Journal of the Korean Nuclear Society
Volume 34, Number 5, pp.421~432, October, 2002

Direct ECC Bypass Phenomena in the MIDAS Test Facility During LBLOCA Reflood Phase

B.J. Yun, T.S. Kwon, D.J. Euh, I.C. Chu, W.M.Park, C.H. Song, and J.K. Park
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yuseung-gu, Daejeon 305-353, Korea
bjyun@kaeri.re.kr

(Received October 24, 2001)

Abstract

As one of the advanced design features of the APR1400, direct vessel injection (DVI) system is being considered instead of conventional cold leg injection (CLI) system. It is known that the DVI system greatly enhances the reliability of the emergency core cooling (ECC) system. However, there is still a dispute on its performance in terms of water delivery to the reactor core during the reflood phase of a large-break loss-of-coolant accident (LOCA). Thus, experimental validation is under progress. In this paper, test results of direct ECC bypass performed in the steam-water test facility called MIDAS (Multi-dimensional Investigation in Downcomer Annulus Simulation) are presented. The test condition is determined, based on the preliminary analysis of TRAC code, by applying the 'modified linear scaling method' with the 1/4.93 length scale. From the tests, ECC direct bypass fraction, steam condensation rate and information on the flow distribution in the upper annulus downcomer region are obtained.

Key Words : DVI, reflood, direct bypass, APR-1400, modified linear scaling method

1.Introduction

Multi-dimensional steam-water thermal-hydraulic behavior, such as ECC bypass, ECC penetration, steam-water condensation and accumulated water level, in the downcomer annulus of the APR1400(Advanced Power Reactor) which has 1400 MWe with a DVI mode during LBLOCA is currently being studied [1,2,3,4]. Major technical issues related to the downcomer thermal hydraulics of a PWR with a DVI mode, of which the injection nozzles are located 2.1m above the centerline of the cold leg, include ECC bypass fraction, steam condensation, temperature distribution, subcooling margin, and collapsed water level in the downcomer.

Analysis by both evaluation models and a best estimate code under the same conditions show differences in predicting major parameters such as the downcomer collapsed water level and a peak cladding temperature during the reflood phase of LBLOCA[2]. Because of these differences, experimental data to evaluate and validate the analysis tools as well as to understand the downcomer thermal hydraulics are needed.

The UPTF TEST 21-D is the only available test for the DVI injection mode under LBLOCA reflood phase. The analysis of that data indicated that 40~50% of the injected ECC water was directly bypassed to the broken cold leg [5]. However, major findings from the UPTF tests cannot be directly applicable to the APR 1400 due to the different geometries of the downcomer and flow conditions.

For these reasons, a series of tests were progressed using the MIDAS test facility in KAERI with focused on the steam-water thermal hydraulics inside the reactor vessel downcomer with the DVI injection mode, during the reflood phase of LBLOCA.

In this paper, the test results of direct ECC bypass are presented. To investigate the effect of DVI injection nozzle location to the direct bypass fraction, separate effect tests have been performed in case of DVI-2 (farthest from broken cold leg) injection, DVI-4 (closest to broken cold leg) injection, and DVI-2&4 injection, respectively. The tests are carried out in a wide range of steam flow rates to investigate the effect of steam flow rates on the direct bypass fraction of ECC water. From the test data, the information on the thermal hydraulic behavior of ECC water and superheated steam in the upper annulus downcomer is obtained.

2. Test Facility

2.1. Fluid System

The MIDAS is a steam-water separate effect test facility, which is scaled down from a 1400 MWe PWR type of nuclear reactor. It is mainly focused on the investigation of the multi-dimensional thermal-hydraulic phenomena in the downcomer annulus with various types of safety injection during the refill or reflood phase of a LBLOCA (Large Break Loss-of-Coolant Accident).

The MIDAS is scaled down basically based on the volumetric scaling law[6] even though the standard linear scaling law[7] or modified linear scaling law[8,9] can also be applied by installing a removable blockage at the upper annulus downcomer gap. It is aimed at investigating the effect of scaling laws. The scaling ratios are 1/24.3 and 1/4.93 relative to the APR-1400 for the volumetric scaling law and standard/modified linear scaling laws, respectively. The maximum allowable operating conditions of the MIDAS are 10 bars in pressure and 300 ℃ in temperature.

