Journal of the Korean Nuclear Society
Volume 33, Number 3, pp.315 ~ 326, June, 2001

Air-Water Test on the Direct ECC Bypass During LBLOCA Reflood Phase with DVI : UPTF Test 21-D Counterpart Test

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(Received October 26, 2000)

Abstract

Direct ECC bypass phenomena that occur in a reactor vessel downcomer with a Direct Vessel Injection (DVI) system during the reflood phase of a Large Break Loss-of-Coolant Accident (LBLOCA) are experimentally investigated using a transparent 1/7.5 scaled down test facility of the Upper Plenum Test Facility (UPTF). A series of separate effect tests are performed in order to investigate the mechanisms of direct ECC bypass and to find out its scaling parameters. Various flow regimes and phasic distribution in downcomer are identified and mapped, and the fraction of direct ECC bypass is measured under a wide range of air and water injection conditions. From the counterpart test of the UPTF Test 21-D, the dimensionless gas velocity ($j^*_{g,eff}$) is derived experimentally, which is believed to be a major scaling parameter for the fraction of direct ECC bypass. And it is found out that the direct ECC bypass is greatly affected by the spreading width of ECC water film and the geometric configuration of the downcomer.

Key Words : DVI, reflood, direct ECC bypass, UPTF, air-water

1. Introduction

The Korean Next Generation Reactor (KNGR) is an evolutionary type of pressurized water reactor (PWR), which has a capacity of 4000 MWth with 2×4 loop arrangement of the reactor coolant system (RCS). It adopts new safety features in the emergency core cooling (ECC) system. One of them is the DVI system that injects ECC water directly into the reactor vessel downcomer, as shown in Fig.1 [1], through 4 independent trains of the safety injection system (SIS).

Incorporation of the DVI system eliminates complicated piping inter-connections to other systems. Also, it is expected to deliver more ECC water to the reactor core since whole ECC water

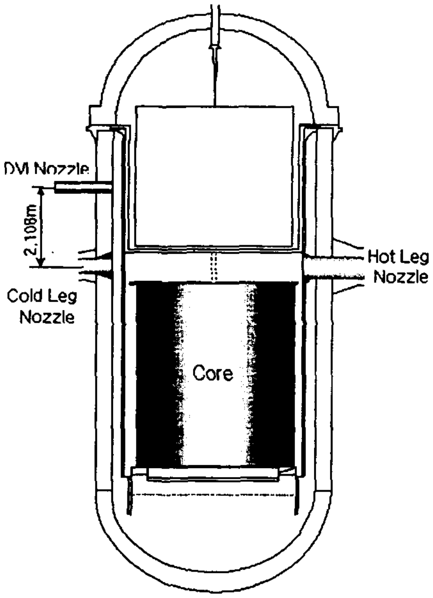

Fig. 1. Location of the DVI Nozzle in the KNGR Reactor Vessel

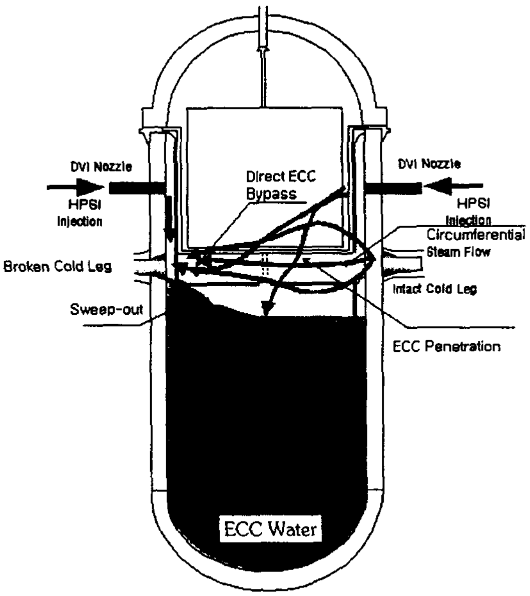

Fig. 2. ECC Bypass Mechanism in DVI System During the Reflood Phase

can be injected into the downcomer irrelevant to the location of RCS piping break during LBLOCA. It is expected, however, that the thermal hydraulic phenomena in downcomer with the DVI mode of SIS be much different from those of the cold leg injection (CLI) mode of SIS during LBLOCA, especially, during the reflood phase. The differences mainly come from the following facts [2]:

- With the CLI mode, subcooled ECC water is mixed with steam in cold legs and then, flows into the downcomer. Whereas, with the DVI mode, subcooled ECC water is directly injected into the downcomer and it produces ECC water jet impingement on the core barrel wall as well as the falling water film in the downcomer wall.
- Steam flow rate, coming through intact cold leg nozzles and going out to broken cold leg via the downcomer, is higher in DVI mode because of less condensation in intact cold legs.
- Since DVI nozzles are located above the cold legs, ECC water has a greater chance to interact with steam within the downcomer. It results in an increase of interfacial energy and momentum transfer between steam and ECC water, especially in the upper downcomer region.

