ECC WATER BYPASS IN THE DOWNCOMER WITH DVI OF APR1400 UNDER LBLOCA

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ABSTRACT

In the present study, several experiments related to the thermal-hydraulic phenomena in 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 length-scale 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 was 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. 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 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 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.

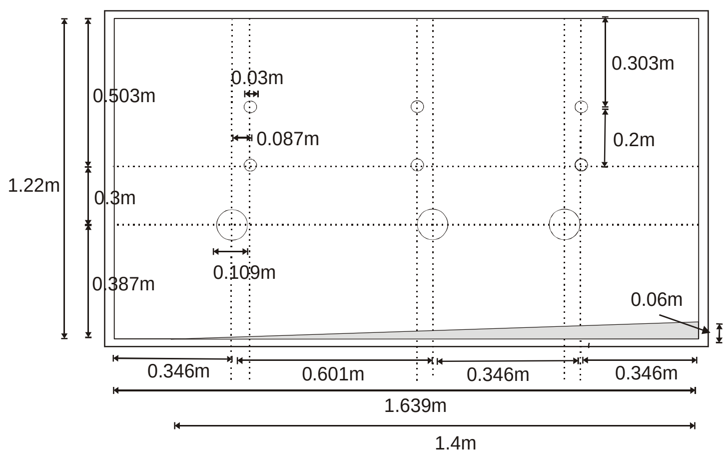

Figure 1. Schematic of test section

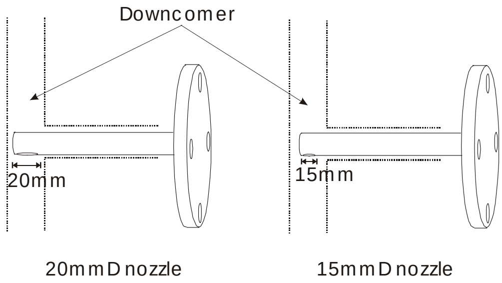

Figure 2. Schematic of nozzles

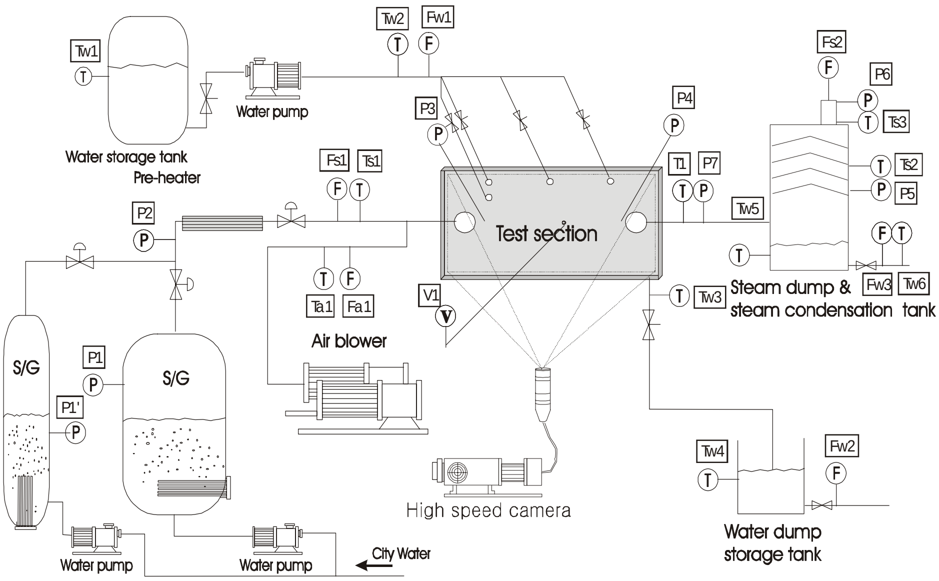

Figure 3. Schematic of experimental facility

3. EXPERIMENTAL RESULTS

With this experimental facility, 3 sub-experiments were carried out as follows; (1) 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 (2) ECC water mixing phenomena in downcomer are observed with focusing on the ECC water film behavior and ECC water direct bypass. Before starting these two experiments, ECC water film spreading test were carried out to confirm the used scaling law and curvature effect. This test results are briefly described in section 3.1.