The MIDAS is an open loop type of test facility and it consists of a downcomer simulator, four cold legs, two hot leg nozzles, a core barrel simulator, a containment simulator with a steam-water separator, four HPSI(High Pressure Safety Injection) simulators, four SIT(Safety Injection Tank) simulators, and an external steam supply system. The isometric arrangement of major components is shown in Fig. 1, and the details of cold legs and the configuration of the direct vessel injection nozzles are shown in Fig.s 2 and 3. By

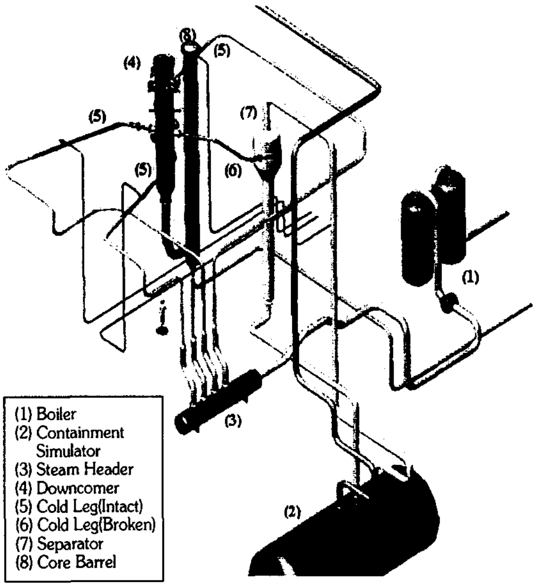


Fig. 1. Isometric View of the MIDAS Facility

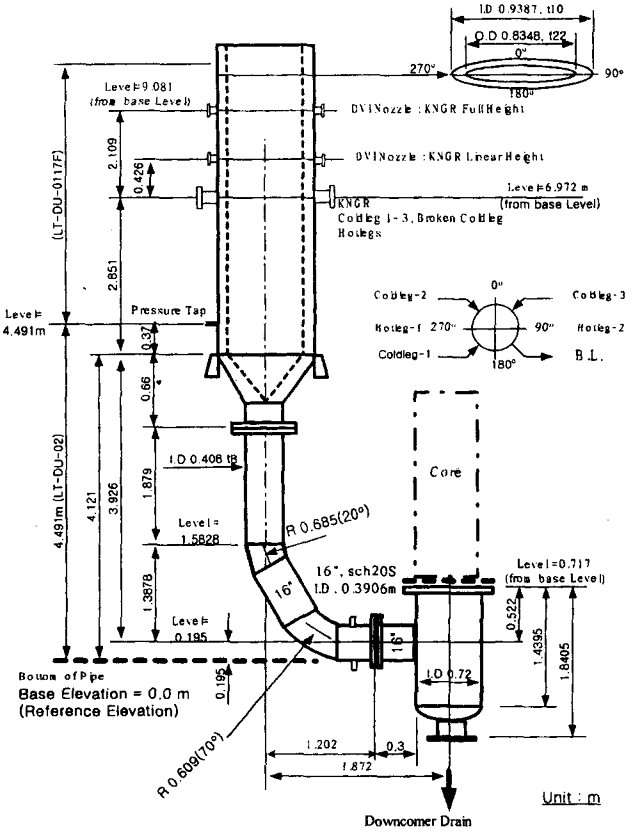


Fig. 2. Sketch of the Downcomer

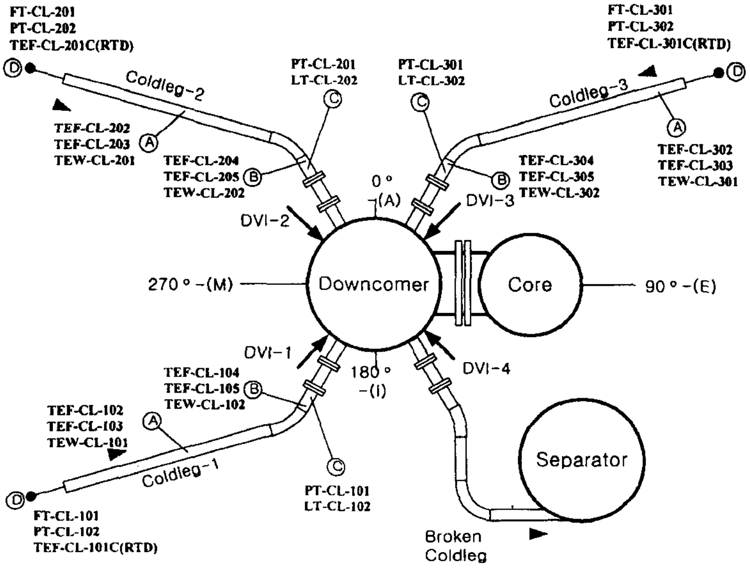


Fig. 3. Top View of the Test Facility Arrangement and Instrumentation Location

separating the downcomer annulus and core regions in the MIDAS test facility, as shown in Fig. 2, it makes easy to enhance the accessibility of instrumentation to both inside and outside walls of the downcomer region. The upper and middle section of the downcomer, starting from 2.8 m below the cold leg elevation, is designed as an annulus type, whereas the lower part of downcomer is designed as a single pipe which is connected to the core barrel simulator. In this experiment, thermal-hydraulic interaction between the core and downcomer regions is intentionally eliminated by installing a removable plate at the inlet of the core barrel simulator in order to well establish the steady-state flow behavior in the downcomer.

The steam is supplied from a steam boiler and a super heater. Saturated or superheated steam can be delivered in the pressure range of 2-10 bars and it can be superheated to the maximum temperature of 300 ℃ at a given pressure.

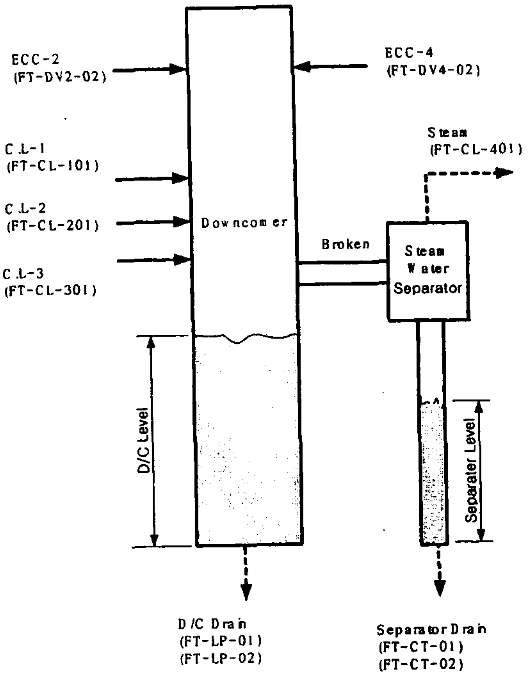


Fig. 4. Inflow and Outflow of Downcomer

2.2. Instrumentations

