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Effect of ECC Injection Angle on the Bypass Fraction

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Abstract

The comparison tests for the direct ECC bypass fraction were experimentally performed with a typical DVI nozzle and an ECC column nozzle having injection angle to the gravity axis. The ECC column nozzle is newly introduced to make an ECC water column in the downcomer region. The injection angle of the ECC water relative to the gravity axis is varied from 0 to ±90 degrees stepped by 45 degrees. The tests are performed in the air-water separate effect test facility (DIVA), which is 1/7.07 linearly scaled-down of the APR1400 nuclear reactor. The test results show that the direct ECC bypass fraction is affected by the ECC injection angle when the ECC water is injected using an ECC column nozzle as a single water column. The injection angle of an ECC water column relative to the circumferential air jet in the DVI system affects the direct ECC bypass fraction during the reflood phase of a LBLOCA.

1. Introduction

Multi-dimensional hydraulic behaviors in the downcomer annulus, such as ECC bypass, ECC penetration, and accumulated water level, occur in the DVI system during the reflood phase of a LBLOCA (Large Break Loss-of-Coolant Accidents). The thermal-hydraulic behaviors in the downcomer are strongly dependent on the DVI system, which is a currently under going a study for APR1400 DVI features during a LOCA (K.H. Bae et. al., 2000, C.H. Song et. al, 2000). Each train of ECCS in APR1400, which consists of a high pressure Safety Injection Pump (SIP) and a Safety Injection Tank (SIT), is connected to a DVI nozzle located approximately 2.1 m above the centerline of cold legs. In APR1400, the ECC water is directly injected into the downcomer through the four DVI nozzles that are located at the upper part of the downcomer. The thermal hydraulic behaviors in the downcomer are governed by steam coming from the intact cold legs and ECC liquid film falling down during the late reflood phase of LBLOCA (D.H Hwang 1999, B.J. Yun et. al., 2000 and 2001,T.S. Kwon et al. 2001). The steam-water interaction in the region may result in ECC bypass and ECC jet break-up around the cold leg elevation. If the ECC water is directly injected into the upper downcomer region, the steam coming from the intact cold legs will interfere with the ECC water in the downcomer.

In this study, separate effect tests are performed in order to understand the effect of the ECC water injection angle on the ECC bypass fraction. The difference of the air-water interaction shape between the ECC water film and the ECC water column is investigated from the viewpoint of ECC bypass fraction. Multi-dimensional hydraulic behaviors, such as ECC bypass, ECC penetration and ECC jet breakup, occurring in the downcomer annulus during the reflood phase of a LBLOCA, are experimentally visualized in the air-water test facility. Through the various test runs, the direct ECC bypass fraction is measured with variation of ECC injection angle at a given location of ECC nozzle.

2. TEST Description

2.1 Facility

The test facility (DIVA: *D*irect *I*njection *V*isualization and *A*nalysis) is designed to study the reflood phase of a double-ended guillotine cold leg break of the APR1400 geometry: in particular, direct vessel injection of the ECCS. The main test section is a 1/7.07 linearly scaled model of the downcomer geometry of the 2×4 loops APR1400. The working fluids are air-water. Air is supplied from three blowers and delivered into three intact cold legs. To reduce the pressure and flow oscillations, a damper tank is installed at each blower. The ECC water is delivered to each DVI nozzle by four vertical type pumps. The reactor core and the lower plenum are not simulated in this test because the object of this study is to investigate the direct ECC bypass phenomena in the downcomer annulus. Two hot leg nozzles inside the annulus, just playing a role of the flow blockage, are installed in the downcomer annulus. The scaling parameters of the test facility are summarized in the Table 1.

Table 1 Linear Scaling Scaling parameters of the DIVA

Item	Dimension	Scaling Ratio
Cold leg-to-DVI length (m)	0.298	1/7.07
Downcomer I.D (m)	0.582	1/7.07
Downcomer O.D (m)	0.654	1/7.07
Downcomer Gap (m)	0.036	1/7.07
Cold leg I.D (m)	0.108	1/7.07
Hot leg O.D (m)	0.160	1/7.07
DVI Nozzle I.D (m)	0.031	1/7.07

The experimental test facility consists of a cylindrical downcomer annulus, air supply blowers, and water supply pumps. The ECC water is injected as a single water column into the downcomer. Major nozzles and their elevations are shown in Fig. 1, and the downcomer test section is shown in Fig. 2. Two hot legs and four cold legs are located every 60 degrees. The elevation of the DVI nozzle, which can be altered to investigate its effects, is 0.2987m above the cold leg centerline.