LBLOCA issues with a DVI mode of SIS were studied experimentally for the first time in the UPTF Test 21-D [3], and it was reported that there are two different bypass mechanisms of ECC water injected through the DVI nozzles during the reflood phase of LBLOCA, as shown in Fig. 2. One is the 'direct ECC bypass' and the other is the so-called 'sweep-out' of accumulated ECC water from the downcomer region below the cold leg elevation. Analysing those data indicates that 40~50% of the injected ECC water is directly bypassed from the upper downcomer region to the broken cold leg, and the amount of ECC bypass flow due to the sweep-out is not so large when compared to that of direct ECC bypass. And it shows that the direct ECC bypass is the major mechanism of ECC bypass during the reflood phase of LBLOCA with the DVI mode.

Major concerns of the UPTF Test 21-D, however, was not the direct ECC bypass phenomena, but the water level reduction induced by the sweep-out. And the direct ECC bypass was not thoroughly tested in the UPTF test program, and its characteristics were not so sufficiently investigated in the past as well. In addition, major findings from the UPTF tests cannot be directly applicable to the KNGR DVI system because of geometrical differences, that is, the differences in the elevation and orientation of DVI nozzles between them. The DVI nozzles are located 2.108 m and 0.35 m above the center of cold leg in the KNGR and UPTF, respectively. And the KNGR has four cold legs, two hot legs and four DVI nozzles, whereas the UPTF has four cold legs, four hot legs and two DVI nozzles.

In recognition of these, separate effect tests (1/4.9 linear scale) using steam-water for the KNGR DVI system are being planned at the Korea Atomic Energy Research Institute (KAERI) [4]. These tests are aimed at providing experimental data on the reflood phase of LBLOCA for evaluating or validating relevant thermal-hydraulic models and correlations in best estimate codes.
For proper scaling and design of the steam-water test facility, it is important to understand major hydraulic phenomena to occur in the downcomer a priori. For these, a series of preliminary tests using air-water are also planned in the test facilities with both the UPTF (1/7.5) and the KNGR (1/7) downcomer geometries. From these preliminary tests, it is hoped to understand basic mechanisms of the direct ECC bypass and to find its major scaling parameters. [5]

In this paper, the experimental results of 1/7.5 scale UPTF downcomer are presented from the counter-part test of UPTF Test 21-D. The multi-dimensional behaviors of two-phase flow in the UPTF downcomer geometry during the reflood phase of LBLOCA are investigated in an air-water test facility with transparent test sections. From the tests, various flow regimes and phasic distribution of direct ECC bypass are identified and mapped from the visual observation. Comparing the experimental data with those of the UPTF Test 21-D enables us to derive the scaling parameter for gas velocity to govern the direct ECC bypass phenomena. Also a set of tests for water injection velocity with different cases of the upper downcomer length and the DVI nozzle elevation are carried out and some clues for the development of scaling methodology are found from the test results.

2. Experimental Facility

The test facility is designed to study the reflood phase of a double-ended guillotine cold leg break in the UPTF geometry with the DVI mode of ECC system using air and water. The test section is about 1/7.5 linear scale model of 4(4 loop UPTF downcomer geometry. The detailed geometric scaling ratios are summarized in Tabel 1. The discrepancy of some geometrical similarity between the test facility and UPTF is due to the fact that the present test section is modified using

Table 1. Geometrical Scaling Ratio of Air/Water UPTF Test Downcomer

Parameter	UPTF	Air-water Test	Scale Ratio
Downcomer Outer Diameter(m)	4.79	0.654	7.324
Downcomer inner Diameter(m)	4.37	0.582	7.509
Downcomer Gap Size (m)	0.21	0.036	5.833
Hot Leg Diameter (m)	0.75	0.100	7.470
Cold Leg Diameter (m)	0.75	0.100	7.470
DVI Nozzle Diameter (m)	0.308	0.041	7.470
DVI Nozzle Elevation (m)	0.35	0.047	7.470
		0.35	1.000