Typical instrumentations in the cold legs are shown in Fig. 3. The flow paths from or to the fluid system consist of steam injection from three intact cold legs, ECC injection flow through the DVI nozzle, the downcomer lower drain, steam discharge flow from the steam-water separator and water drain from the separator, as shown in Fig.4. The steam flow rates at each intact cold leg and the separator outlet are measured by a combination of vortex flow meter, K-type TC, and pressure transmitter. The ECC inflow is measured by a combination of turbine flow meter, K-type TC and pressure transmitter. The water drain flow rate out of the downcomer and separator are measured mainly by Coriolis true mass-flow meter and it is also measured by a combination of turbine flow meter, K-type TC and pressure transmitter. The former is for the measurement of high flow condition and the latter is for the measurement of low flow condition. The water levels at the downcomer and the separator are measured by differential pressure transmitters. The downcomer water level is measured at four locations, which are 90 degree apart around the circumferential angle, respectively.

The total break flow is estimated as the sum of both the steam and water flows at the steam-water separator and the accumulated water in the separator and downcomer. In order to reduce the measurement error of accumulated water inside the separator at low flow injection mode, a dummy pipe with 508mm in outer diameter and 3.3 m in length is installed inside the lower part of the separator.

To estimate steam condensation and flow distribution in the annulus downcomer region, many K-type TCs are installed. The TCs are

Table 1. Scaling Ratio of the "Modified Linear Scaling Law"

Parameter	Scale Ratio	MIDAS
Length Ratio	l_R	1/4.9
Area Ratio	l_R^2	1/24.3
Volume Ratio	l_R^3	1/119.8
Time Ratio	$l_R^{1/2}$	1/2.2
Velocity Ratio	$l_R^{1/2}$	1/2.2
Flow Rate Ratio	$l_R^{5/2}$	1/54.0
Temperature & Pressure Ratio	--	1/1