2.2 Experimental Method

For the test of the injection angle, the injection velocity of water is fixed at a reference value to equalize the momentum of water jet to that of original ECC nozzle. If the injection velocity of water jet is conserved, the radial velocity distribution of the impinging water around the stagnation point is also conserved. The injection rate of the ECC water is the same as the typical ECC nozzle. The major test parameters are the injection angle of the ECC water and the air velocity.

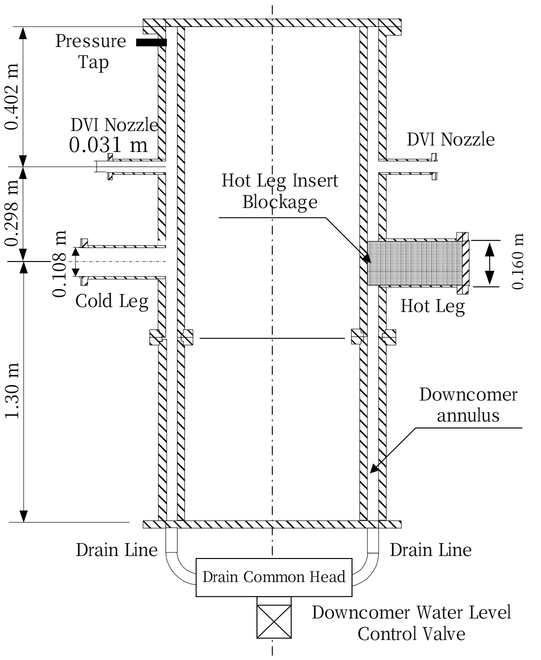


Fig.1 Downcomer test section

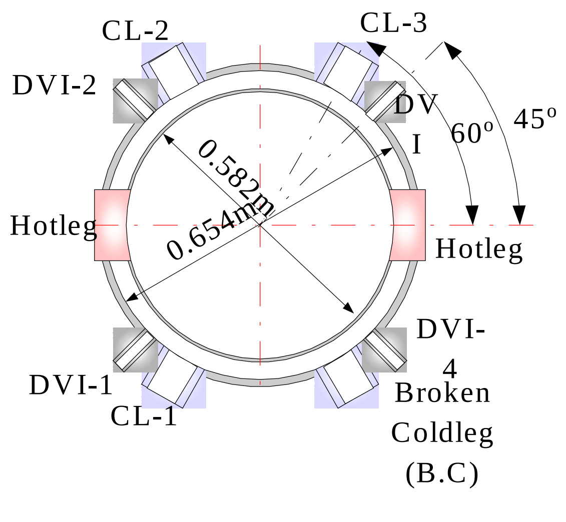


Fig.2 Nozzle orientation in the test section

The ECC water, as shown in Fig.3 , is directly injected as a shape of a single water column into the downcomer annulus. Therefore, the typical ECC water film does not form around the column nozzle. The injection angle of the column nozzle is varied from 0 to ±90 degrees stepped by 45 degrees relative to the gravity. The initial and boundary conditions, such as the ECC injection flowrate and the air velocity, are scaled down from the pre-test results of the TRAC code. Two of four DVI nozzles are considered in this study. The scaled down air flowrate is equally injected through three intact cold legs into the downcomer