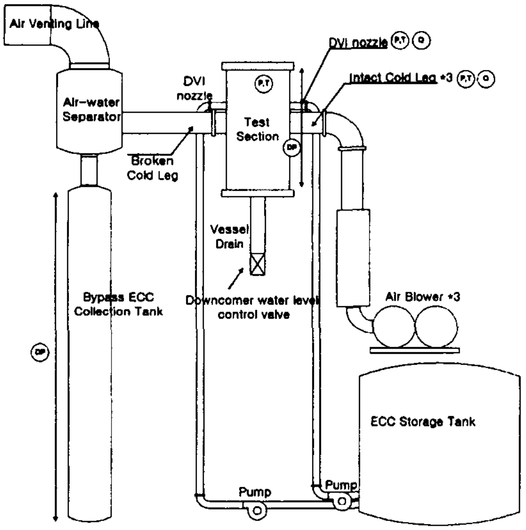

Fig. 3. Schematic Diagram of Test Facility

the KNGR downcomer test section. Air is supplied by three blowers (roots type) and delivered to the intact cold legs. A damper tank is installed at each exit pipe of blowers to reduce a pressure and flow oscillation. ECC water is delivered to each DVI nozzle by four vertical type pumps. The reactor core and lower plenum are not simulated since the objective of this study is to investigate the direct ECC bypass phenomena in the downcomer region only. Four hot leg nozzles, which just play a role of flow blockage, are installed inside the downcomer region.

Major parts of the hydraulic circuit and instrumentation locations are shown in Fig. 3 and the test section is shown in detail in Fig. 4. Four hot legs and four cold legs are positioned uniformly with a spacing of 45° between the adjacent two legs. Two different sets of DVI nozzle are made to investigate the effects of its elevation. Each DVI nozzle is located 0.047m and 0.35m above the centerline of cold leg, which is determined by the volume scaling law and the linear scaling law, respectively, and is spaced between two adjacent cold legs. In addition, a

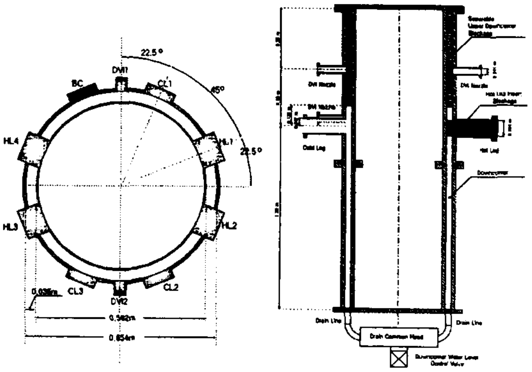

Fig. 4. Detailed View of the Test Section

removable downcomer blockage can be installed in the upper downcomer region in order to investigate the effect of upper downcomer length.

The test condition covers the water injection mass flow from 0 to 4.4 kg/s, the air injection mass flow from 0 to 1.6 kg/s. The absolute pressure in the test section changes from 1.0 to 1.7 bars by depending on air and water injection condition. The break flow is discharged to the collection tank, which is open to the atmosphere. The characteristics of direct ECC bypass are evaluated from the measurement of four main parameters such as total air injection flow, total water injection flow, fraction of direct ECC bypass and air density. Air flow rate is measured by a vortex flow meter at each intact cold leg and water injection flow is measured by a turbine flow meter at each DVI nozzle. Air density in the downcomer and cold legs is determined by measuring the pressure and temperature of air in each location. The temperature of all fluids is measured by a RTD sensor. The fraction of direct ECC bypass is calculated from the change of water level measured by a differential pressure transmitter at a collection tank. A control valve is installed in the drain line of the test section, and the water level in the downcomer can be controlled at a certain value. The uncertainties of measuring parameters

Table 2. Uncertainties of Major Measuring Parameters

Parameter	Uncertainty
Air Flow Rate (kg/s)	1.1 %
Water Flow Rate (kg/s)	0.3 %
Bypass Fraction (%)	4% (more than 10 %) 10% (less than 10 %)
Absolute Pressure (Pa)	0.2 %
Air Temperature (℃)	1.0℃

are summarized in Tabel 2.

A series of experiments is carried out by changing the water injection flow rate, air injection flow rate, the operating DVI nozzle and its elevation, and the length between the center of cold leg and the top of upper downcomer. A video recording is taken through the transparent test channel for the identification of flow pattern in the downcomer.

3. Observed Flow Patterns of the Direct ECC Bypass

The flow patterns of direct ECC bypass are discussed here for two typical cases of low and high gas injection velocity. In the tests, ECC water is injected through two DVI nozzles with the injection velocity of 1.6m/s, at each DVI nozzle, which is the same as that of UPTF Test 21-D. Water level in the downcomer is maintained at 1.1m below the center of cold leg.

3.1. Low Gas Injection Velocity

Air is injected with the average velocity (v_g) of 8 m/s through each intact cold leg. At this flow condition, it is observed that the fraction of ECC bypass to the total ECC injection flow rate is 35%. Flow pattern in the downcomer is so complicated, as shown in Fig. 5. ECC water injected into the downcomer annulus through the DVI nozzles forms a round jet and is impinged onto the core barrel wall.