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 test was carried out and its results were compared with the preceding experimental results and KAERI experiment to verify the curvature effect and the used scaling law in this study.

This pretest 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 DVI at the same time. Figure 4 shows a photo of water film spreading test, which is the case of 1.0 kg/sec of water mass flow rate. And also, 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 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 high and also, it is confirmed that the water film width can be much narrow with a nozzle. This reduction of water film width can affect the amount of ECC water bypass and this affection will be mentioned in detail in later part.

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

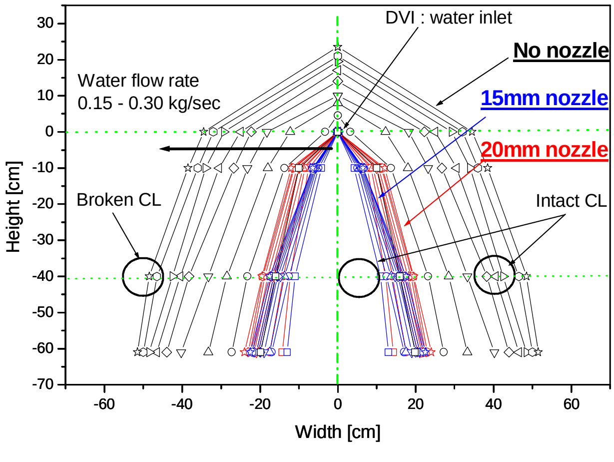

Figure 5. Experimental results of water film spreading width with/without nozzle

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.

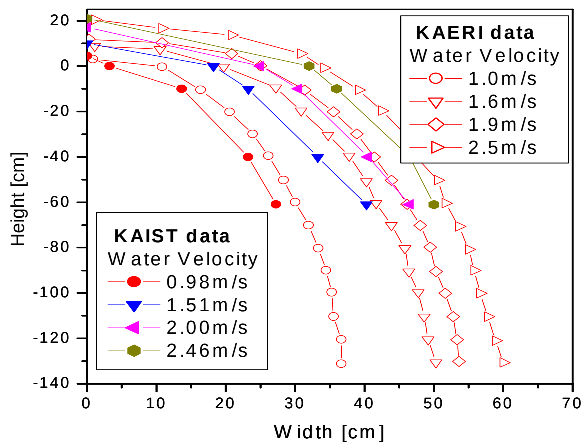

Figure 6. Comparison with results from KAERI experiment with the 1/7 scaled annulus downcomer

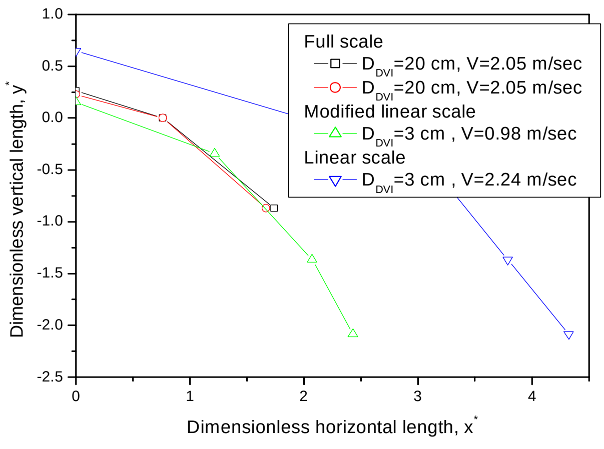

Figure 7. Comparison with results from full-scaled flat-type water-scaling experiment

3.2 Sweep-out Test

ECC water accumulated in the downcomer is fluctuated by high-speed steam from the intact cold leg. In this procedure, the 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 fluctuated ECC water comes out from the surface and 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 which case is