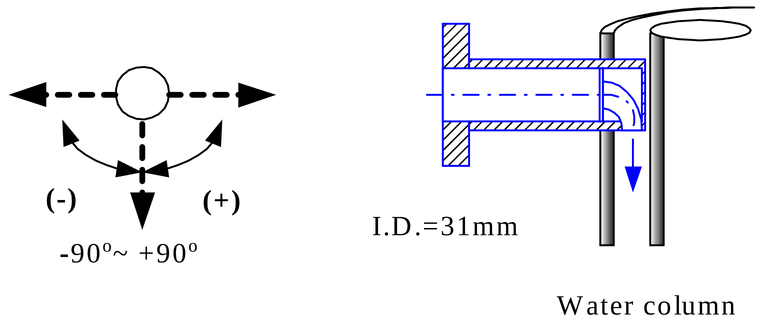


Fig. 3 DVI nozzles

2.3 Test Conditions

The inlet air velocity is varied from 5 to 32 m/sec and the downcomer pressures varied from 102 to 125 kPa. The back pressure of the broken cold leg is restricted to the atmospheric pressure. The characteristics of the direct ECC bypass are established from the measurement of four parameters: total inlet air flow rate, total inlet water flow rate, direct bypass fraction and air density. The air flow rate is measured by three vortex flow meters at each intact cold leg and the liquid flow rate is measured by two turbine flow meters at each DVI nozzle. The density of air in the downcomer and cold legs is determined by measuring the air pressure and temperature in the upper downcomer and cold legs. The fluid temperature is measured by RTDs. The ECC bypass fraction is calculated from the water level measured by a differential pressure transmitter at a collection tank. A control valve is installed at the drain channel to control the downcomer water level. The test conditions are summarized in Table 2. The instruments and their accuracy are also summarized in Table 3.

Table 2 Test condition

Operating DVI Nozzle	**DVI-2, DVI-4, DVI-2&4**
Injection angle (degree)	± 90, ± 45, 0
Air Velocity (each cold leg)	5~32 m/s
Air Temperature	15~35 °C
ECC Injection Velocity	0.76 m/s
ECC Temperature	12 °C
Downcomer Pressure	102~125 kPa

Table 3 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 (^{o}C)	1.0 ^{o}C

3. Experimental Results And Discussion

The ECC bypass fraction is defined by

$$\text{Bypass Fraction} = \frac{m_{ECC,out}}{m_{total,ECC,in}}. \qquad (1)$$

Pre-description of Downcomer Hydraulics

The major ECC penetration, named as the high penetration region in Fig. 4, is observed near the wake region around the hot leg nozzle which is located at the right side (the positive injection angle of the ECC water column) of the broken cold leg. The ECC water can be entrained into the wake region because the velocity vector of the air jet stream has the downward direction. However, in the left side of the broken cold leg (negative injection angle of the ECC water column), the ECC water is directly bypassed due to the high jet stream which is injected through the intact cold legs.

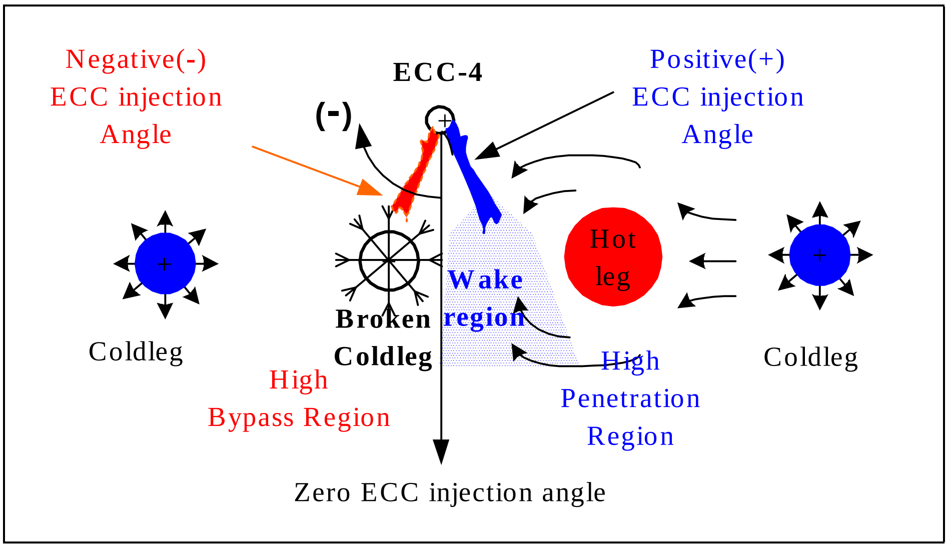
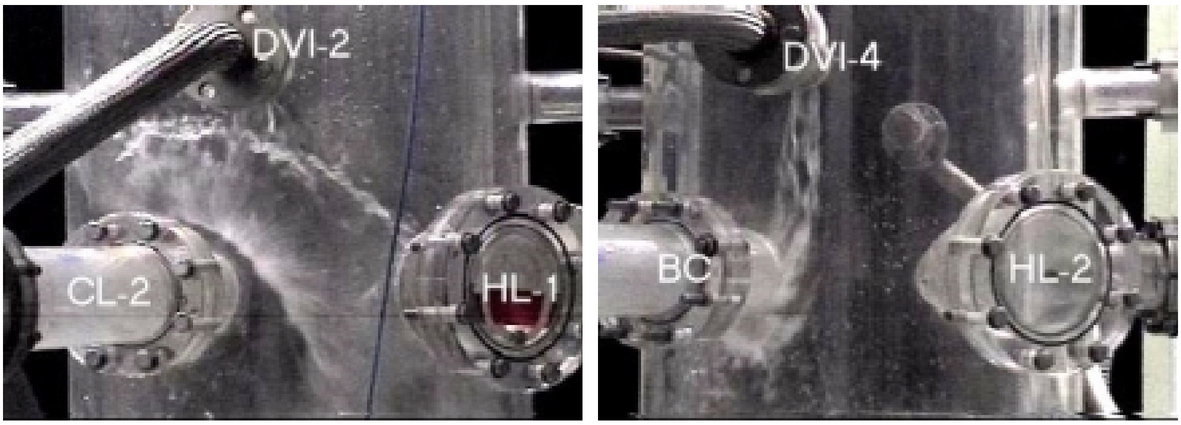