The ECC water impinged through the DVI-1 nozzle, located near the broken cold leg, is spreading on the core barrel wall, and then it is diverted to the break and flowing out directly to the broken cold leg due to transverse air flow coming from the intact cold legs. Most of the diverted water fills completely the downcomer gap in the region of angles between the DVI-1 nozzle and broken cold leg. At the lower boundaries of the diverted water film, the droplet entrainment takes place. However, most of the droplets are de-entrained at both the inner and outer walls and flowing downward to re-form a water film. Thus, the cross flow of air and water is observed in this region, which is associated with downward flow of water film and circumferential air flow. The dominant flow regime near the break is typically a co-current annular wispy flow.

The DVI-2 nozzle is located in the region between the cold legs-2 and -3, in which air velocity is extremely high. The water film is broken up by the air jet impingement and then it moves in an isotropic direction. The typical flow regime in this region is an annular wispy flow. Some complicated flow regimes, however, are also found in the other regions as shown in Fig. 5. The flow path of ECC water is the same as that of the air flow stream.

In the region between two cold leg nozzles near the DVI-2 nozzle, thick water film flow is formed and moves in a downward direction. This is a local penetration path of ECC water, which is formed at a stagnation zone between two adjacent air flow from the cold leg-2 and -3. Other local penetration zones are found in a region between the hot leg and its adjacent cold leg nozzles. It is due to the blockage effect of the hot leg blunt body, in which laterally flowing air stream becomes stagnant near it and some of air flow moves in a downward

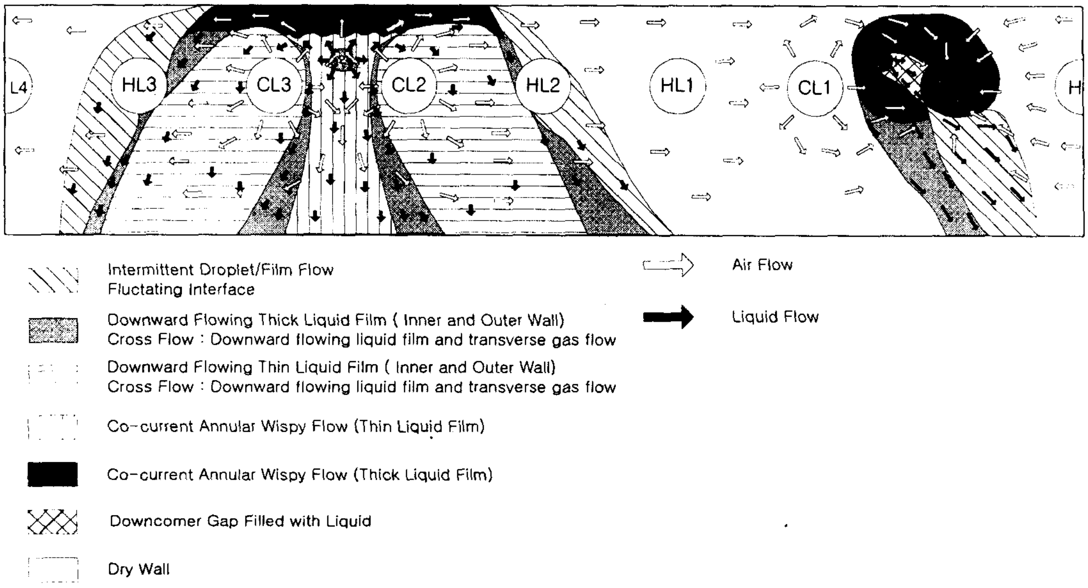

Fig. 5. Flow Pattern of Direct ECC Bypass at Low Gas Injection Velocity(v_g=8m/s)

direction. On the top of two cold leg nozzles near the DVI-2 nozzle, a high velocity of air stream is also found and most of the ECC water injected through the DVI-2 nozzle is flowing laterally along this path.

It shows also that the distance between the cold leg and the top of upper downcomer region can affect the average velocity of the air flow and thereby the amount of ECC water which is penetrated downward or bypassed laterally. The flow regime observed in this area is a co-current annular wispy flow. From these observations, it can be said that the ECC penetration rate is highly dependent on the geometry of the downcomer and the configuration of each nozzle.

3.2. High Gas Injection Velocity

The flow pattern map, observed at v_g= 22 m/s at each cold leg, is indicated in Fig. 6. Under this flow condition, 59.3% of ECC bypass rate is observed. The hydraulic phenomena in the downcomer is significantly affected by the high velocity of gas stream and the water flowing out through the break originates from both of the DVI nozzles, which is different from the case of low gas injection velocity.

Near the break, the high velocity of transverse gas flow restricts the ECC water penetration to the lower downcomer region. The local zero penetration zone is observed between the CL-1 and the broken cold leg. All of the ECC water injected through the DVI-1 nozzle is apparently bypassed to the break. The flow pattern near the break is so difficult to identify, but is believed to be a transverse co-current annular wispy flow.

