeting, KNS 2000

2. D.H. Hwang, "Air-Water Mixing Experiments for Direct Vessel Injection of KNGR", Master Thesis, KAIST, 2000

3. Dong Won Lee and Hee Cheon NO, “Experimental study on the film spreading, sweep-out of ECC water in the downcomer with DVI under LBLOCA”, *Proc. of the KNS Autumn Meeting*, Suwon, Korea, Oct. 2001

4. B.J. Yoon, T.S. Kwon and C.H. Song, "Air/Water Test on DVI ECC Direct Bypass during LBLOCA Reflood Phase : UPTF Test 21-D Counterpart Test", KNS Autumn Meeting, KNS, 2000

5. KAERI, “A State-of-the-Art Report on Modeling of Liquid Entrainment Phenomena in Two-Phase Flow, KAERI/AR-450/96

6. KEPRI, “A Study of the Mixing Phenomena of Subcooled Water with Superheated Steam “, TR.99NJ13.j2001.614