Fig. 4 Schematic drawing of regional characteristics

Injection Angle of 0 Degree

The shape of the ECC water accumulated above the impinging air jet around the cold leg-2 (CL-2), as shown in Fig. 5 (a), has a very similar shape for both ECC film and ECC column injection modes. At the upper part of the impinging jet of cold leg-2 (CL-2), a thick liquid film is formed and bowed in a downward direction. The cold leg-2 is located at the opposite side of the broken cold leg 4.   For the zero ECC injection angle, the liquid from DVI-2 is broken-up by the air jet impingement of cold leg-2 (CL-2). The typical flow regime in this region is an annular wispy flow. The flow path of DVI-2 water bypassing is the same as that of the stream-line of the circumferential air flow to the broken cold leg. However, the water column from DVI-4 which is injected near region of the broken cold leg(B.C) is pulled out directly through the broken cold leg by the air break flow. The ECC bypass at the broken cold leg is enhanced when the injection angle has zero degree. As shown in Fig. 5 (b), the ECC column is pulled out all.

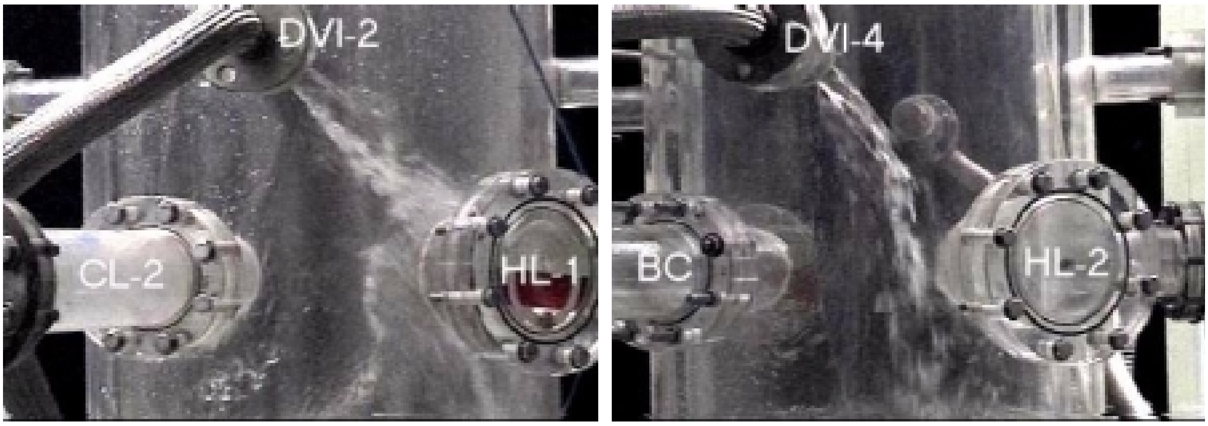


(a) DVI-2: Opposite side of the broken cold leg (b) DVI-4 : Broken C.L

Fig. 5 DVI Injection angle of 0.0 degree

Positive Injection Angle of (+) 45 Degrees

Both the DVI-2 and DVI-4 nozzles have the positive injection angle of 45 degrees. The ECC water columns, as shown in Figs. 6 (a) and 6 (b), are formed around the wake region of the hot leg. The wake region of the hot leg is the high penetration region of the ECC water. Almost all the ECC water is penetrated toward the lower downcomer passing through the wake region.

