Direct Vessel Injection Flow into Reactor Downcomer: Experiment and Analysis

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ABSTRACT

Experiments are performed to investigate the direct vessel injection (DVI) flow bypass in the Advanced Power Reactor 1400 MWe (APR1400) Emergency Core Cooling System (ECCS) during a large-break loss-of-coolant accident (LBLOCA). The DVI system is one of the salient features in the APR1400 design. Albeit a number of experimental and analytical studies were performed for the cold leg injection (CLI), it is relatively difficult to design the DVI system for the APR1400 due mostly to lack of readily applicable experimental data and code analysis. The flow behavior in the downcomer during the reflood phase is experimentally studied using the 1:10 linear scale model for the APR1400. The ECC water direct bypass rate is measured under the various air and water injection conditions. Results indicate that the bypass rate of the intact DVI line located near the break is considerably large and the initial conditions are important because of the spreading width of the liquid film. It is also found that the relation between the air and the ECC water velocities is the determining factor for the bypass rate.

INTRODUCTION

LOCA analysis for the DVI system is geared to optimizing the ECCS performance for the APR1400 [1]. The APR1400 is an advanced light water reactor (ALWR), whose design resembles the ABB-CE System 80+. The DVI system is firstly applied to the APR1400, while the involved thermal-hydraulic phenomena are not yet fully known. The ECC bypass in the reactor vessel downcomer is one of the unknown important hydraulic phenomena during a LOCA [2]. As the ECC water is injected directly into the reactor downcomer rather than through the cold leg, the steam condensation does not take place in the cold leg. as opposed to the case with the CLI. As the injection velocity and superheat of steam through the cold leg increases, the bypass of the ECC water will tend to increase through the break. In this situation the bypass mechanism will be different from the cold leg injection in the downcomer during a LBLOCA.

In the high steam velocity and the low water level, the direct bypass is a principal hydraulic phenomenon in the reactor downcomer. The direct bypass occurs in the whole downcomer when the ECC water injected vertically against the inner barrel interacts with the horizontal steam flow from the three intact cold legs to the broken cold leg. Figure 1 visualizes the ECC water film spreading downward and being broken by the air jet impingement.

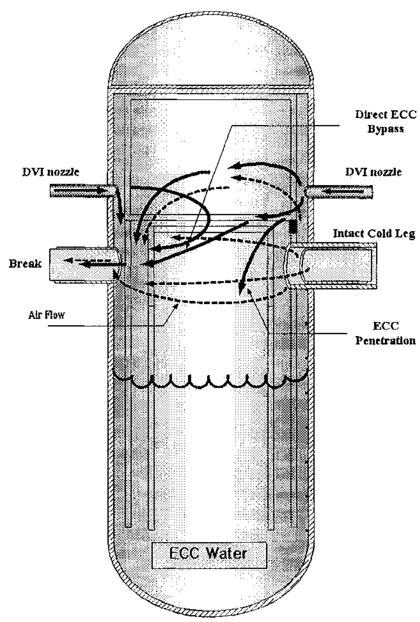

Fig. 1 ECC Water Direct Bypass During LBLOCA

In this study the bypass rate was measured given the water level which is pre-set at 0.38 m below the cold leg centerline, as the air and water velocities are changed. The results demonstrate the relations amongst the initial condition, the boundary condition and the geometry.

EXPERIMENTAL SETUP

The test vessel was built as a 1:10 linear scale-down model, which has four DVI nozzles, three cold leg nozzles, one break and two hot leg tubes [3]. To facilitate visualization, the reactor simulator was made of the cylindrical acryl, and the test fluids were air and water. As this facility was designed for the separate effect test of the direct bypass in the downcomer, the heat generating core was not included in the test vessel, and the hot leg nozzles were installed only as the barrier that interferes with the water and air flows. The major geometric data are provided in Table 1 in comparison to the APR1400 design parameters.