0.30 kg/sec of air flow rate. It is considered that sweep-out is an important factor to determine the ECC water bypass amount and the water level in the downcomer. In this study, sweep-out was investigated on the focus of the following two items; (a) onset of sweep-out by air or steam flow rate and 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) and one of experimental results, h_b, which can be subjectively determined. Generally, the definition of onset is determined from starting point of sweep-out, even when the very small amount of sweep-out is started, and this time is regarded as the onset of sweep-out. However, this is happened too intermittently to decide the onset and also, the amount of ECC water bypass by sweep-out was too small to affect the loss of ECC water. Therefore, the continuous onset of sweep-out was introduced and used in this study, which was determined when the sweep-out was happened continuously. Continuous onset of sweep-out is more meaningful than intermittent one because continuous onset is more related to the amount of ECC bypass and safety analysis. And also, the geometry effect is not happened with this continuous onset as shown in figures 9 and 10, which show the intermittent and continuous onset of sweep-out respectively according to the each intact cold leg position. This test result using continuous onset with air and steam are shown in figure 11. As shown in this figure, the A value in Crowley and Rothe correlation is 1.63 and 2.38 with the air and steam, respectively.

$$Fr_g \left[\frac{\rho_g}{\Delta\rho} \right]^{0.5} = A \left[\frac{h_b}{d} \right]^{2.5} \quad (1)$$

The amount of ECC bypass by sweep-out is described with flow quality in the broken cold leg, which is expressed by equation (2). Figures 12 and 13 show the experimental results of ECC water bypass by sweep-out according to the water height in downcomer and gas flow rate. As shown in these figures, the bypass amount is highly dependent on the water height rather than the gas flow rate, and as the level in the downcomer goes high, i.e. h_b goes small, much more amount of ECC is bypassed to the broken cold leg. Also, these results are compared with the existing experimental results and correlations such as UCB and KfK [4] in figure 13, it is concluded that the data from the present experiment lie between the predictions by the two correlations from this result.

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

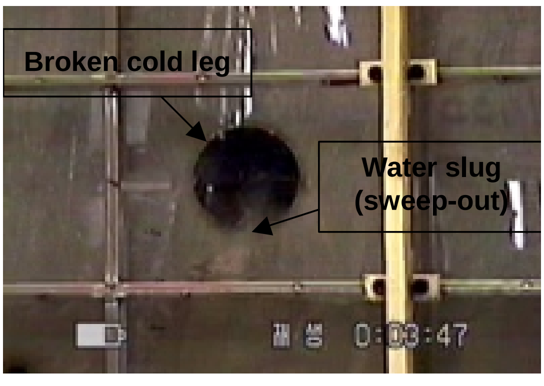

Figure 8. Experimental photo of sweep-out
(Air flow rate = 0.30 kg/sec)