Since the hot leg nozzle inside the downcomer region plays a role of blockage against the transverse air-water flow, the local penetration of ECC water occurs in a region between CL-2 and HL-1 or HL-3 and CL-3 nozzles. The cross flow between ECC water and gas are observed in these regions near the hot leg.

At the regions far from the break inside the

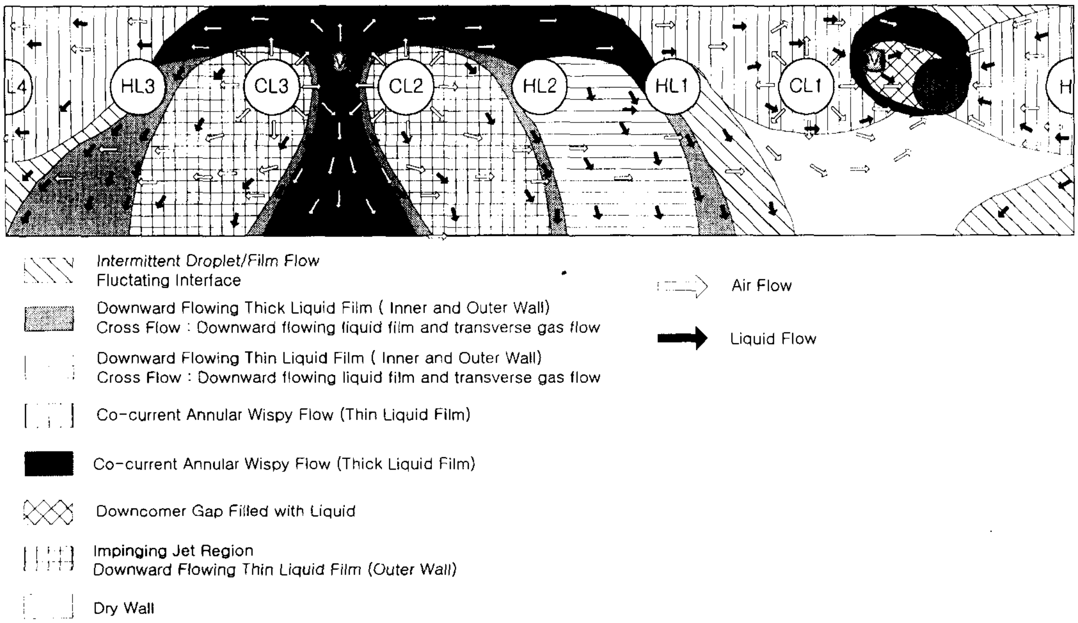

Fig. 6. Flow Pattern of Direct ECC Bypass at High Gas Injection Velocity(v_g=22m/s)

downcomer, the air jet impingement results in more distinguished breakup of water film and then the interfacial momentum exchange between air and ECC water is sharply increased due to the increased interfacial area. The large interfacial shear force overcomes sufficiently the gravity force of falling water, and it makes an increase of water entrainment and then direct ECC bypass. Thus the increased break-up of water film than in case of low air flow gives more chance for the direct bypass of ECC water injected from the DVI-2 nozzle.

In the region between CL-2 and CL-3 nozzles, water region does not exist on the downcomer inner wall due to a higher air jet, but small portions of ECC water could flow downward on the outer wall, which corresponds to the rear of air jet, due to relatively small gas velocity. So, the cross flow between the downward thin water film on outer wall and the transverse gas flow on inner wall is formed. At the center of the CL-2 and CL-3 nozzles, high velocity vertical (downward or upward) gas flow appears since the impinged air collides with each other. The downward gas flow in this region makes a large portion of water penetrated. Thus, the local ECC penetration is observed in this region and the flow pattern is identified to be a downward co-current annular wispy flow.

4. Parametric Effects on the Direct ECC Bypass

A series of experiments are conducted in order to quantify the characteristics of direct ECC bypass for various combination of ECC water injection flow rate, operating DVI nozzle, DVI nozzle elevation and upper downcomer length.

4.1. Effect of the Downcomer Scale

Figure 7 shows a comparison of the experimental data obtained from the 1/7.5 scale air-water test and the full scale UPTF test results.