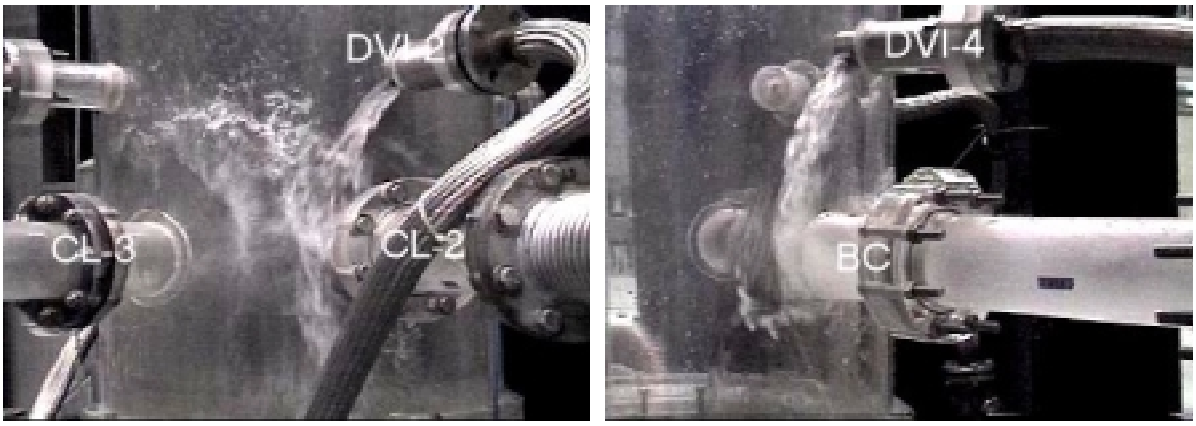


(a) DVI-2 : Hot leg Wake (b) DVI-4 : Hot leg Wake

Fig. 6 DVI Injection angle of (+)45.0 degrees

Negative Injection Angle of (-) 45 Degrees

In this case, both the DVI-2 and DVI-4 nozzles have negative a injection angle of 45 degrees. The water column injected through the DVI-4 is toward the broken cold leg while the water from DVI-2 towards the cold leg-3 (CL-3). As shown in Fig.7 (a), a large amount of ECC water injected from the DVI-2 is shifted toward the hot leg wake region due to the impinging jet of cold leg-3, and is penetrated toward the lower downcomer. However, all water from the DVI-4 is directly bypassed through the broken cold leg. The ECC penetration is increased by DVI-2 while the bypass is increased by DVI-4, compared with the case of the original ECC injection.

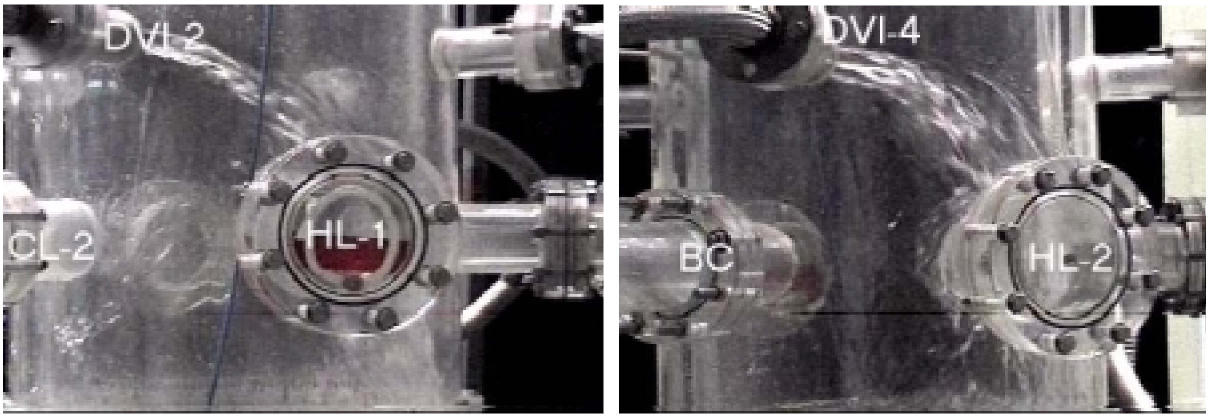


(a) DVI-2: Opposite side of the broken cold leg (b) DVI-4 : Broken cold leg(B.C)

Fig. 7 DVI Injection angle of (-)45.0 degrees

Positive Injection Angle of (+) 90 Degrees

Both the DVI-2 and DVI-4 nozzles have a positive injection angle of (+)90 degrees. In this case, the ECC water column is injected around the hot leg. Almost all the ECC water injected above the hot legs are penetrated toward the lower downcomer annulus through the wake region of the hot leg as shown in Figs. 8 (a) and 8 (b). The ECC penetration is increased at both DVI-2 and DVI-4, compared with the case of the original ECC injection.