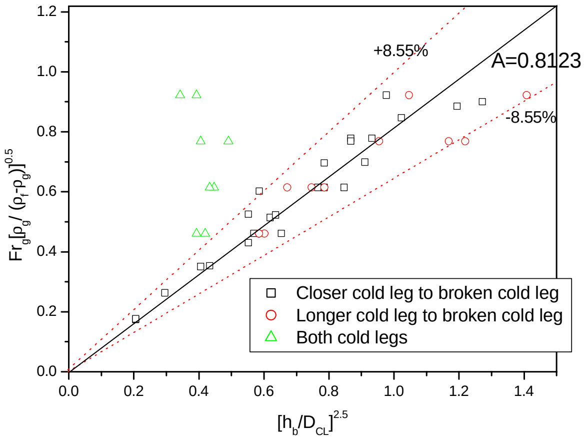

Figure 9. Onset of intermittent sweep-out

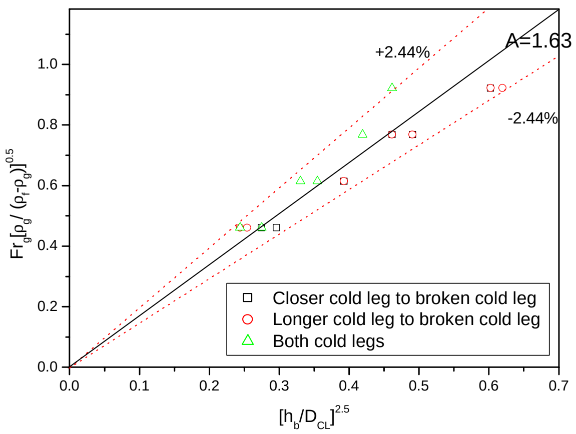

Figure 10. Onset of continuous sweep-out

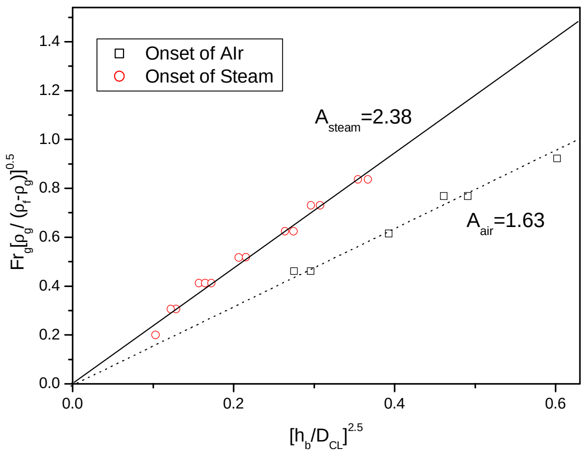

Figure 11. Result of onset of sweep-out with air and steam

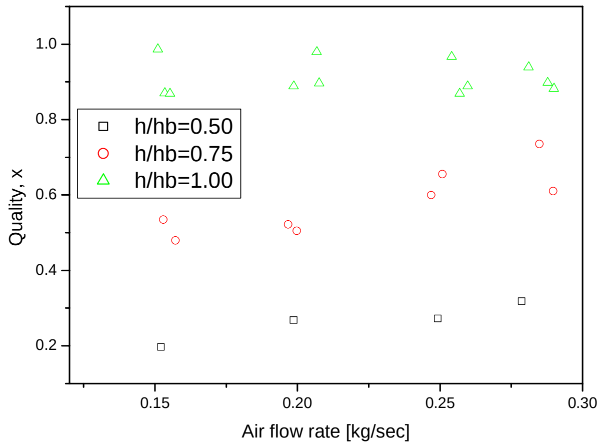

Figure 12. The amount of ECC water bypass by sweep-out vs gas mass flow rate

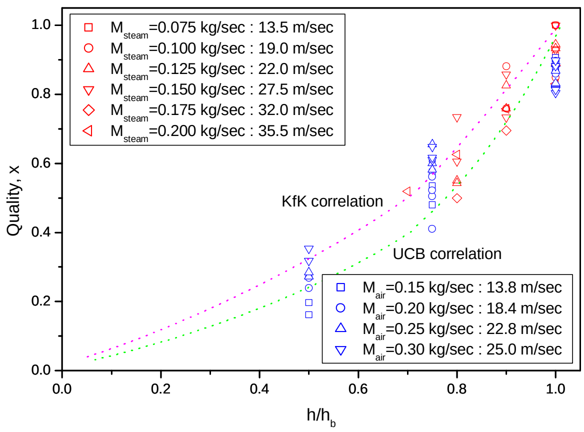

Figure 13. Amount of ECC water bypass by sweep-out from the present experiment with UCB and KfK correlations

3.3 ECC Water Bypass Test

As mentioned before, when ECC water is injected through DVI in reflood phase, injected ECC water is mixed with the high-speed steam from intact cold leg and ECC water was bypassed to broken cold leg at this time. Figure 14 shows an experimental photo of these phenomena of ECC water mixing with high-speed steam. As shown in this figure, ECC water from each DVI was mixed with steam and a part of ECC water was bypassed to the broken cold leg with remained steam after condensation.

To investigate these ECC water mixing phenomena, the following tests were carried out according to the test matrix as shown in table 1, which reflected modified linear scaling suggested by KAERI; (1) air/water mixing test was carried out to investigate the ECC water bypass without condensation and (2) steam/water mixing test was also accomplished.