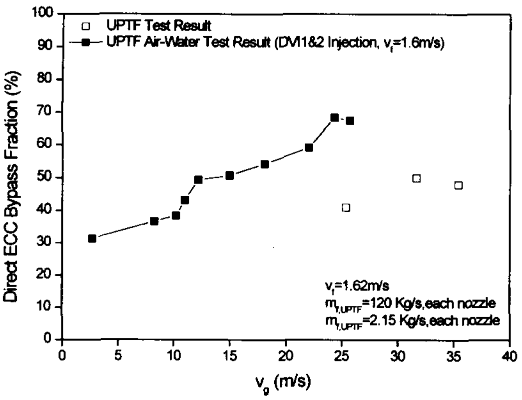

Fig. 7. Effect of Actual Average Gas Velocity on the Direct ECC Bypass

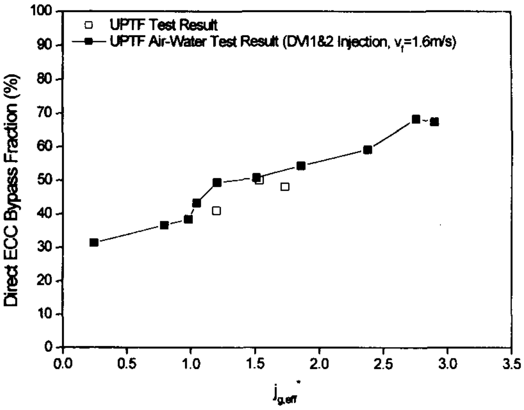

Fig. 8. Effect of Dimensionaless Gas Velocity on the direct ECC Bypass

The fraction of direct ECC bypass in UPTF Test 21-D was not directly measured but calculated from the analysis of mass balance [3]. To compare the present data using air-water with the UPTF steam-water test data, the effective steam injection velocity in UPTF data is introduced by subtracting the condensation rate from the total gas mass flow rate to define a effective gas flow. As shown in Fig. 7, it is noted that the bypass fraction curve of air-water test is absolutely above that of the UPTF test. This means that the fraction of direct ECC bypass in a small scale facility is markedly larger than that in a full scale facility at the same injection condition of gas and water. Thus, it is necessary to analyze these data using a dimensionless parameter that makes the small scale data be in accordance with the full scale data.

In the present study, the dimensionless circumferential gas velocity, $j^*_{g,eff}$, is introduced for the scaling parameter of direct ECC bypass. It is developed from the analysis of the UPTF sweep-out test results [3,6] and is defined as follows:

$$j^*_{g,eff} = \frac{\dot{M}_{g,eff}}{\rho_g \cdot A_{Flow}} \left[\frac{\rho_g}{(\rho_f - \rho_g) \cdot g \cdot L_{DC}} \right]^{1/2},$$

$\dot{M}_{g,eff}$: Effective gas flow rate (kg/s)

L_{DC} : Characteristic length - between upper downcomer length and bottom of cold legs

A_{Flow} : Downcomer circumferential flow area $(=L_{DC} \times D_{Gap})$

D_{Gap} : Downcomer gap width

Using the dimensionless gas parameter, the experimental data of the present study and the UPTF test are compared in Fig. 8. It shows that the Wallis type parameter is appropriate for a scaling parameter to represent the fraction of direct ECC bypass even though there is a slight deviation of data between a small scale test facility and the UPTF at the same Wallis number.

4.2. Effect of ECC Water Injection Flow Rate

The experimental results to investigate the effect of water injection flow rate are shown in Fig. 9. The experiments are performed under the conditions of three different water injection rates of 0.8m/s, 1.2 m/s and 1.6 m/s at each DVI nozzle. To find the contribution of each DVI nozzle to the direct ECC bypass, ECC water

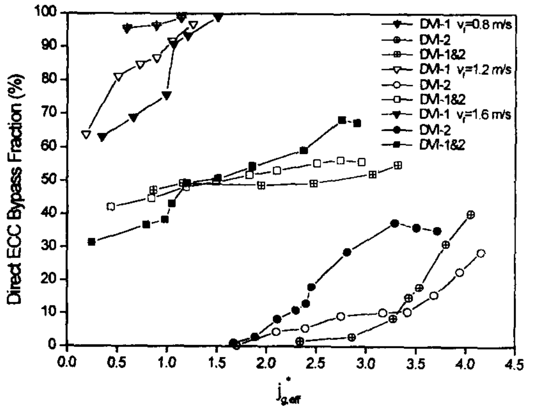

Fig. 9. Effect of Liquid Injection Rate on the Direct ECC Bypass

injection is performed under the three cases: DVI-1 injection only, DVI-2 injection only, and simultaneous injection through two nozzles.

From the experimental results for the cases of one DVI nozzle injection only, it is found that the direct bypass of ECC water through the DVI-1 nozzle decreases with increasing water injection flow rate, but the case of DVI-2 shows a reverse trend. The reason for two different trends can be explained in terms of the circumferential momentum of ECC water and the film spreading width after being impinged on the core barrel wall. When the ECC water is injected through the DVI-1 nozzle, the momentum of ECC water flowing to the opposite direction of the break increases with the injection flow rate. As a result, an increase of water injection flow rate results in a lower bypass fraction of ECC water injected through the DVI-1 nozzle. If the water is injected through the DVI-2 nozzle, however, the increase of ECC water injection flow results in the increase of transverse water momentum flowing to the break. And it makes an increase of the bypass fraction of ECC water injected from the DVI-2 nozzle.