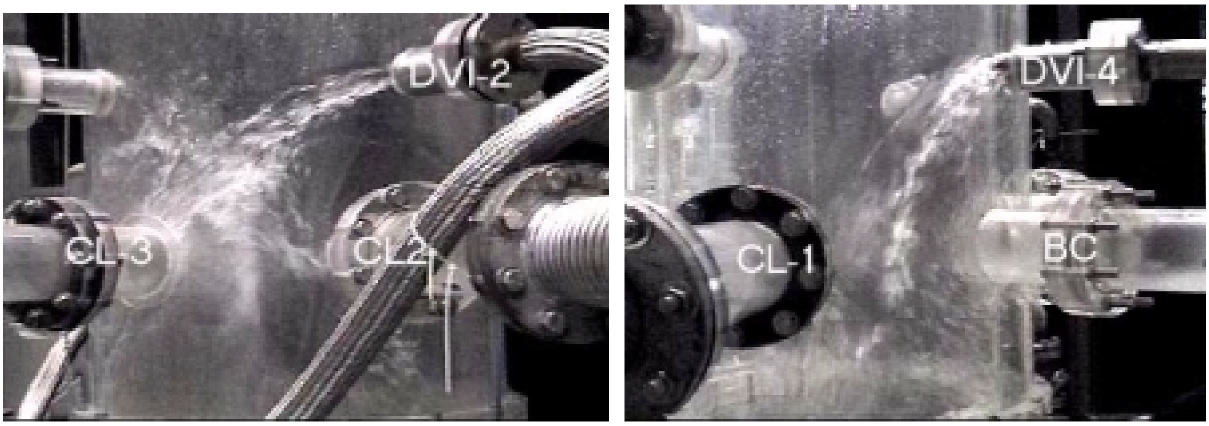


(a) DVI-2 : Hot leg Wake (b) DVI-4 : Hot leg Wake

Fig. 8 DVI Injection angle of (+)90.0 degrees

Negative Injection Angle of (-) 90 Degrees

Both the DVI-2 and DVI-4 nozzles have a negative injection angle of (-)90 degrees. The ECC water column injected through the DVI-4 nozzle is toward the bypass region between the broken cold leg and the cold leg-1 due to the momentum of the air jet stream from the cold leg-1 to the broken cold leg. When Fig. 7 (b) for (-)45 degree and Fig.9 (b) for (-)90degree are compared, the difference of the injection angle of ECC water makes differences in bypass modes. The penetration fraction of the DVI-4 water for (-) 90 degree is increased compared with those of ECC film.



(a) DVI-2: Opposite side of the broken cold leg (b) DVI-4 : Broken cold leg(B.C)

Fig.9 DVI Injection angle of (-)90.0 degrees

ECC Bypass at DVI-4

Fig. 10 shows the total bypass fraction induced by DVI-4 with the variation of the ECC injection angle. The maximum air velocity varies from 5 to 13 m/sec. The data indicated by square symbols in Fig. 10 represents that the variation of the ECC injection angle has no effect on the bypass fraction for the lowest air velocity of 5m/sec. It also shows that the bypass fraction is greatly affected by the ECC injection angle for both 10 and 13 m/sec. When the ECC injection angle has either 0 or (-)45 degrees, the ECC water column forms around the broken cold leg region. The region is a highly bypassed region. If the ECC water is injected with (+)45 degree, the ECC column forms near the wake region of hot leg which is the high penetration region. The difference in the total bypass fraction has more than 3 times between (-)45 and (+)45 degrees of injection angles. Fig. 10 shows that the effective ECC injection angle to reduce the ECC bypass fraction is a positive angle, i.e., toward the hot leg wake regions.

The DVI-4 nozzle between the broken cold leg and the hot leg blunt body is located at the right side of the broken cold leg with the relative attachment angle of 15 degrees. If the ECC injection has a positive angle toward the hot leg, the ECC water column is easily entrained into this wake region of the hot leg blunt body. However, when the ECC injection has a negative angle toward the broken cold leg, the ECC water column is easily bypassed through the broken cold leg. In the case of an ECC film induced by an ECC wall jet, which is injected vertically to the downcomer wall, the penetration and the bypass regions are shared at both sides of the broken cold leg. However, if the single ECC water column is injected into the downcomer region, the ECC water is not shared on both highly penetrated and bypassed region.