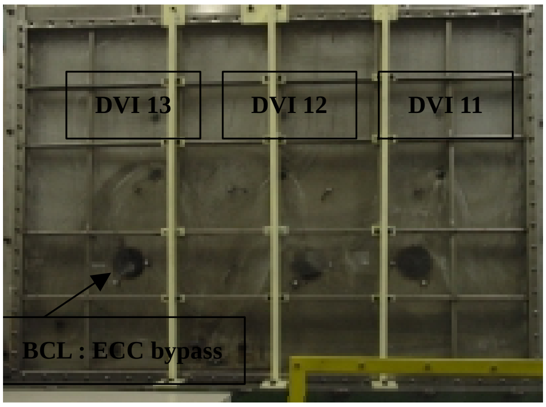

Figure 14. Experimental photo of ECC water bypass by ECC water mixing with steam

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**

Air and water mixing test was carried out to investigate the ECC water bypass to the broken cold leg without condensation by steam. In addition to the ECC water bypass fraction, effects DVI position and the effect of nozzle 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 also, total amount of ECC water bypass is showed less than 10 % of injection ECC water. Figure 16 shows the ECC water bypass fraction according to the existence of nozzle. As mentioned before, the nozzle has a role of reducing the water film width and it can also affect the ECC water bypass. This role is well shown in this figure.

For steam and water mixing test, the steam and water were injected up to 0.22 and 1.71 kg/sec, respectively. The errors of results were analyzed by mass and energy balance and these errors were about ± 10 %, ± 12 %, respectively. The following results like steam condensation rate and ECC water bypass fraction were obtained. Figures 17 and 18 show the ECC water bypass fraction with a flow rate of injected steam and vent steam, respectively. From this result, ECC water bypass fraction with steam injection was under 1.5 % and was much less than that with air injection because of the condensation in the downcomer. As shown in these figures, as the water mass flow rate goes high, the ECC water bypass fraction goes small, and also, the amount of vent steam goes small because of steam condensation. Figure 19 shows the temperature of drain ECC water after mixing with steam. As shown in this figure, the drain water temperature does not reach the saturation temperature, i.e. this can be penetrated into the core with subcooled margin.

In figure 20, the effective superficial velocity 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.

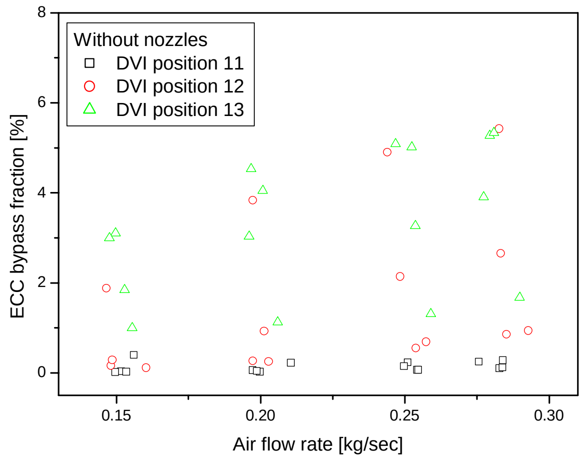

Figure 15. ECC water bypass by ECC water mixing according to DVI position

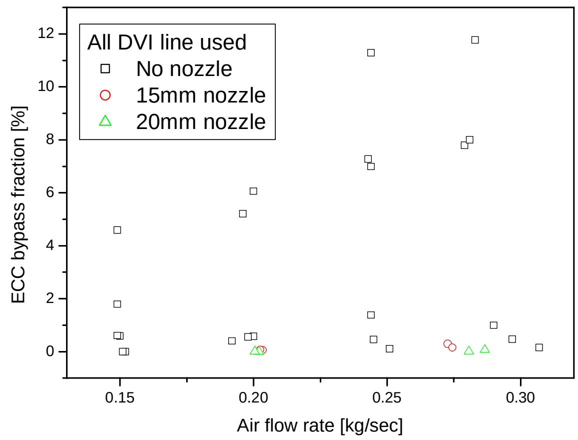

Figure 16. ECC water bypass by ECC water mixing according to the existence of nozzle