These characteristics directly influence the fraction of direct ECC bypass in case of simultaneous injection through both the DVI-1&2 nozzles. If $j^*_{g,eff}$ is less than 3.0, the ECC water leaving the downcomer through the break is mostly originated from the DVI-1 nozzle and the bypass curves have the same tendency as those at the case of DVI-1 injection only. Therefore, the bypass fraction at a lower gas injection flow rate becomes larger than that of higher gas injection flow rate. As the gas velocity increases, however, almost all of the ECC water from the DVI-1 nozzle is bypassed and the ECC water from the DVI-2 nozzle begins to flow out to the break. Since the bypass fraction of the DVI-2 injection only has a tendency opposite to the case of DVI-1 injection only, the total bypass fraction curves in case of simultaneous injection through the DVI-1&2 nozzles are reversed at a certain point and then follow the tendency of DVI-2 injection only.

4.3. Effect of the Upper Downcomer Length

The upper downcomer geometries of the UPTF and the KNGR are different from each other, as shown in Fig. 10 [5]. The difference of upper downcomer length between KNGR and UPTF might affect the stream of air flow in the downcomer and then ECC bypass fraction. A series of sensitivity test is carried out to find the effect of upper downcomer length on the direct bypass phenomena. For this, the upper downcomer length is adjusted from 0.9 times to five times of the cold leg diameter.

The extension of the upper downcomer length makes a decrease of the average circumferential air velocity at the upper downcomer region. Due to this, the fraction of direct bypass at a long downcomer decreases about 10-30% when compared to that of short downcomer as shown in Fig. 11. By the way, some different trends are observed at the bypass curves for the case of DVI-

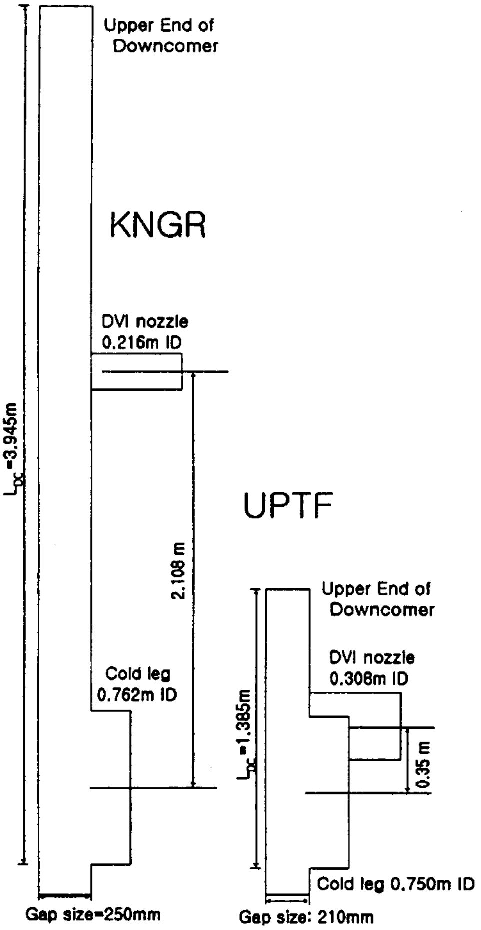

Fig. 10. Comparison of the Upper Downcomer Geometries Between the KNGR and UPTF

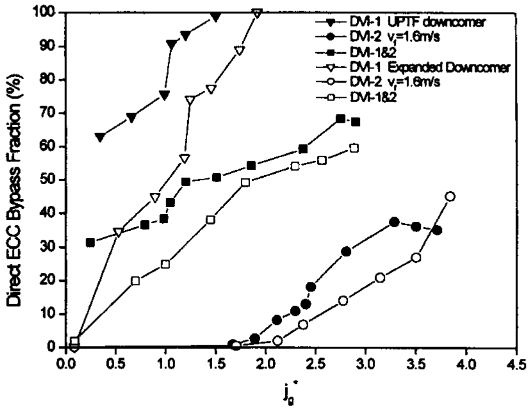

Fig. 11. Effect of Upper Downcomer Length on the Direct ECC Bypass

2 injection only. In a shorter dowcomer, the bypass fraction gradually increases with the air velocity. When it reaches a certain value, the bypass fraction slightly decreases with it. With a longer downcomer, however, the bypass fraction increases with the air velocity for the whole flow condition.

The reason for this result can be explained as follows: when the upper downcomer is limited by the structure, the upward flow caused by air jet impingement could not go up sufficiently and then downward air flow is much dominant as explained in section 3.2. Since the portion of the ECC water accompanied by the downward air flow increases with air injection velocity, the water penetration also will be increased. When a vertical length of the upper downcomer is long, however, the upward flow induced by air jet impingement is increased. And the ECC water delivered to the upper downcomer region will not penetrate to the lower downcomer region because of the air jet impingement near the cold leg elevation and flows to the circumferential direction by a high velocity of air stream. The amount of ECC water flowing to the circumferential direction increases with air velocity and thus the bypass fraction for the case of DVI-2 injection only increases with it. Because of the complicated hydraulic phenomena near the DVI-2 as stated above, the bypass fraction for the DVI-2 injection only in a long downcomer is larger than that in a short downcomer at high water injection conditions.