The upper wake region of two hot legs in the downcomer annulus has a downward velocity vector. Thus, the penetration occurs strongly in the wake region. When the ECC water column has an injection angle relative to the circumferential air (or steam) jet in the downcomer, the injection angle plays the most dominant role to the ECC bypass fraction.

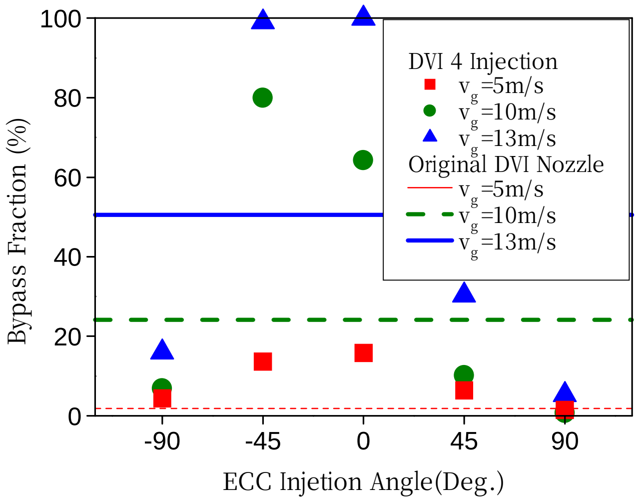


Fig.10 ECC bypass fraction with injection angle for DVI-4 nozzle

ECC Bypass at DVI-2

Fig. 11 shows the total bypass fraction induced by DVI-2 with the variation of the ECC injection angle. The maximum air velocity varies from 22 to 32 m/sec. In the region of the DVI-2 nozzle, the ECC bypass fraction is much lower compared with the DVI-4 region. The ECC water is broken-up by the air jet impingement of the cold leg-2 (CL-2), and is penetrated at both ends of the bowed edge. Fig.11 shows the ECC injection angle affects on the ECC bypass fraction even in the lower bypass region of cold leg-2 (CL-2).

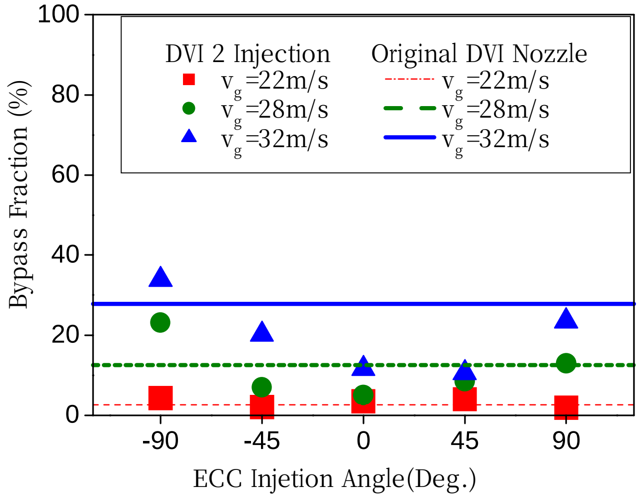


Fig.11 ECC bypass fraction with injection angle for DVI-2 nozzle(far from the broken cold leg)

<u>Combined Effects of DVI-2 and DVI-4</u>

Fig. 12 shows the ECC bypass fraction with combined injection of DVI-2 and DVI-4 nozzles under the variation of ECC injection angle. The range of the air injection velocity is from 10 to 22 m/sec. The constant bypass fraction range from (-)45 to (+) 45 degrees indicates that the DVI-4 nozzle has a high bypass fraction, typically larger than 80%, while the DVI-2 is fully penetrated. For the injection angle of (+)90 degrees, the bypass fraction has lower values for all air velocities in this study compared with the typical ECC injection which has a film shape. If the scaled steam velocity is less than 10 m/sec, the effective ECC injection angle to minimize the ECC bypass fraction is either (+)45 or ($\pm$)90 degrees. The ECC injection angle toward the hot leg is the most effective direction to reduce the ECC bypass fraction in the DVI injection system.