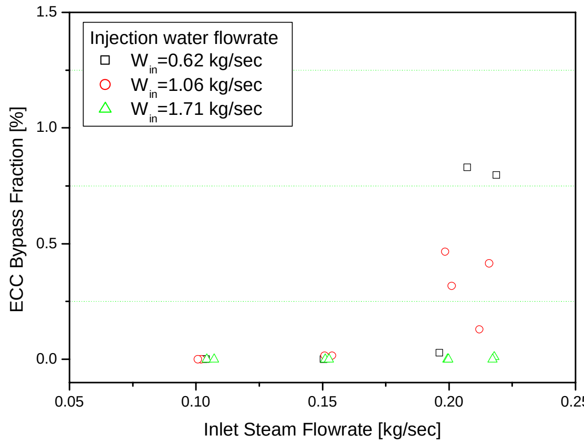

Figure 17. ECC water bypass by ECC water mixing with steam flow rates injected from the intact cold leg

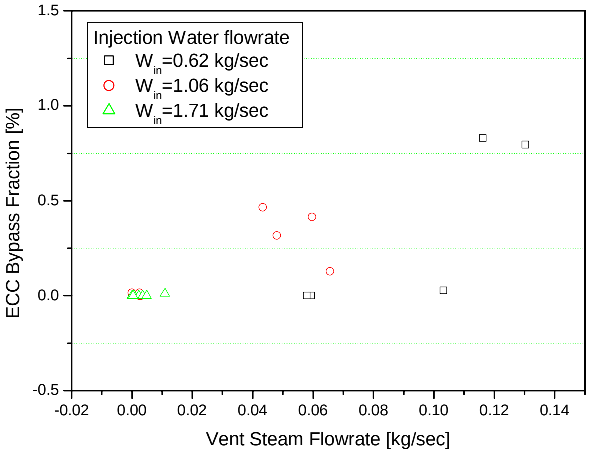

Figure 18. ECC water bypass by ECC water mixing with steam flow rates vented to the inlet of the broken cold leg

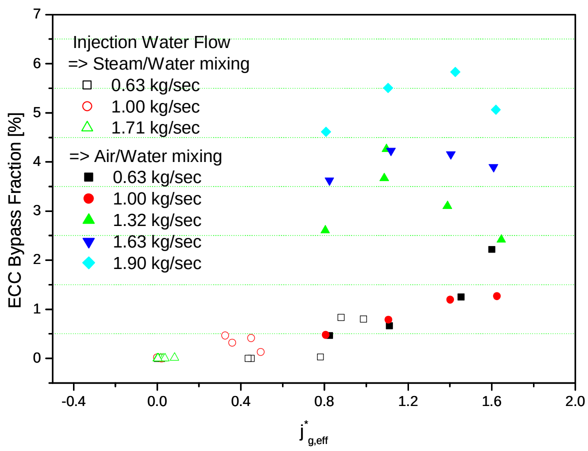

Figure 19. ECC water bypass fraction with air and steam injection

CONCLUSIONS

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

The experiment for the 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 proper from the comparison with cylindrical type facility of 1/7 scale and real-scale preceding 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 continuous onset of sweep-out was used to analyze the water height in the downcomer and the A value in Crowley and Rothe correlation was 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 preceding UCB and KfK correlations, the data from the present experiment lied between the predictions by the two correlations.

The air and water mixing test was carried out to investigate the ECC water bypass without condensation. From this result, it is concluded that ECC water bypass fraction is highly dependent on DVI position rather than gas flow rate and also, ECC water bypass fraction is showed less than 10 % of injection ECC water. From the steam and water mixing test, it is concluded that ECC bypass fraction with steam injection is under 1.5 % and is much less than that with an air injection because of the condensation in the downcomer. And it is also concluded that the temperature of drain water after mixing with steam has a subcooled margin about 10 °C.

ACKNOWLEDGEMENT

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NOMENCLATURE

A_{flow} : Flow area of steam

D_{CL} : Cold leg diameter

h : Height of liquid in the downcomer

h_b : Height of liquid 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

ρ_f : Density of fluid (water)

ρ_g : Density of gas

$\Delta\rho$: Density difference ($\rho_f - \rho_g$)

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