4.4. Effect of the DVI Nozzle Elevation

Finally, a set of tests for the DVI nozzle

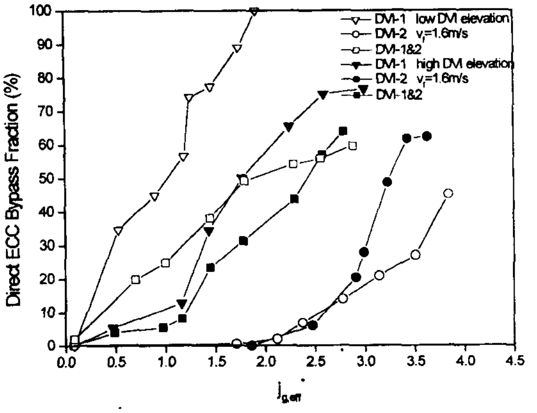

Fig. 12. Effect of DVI Elevation on the Direct ECC Bypass

elevation effect is performed in an enlarged UPTF downcomer geometry. The DVI nozzles are located 0.047m and 0.35m above the center line of cold leg. From the test, it is found that the higher DVI nozzle elevation makes a wide ECC water film at the cold leg elevation and this gives rise to a change in the fraction of direct ECC bypass. As the width of falling water film becomes wide, the film edge of ECC water delivered through the DVI-1 nozzle becomes located far away from the break and the bypass faction of DVI-1 injection decreases. If a falling film width becomes large, however, more ECC water injected through the DVI-2 nozzle reaches the break and then the bypass fraction of DVI-2 injection increases as shown in the Fig. 12. Thus, the bypass fraction curve of combined injection through higher elevation of DVI-1&2 nozzles is below that of the lower elevation at low air injection velocity condition. As air injection velocity is increased, the trend is reversed and the direct ECC bypass from a higher elevation of DVI nozzles becomes larger than that of a lower one.

From these observation on the effects of ECC water injection flow rate and DVI elevation, it is found again that the direct ECC bypass is highly dependent on the circumferential momentum of air flow and the film spreading width. It should be noted, however, that the width of ECC water film may not be preserved in the model and the prototypic downcomer since the curvature of the core barrel is different in both cases. Thus, an additional consideration of local scaling for the ECC water spreading width should be performed to preserve the fraction of direct ECC bypass exactly in the small scale test facility.

5. Conclusions

The UPTF Test 21-D counterpart test is carried out in a 1/7.5 scaled transparent downcomer geometry using air and water. The flow condition is limited to the reflood phase of a guillotine cold leg break. Some sensitive studies are also performed to investigate the effect of ECC water injection flow rate, operating DVI nozzle at the same elevation, different DVI nozzle elevation and upper downcomer length.

Major findings can be summarized as follows:

- The flow regime in the downcomer is very complicated. The typical flow regime is an annular wispy flow with thin or thick film. The distribution of local flow regime is highly dependent on the gas and liquid injection flow and the downcomer configurations.
- It turns out that the breakup of water film due to the impingement of gas jets injected through cold leg nozzles is the most important phenomena affecting the direct ECC bypass.
- Local penetration zones are found in the region between the hot leg and its neighboring cold legs and they are highly dependent on the arrangement of each injection leg.
- The bypass fraction of ECC water in a small

scale test facility is larger that that of the full scale test facility at the same air injection velocity. However, it can be well represented by introducing a dimensionless circumferential gas velocity.

- The bypass fraction of ECC water injected through each DVI nozzle is highly dependent on the transverse momentum and film spreading width of injected ECC water. At the DVI nozzle near the break, the bypass fraction decreases with the injection flow rate at DVI. In the case far away from the break, however, the trend is reversed.
- A longer length of the upper downcomer region above the center of cold leg results in the lower average velocity of transverse air and thereby a smaller bypass fraction.
- The higher DVI nozzle elevation makes a wide spreading width of falling ECC water film at the cold leg elevation and then it gives rise to a decrease in the bypass faction for the case of DVI-1 injection only, but an increase in case of DVI-2 injection only. The trend of total ECC bypass fraction in simultaneous injection through both DVI nozzles follows the combination of the trends separately observed in each of the DVI-1 or DVI-2 injection case.
- In the further studies, effect of the spreading width of falling ECC water film on the direct ECC bypass fraction should be evaluated in a small scale test facility.

Acknowledgment

This research has been performed under the nuclear R&D program supported by the Ministry of Science and Technology of the Korean Government.

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