Table 1 Main Parameter and Scaling Ratio

Parameter	APR1400	Test facility	Ratio
Downcomer outer diameter (m)	4.623	0.46	1/10.05
Downcomer inner diameter (m)	4.115	0.41	1/10.04
Downcomer gap size (m)	0.25	0.025	1/10
Hot leg diameter (m)	1.067	0.1	1/10.67
Cold leg diameter (m)	0.762	0.076	1/10.03
DVI nozzle diameter (m)	0.216	0.022	1/9.82
DVI nozzle elevation (m)	2.108	0.21	1/10.04

The DVI, the cold leg and the hot leg nozzles were arranged as shown in Fig.2 and Fig. 3. The break was located in one of the cold legs. The water level transmitter and the control valve weare installed to maintain the water level in the simulator centerline and the lower plenum, respectively. Two air blowers were used to simulate the steam flow through the cold legs. Four vertical pumps, each having the maximum capacity of 80 ℓ /min, were employed to inject the water through the DVI nozzles. The amount of the bypassed ECC water was determined by measuring the total amount of the water injected from the four water tanks and the water drained from the lower plenum to maintain the water level in the core.

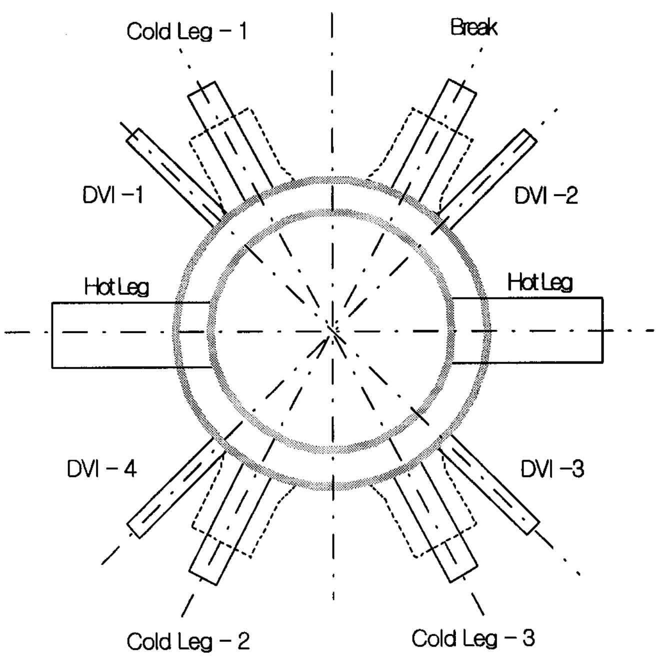

Fig. 2 Nozzle Arrangement

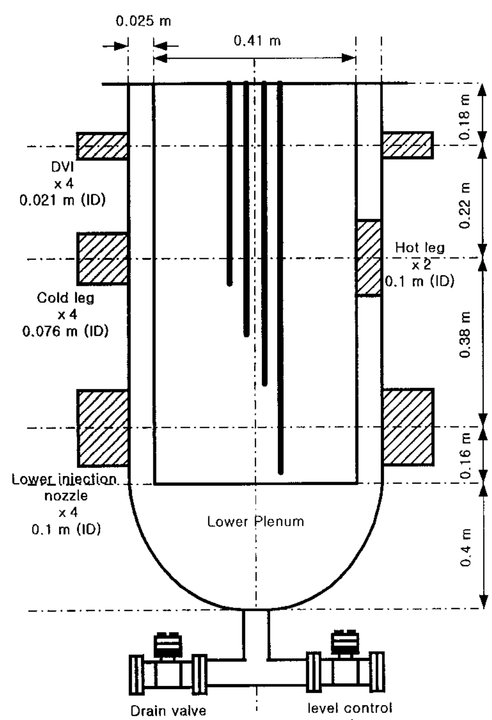

Fig. 3 Test Vessel Schematic Diagram

The input ranges of the ECC water and the air were 0 to 1.2 m/s per unit and 17 ~ 25 m/s per unit, respectively. The break pressure was fixed at the atmospheric pressure, while the system pressure was measured. Also, the air velocity meter and turbine flow meter, pressure gauge, thermometer, water level indicator were used to investigate the characteristics of the ECC bypass. The test facility is shown in Fig. 4 along with the instrumentation and control system.