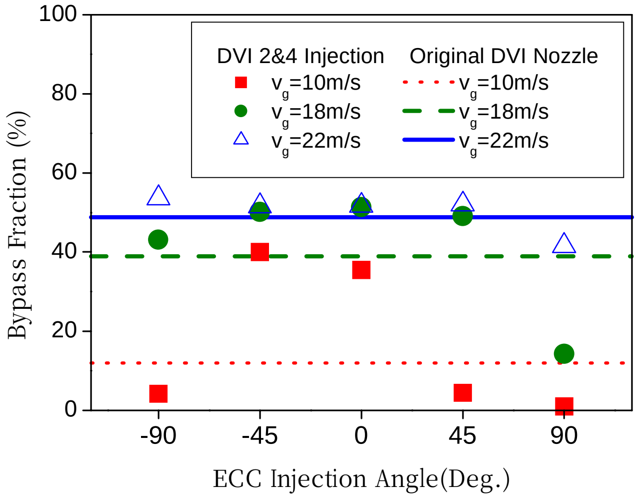


Fig.12 ECC bypass fraction with injection angle for DVI-2 & -4 nozzle

4. Summary And Conclusion

An experimental investigation on the effects of ECC injection angle on the direct ECC bypass has been performed on the variation of the air jet velocity, and the ECC injection angle. The major results show that (1) If the ECC water column is injected into the wake region which is induced by the hot leg blunt body in the downcomer annulus, the ECC bypass fraction is much reduced compared with the typical ECC injection which makes ECC film on the downcomer wall. At the same time, the ECC penetration toward the lower downcomer region becomes larger than those of typical direct vessel injection on the downcomer wall vertically. (2) If the ECC water column is injected to the broken cold leg, the ECC water is directly bypassed. Thus, the ECC penetration fraction is much reduced compared with the typical film type of ECC injection. (3) In order to minimize the ECC bypass fraction, the ECC water should be injected toward the wake region of the hot leg blunt bodies.

Acknowledgments

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References

(1) Sang hyuk Yoon, Kune Yull Suh, Byung Jo Yun, Chul- Hwa Song and Moon Ki Chung, "Jet Impingement width calculation for flat plate", Proc. the Korea Nuclear Society Spring Meeting, Pohang, Korea, May 1999.

(2) Chan Eok Park, Sang Yong Lee, Sang Il Lee, Chul Jin Choi, Sang Jae Kin, and Hee Cheon No, "An estimation of ECC Bypass during the reflood phase of a cold leg break LOCA in KNGR", Proc. the Korea Nuclear Society Spring Meeting, Pohang, Korea, May 1999.

(3) Do Hyun Hwang, Air-water Mixing experiments for direct vessel injection of KNGR, Master Thesis, KAIST, 1999.

(4) Byung Jo Yun, Tae Soon Kwon, Chul-Hwa Song, et al., “Experimental Observation on the Hydraulic Phenomena in the KNGR Downcomer during LBLOCA Reflood Phase”, Proc. the Korea Nuclear Society Spring Meeting, Kori, Korea, May 2000.

(5) Kyoo H. Bae, Tae Soon Kwon, Yong Jong Chung, Won Jae Lee, Hee Chul Kim, and Yoon Young Bae, “Pre-test Analysis for the KNGR LBLOCA DVI performance test using a best estimate code MARS”, NTHAS2: 2nd Japan-Korea symposium on Nuclear Thermal Hydraulics and Safety, Fukuoka, Japan, October 15~18, 2000.

(6) C.H. Song et al., “Thermal Hydraulic Test Program for Evaluating or Verifying the Performance of New Design Features in KNGR”, 2000 KNS Autumn Meeting, Korea Nuclear Society (2000).

(7) B.J Yun, H.K. Cho, T.S Kwon, C.H Song, J.K Park and G.C Park, "Experimental Observation of the Direct ECC Bypass during LBLOCA Reflood Phase in the Air/Water Test: UPTF Test 21-D Counterpart Test", ICMF-2001,LA, USA, 2001.

(8) Tae Soon. Kwon, B.J Yun C.H Song, J.K Park, "A Study on the liquid film width of ECC water jet for DVI injection", ICMF-2001,LA, USA, 2001.

(9) B.J Yun, T.S. Kwon, C.H Song, J.J Jeong ,"Scaling of the Direct ECC Bypass during LBLOCA Reflood Phase with Direct Vessel Injecion System", ICONE-9.

(10) B.J Yun, T.S. Kwon, C.H Song, G.C Park, "Experimental Study on the Film Spreading Width of ECC Water in the Downcomer with DVI under Late Reflood Phase of LBLOCA", KNS Spring Meeting, 2001/05/25.