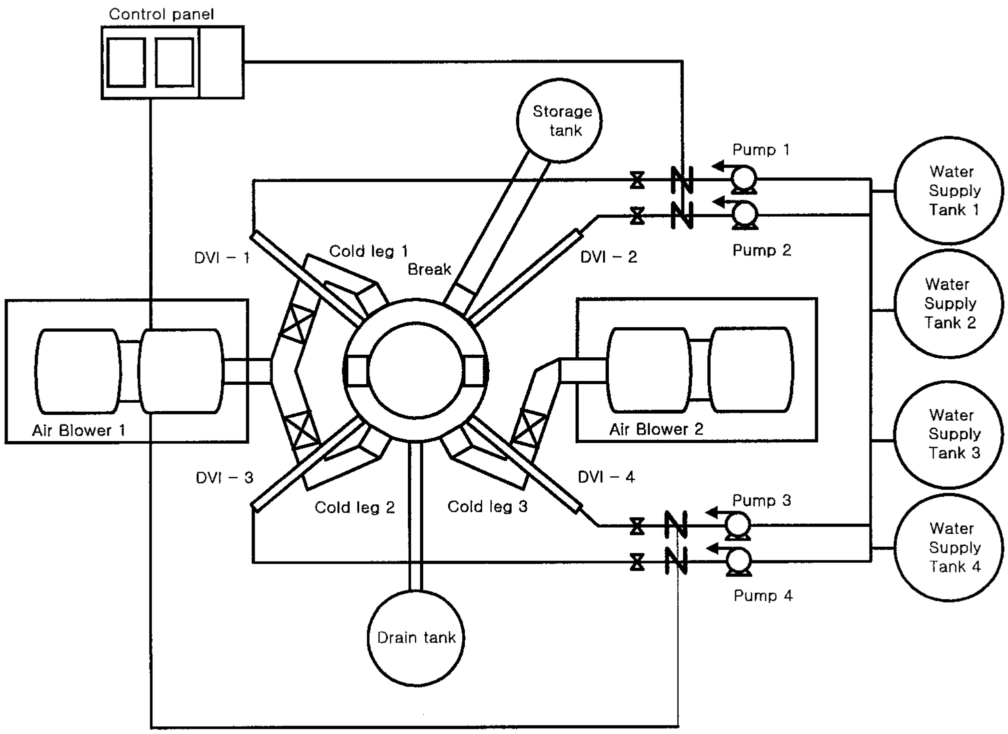

Fig. 4 Test Facility Schematic Diagram

The main variables were the DVI injection velocity and the air injection velocity. The amount of the bypassed water was measured at steady state during 60 s. The programmable logic controller controlled the whole data excepting the air velocity. The errors in the instruments are summarized in Table 2 [4].

Table 2 Measurement Uncertainties in the Instruments

Instrument	Location	Uncertainty (in reading)
Water velocity (m/s)	DVI	0.38 %
Air velocity (m/s)	Cold leg	2.0 %
Bypass (ℓ)	Collection Tank	0.87 %
Pressure (Pa)	Downcomer	0.5 kPa
Temperature (℃)	DVI	1.0 ℃

RESULTS AND DISCUSSION

In the experiment, the initial air velocity of 18 m/s was determined from the scaling of the APR1400 design value of 338.6 m^3/s. The air velocity was increased to 24 m/s tantamount to 33 % addition to the initial value for sensitivity analysis. The ECC water velocity was changed for the sensitivity analysis from 0.5 m/s to 1.2 m/s. The first case of the test involved the single failure that can occur because of the connecting structure of the ECC system in the APR1400. The initial water level was maintained at 38 cm below the cold leg in all the tests that follow.

Results are collected in Table 3 for the ECC water injection through the DVI lines 1 and 3 working while the other two remaining out of service. It is seen that as the ECC water velocity increases, the bypass ratio, i.e. the amount of bypass divided by the amount of total injection, decreases given the air velocities of 18 m/s and 24 m/s. The reason for the bypass ratio decrease is that the downward and opposite flows of the ECC water through the DVI lines 1 and 3 increase.

Results are presented in Table 4 for the DVI lines 2 and 4 operating while the other two inoperational. At the air velocity of 18 m/s, the bypass ratio decreases, if the injected ECC water velocity increases. But at the air velocity of 24 m/s, the bypass ratio does not decrease, because the DVI 2 is located nearest to the break. As the air velocity increases, the ECC water through the DVI 2 mostly bypasses. Therefore, the bypass ratio of the DVI lines 2 and 4 is larger than that of the DVI lines 1 and 3. The bypass ratio turns out to be similar between Tables 3 and 4 at the air velocity of 24 m/s. This is because the considerable amount of the ECC water through DVI 2 bypasses, while the bypass from the DVI lines 1 and 3 is similar but not the same.

Results are summarized in Table 5 for the four DVI lines delivering the ECC water simultaneously. At the air velocity of 18 m/s, the bypass ratio increases, because the amount of the ECC water through the DVI line 2 increases. In contrast, the bypass ratio decreases at the air velocity of 24 m/s, because the total amount of the injected ECC water increases in comparison to the air bypass capacity.

Table 3. Results for DVI 1 and 3 Operating Condition

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Temperature (℃)	8	8	7.8	8	8	8.2
System pressure (kPa)	7.84	7.84	7.84	17.65	18.63	18.63
DVI - 1 velocity (m/s)	0.70	0.80	1.03	0.65	0.68	0.93
DVI - 2 velocity (m/s)	0	0	0	0	0	0
DVI - 3 velocity (m/s)	0.80	0.95	1.15	0.75	0.8	1.05
DVI - 4 velocity (m/s)	0	0	0	0	0	0
Total water injection (ℓ)	33.3	38.67	48	30.67	32.89	43.56
Cold leg-1 velocity (m/s)	18	18	18	25	25	25
Cold leg-2 velocity (m/s)	17.5	17.5	17.5	24.5	25	24
Cold leg-3 velocity (m/s)	17.5	18	17.5	24.5	24.5	23.5
Total bypass (ℓ)	5.18	5.46	4.84	15.59	15.59	19.78
Direct bypass ratio (%)	15.54	14.13	10.28	50.83	47.41	45.4

Table 4. Results for DVI 2 and 4 Operating Condition

	Test 1	Test 2	Test 3	Test 4
Temperature (℃)	8	8	8	8
System pressure (kPa)	7.84	7.84	19.13	18.63
DVI - 1 velocity (m/s)	0	0	0	0
DVI - 2 velocity (m/s)	0.79	0.93	0.89	1.15
DVI - 3 velocity (m/s)	0	0	0	0
DVI - 4 velocity (m/s)	0.65	0.79	0.75	1.01
Total water injection (ℓ)	31.56	37.78	36.0	47.56
Cold leg-1 velocity (m/s)	18	18	25	25
Cold leg-2 velocity (m/s)	17.5	17.5	24	24
Cold leg-3 velocity (m/s)	17	17	24	24
Total bypass (ℓ)	8.27	7.89	15.48	21.59
Direct bypass ratio (%)	26.22	20.87	43.01	45.40

Table 5. Results for DVI 1, 2, 3 and 4 Operating Condition

	Test 1	Test 2	Test 3	Test 4
Temperature (℃)	11.8	8.5	9	8
System pressure (kPa)	9.8	9.8	18.63	18.63
DVI - 1 velocity (m/s)	0.77	0.95	0.40	0.97
DVI - 2 velocity (m/s)	0.97	1.15	0.67	1.17
DVI - 3 velocity (m/s)	0.83	1.15	0.59	1.07
DVI - 4 velocity (m/s)	0.99	1.05	0.47	0.99
Total water injection (ℓ)	78.22	94.67	46.67	92.44
Cold leg-1 velocity (m/s)	17.5	17.0	25.0	23.0
Cold leg-2 velocity (m/s)	17.0	16.5	24.0	23.0
Cold leg-3 velocity (m/s)	18.0	17.0	24.0	22.0
Total bypass (ℓ)	9.27	21.25	21.82	40.72
Direct bypass ratio (%)	11.85	22.44	46.76	44.05

Figure 5 shows the bypass ratio into the break through each of the four DVI nozzles. Individual bypass flow rates were measured for each DVI line utilizing ions in the supply tank. The four positive ions, i.e. NH_3^+, Na^+, K^+ and Ca^{+2}, were separately dissolved in each of the water tanks. After the test, the ion electrode was used to measure the concentration of each ion. Because each bypass ratio is proportional to the ion concentration and each ion does not interfere with each other, one can readily determine the bypass rate for the known injection quantity. Also, it was observed from the tests that the air barrier effect manifests itself as shown in Fig 5. Because of the geometric arrangement in which the DVI line 3 is located right on the air flow path from the cold leg 3 to the break, more water was seen to bypass from DVI 3 to the break than from DVI 1 whose injection flow was being interrupted by the incoming air flow from the adjacent cold leg 1.

In the current tests the air took the place of the steam expected in the reactor downcomer. As use of the noncondensible air may be more conservative than utilizing the condensable steam from the standpoint of the ECC water bypass, the real bypass ratio will tend to be less than the above results. In the reactor condition the condensation effect of the steam and the spreading liquid film will exert a direct impact on the path of the DVI injection flow so that the additional tests must be accounted for in the analysis of the complex mechanism of bypass versus penetration in the reactor downcomer.

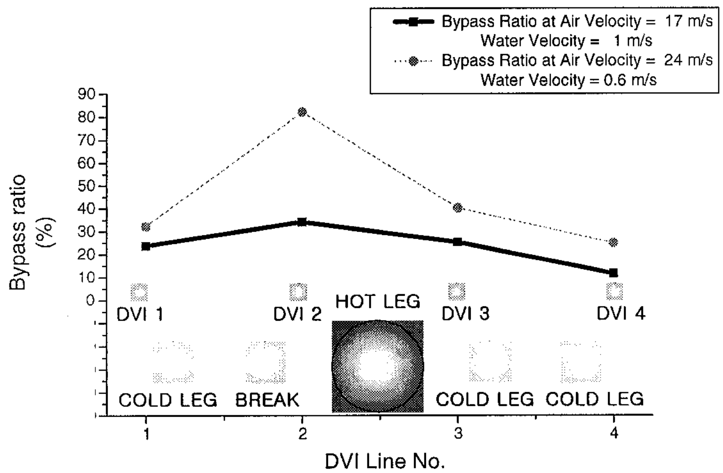

Fig. 5 Bypass Ratio for Each DVI nozzle

CONCLUSIONS

Tests were performed to simulate the direct bypass phenomena in the APR1400 downcomer. The test results shed light on the hydraulic behavior of the ECC water in the downcomer during a LOCA. The conclusions from this study may be summarized as follows.

- For the cases of the DVI lines 1 and 3, the DVI lines 2 and 4, and all four DVI lines, the hydraulic characteristics are different in respect of the bypass rate. Overall water from the DVI nozzles closer to the break tends to more easily bypass through the break together with the air.
- The increase of the ECC water does not necessarily decrease the bypass ratio.
- The air barrier exists because of the geometry arrangement of the DNI lines relative to the break in the cold leg.
- As the ECC injection velocity increases, the region where the bypass ratio decreases exists as well as the region where the bypass ratio increases. These regions may be determined by the spreading liquid film and breakup effects.
- A limiting value exists for the maximum capacity of air to entrain water above which point the injected water begins to penetrate more easily into the reactor downcomer.

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