Table 2. Uncertainties of Major Measuring Parameters

Parameter	Uncertainty
Steam Flow Rate (kg/s)	Less than 1.3 % of Reading
Water Flow Rate (kg/s)	Less than 0.5 % of Reading
Bypass Fraction	0.055 for Less than 10% 3% of Reading for more than 10%
Condensation Fraction	Less than 12% of Reading
Mass Balance Error	±0.05
Energy Balance Error	±0.05
Wallis Number($J^*_{g,eff}$)	Less than 1.5 % of Reading
Absolute Pressure (Pa)	1.0 kPa
Water Level(m)	0.025
Temperature (℃)	2.85 ℃

positioned at each 22.5 degree along the circumferential direction and 496mm spaced along the axial direction in the downcomer annulus. At each location, three TCs are installed to the radial direction and thus the temperature of falling film temperature of ECC water both inner and outer walls and steam temperature at the center of downcomer can be measured. At the regions like a lower part of downcomer in which a single-phase flow is expected to exist apparently, a single thermocouple is installed at the center of the annulus gap. The uncertainties of major measuring parameters are summarized in Table 2.

3. Test Condition

The tests are carried out with the assumption a single failure of ECCS. ECC water is injected into the downcomer through two safety injection nozzles (DVI-2&4 shown in Fig. 3), which are located at the farthest(DVI-2) and the nearest(DVI-4) regions from the broken cold leg (cold leg-4), respectively.

The major experimental conditions are determined from the preliminary calculation results of TRAC code[10]. The applied scaling law is 'modified linear scaling methodology' [9,10] which has the same geometrical similarity with that of linear scaling law, however, its flow conditions such as mass flow rates, velocities are reduced to the power law of length scale. Major scaling ratios of 'modified linear scaling law' and MIDAS test facility are summarized in the Table 1 and detailed derivation of scaling law and its validation is found in the literature[9,10].

The initial and boundary conditions of the tests correspond primarily to those of 250 sec after the initiation of LBLOCA, however, the tests are performed to the extended range of steam mass flow rate. It is for the parametric study to investigate the effect of steam flow rate on the ECC water behavior, degree of subcooling and ECC direct bypass fraction in the downcomer annulus.

The downcomer water level is maintained 2.0 m below the center line of cold leg by controlling the water drain flow rate at the bottom of downcomer. The data analysis performed after the tests show downcomer water level is well maintained constantly and thus water level change is negligible.

The most appropriate water level at the downcomer for the direct bypass test is just below the onset of entrainment point due to sweep out, which is basically entrainment phenomena, starts at that point. The sweep out phenomena in the downcomer is similar with the T-junction entrainment phenomena in the horizontal pipe flow condition. The separate effect test performed in the air/water flow condition shows the onset of entrainment point exists three or four times below of cold leg diameter in the nominal accident condition[4]. From the tests, we concluded that the present water level is sufficiently low so that the sweep out of accumulated water from the below of cold leg elevation is excluded during the tests of nominal and extended steam flow rates. These low water levels can result in the increase of steam condensation rate it affects direct ECC bypass fraction compare to actual accident condition.

In the all of the tests, the downcomer pressure, steam temperature and ECC water temperature are set to be about 1.7bar, 200 °C and 49.4 °C , respectively.

Tests have been performed for the cases of DVI-2 nozzle injection only, DVI-4 nozzle injection only, and the combination of DVI-2&4 injection nozzles, respectively. It is to investigate the effect of the DVI nozzle location on the direct ECC bypass fraction.

Before the tests, the structure of each component is heated until the wall temperature is reached to the saturation temperature by steam injection through the intact cold legs. The measured data of wall temperature shows the wall temperature of downcomer is maintained saturated temperature during tests. It shows the external heat loss can be assumed to be negligible during the tests.

4. Experimental Results and Discussion

The test commences after a steady state condition is reached and data is acquired for 600 seconds for each test. The secondary measurement parameters such as mass balance error, energy balance error, bypass or penetration fraction of ECC water and steam condensation fraction are obtained from the measured data after the tests.

4.1. Conservation of Mass and Energy

Mass balance error in the downcomer, which considers the steam and ECC water injected into the system and the drain and break flow, is defined as follows

$$\text{Mass Balance Error} = \frac{m_{Total,in}(t) - m_{Total,out}(t)}{m_{Total,in}(t)} \qquad (1)$$

Fig. 5 shows the mass balance error for all data. In the figure, the data are averaged for 600 seconds. The average mass balance error observed in this experiment is less than 4 %.

Energy balance error in the downcomer, which considers the energy flows of steam flow, ECC water flow and the drain and break flow, is defined as follows

$$\text{Energy Balance} = \frac{e_{Total,in}(t) - e_{Total,out}(t)}{e_{Total,in}(t)} \qquad (2)$$

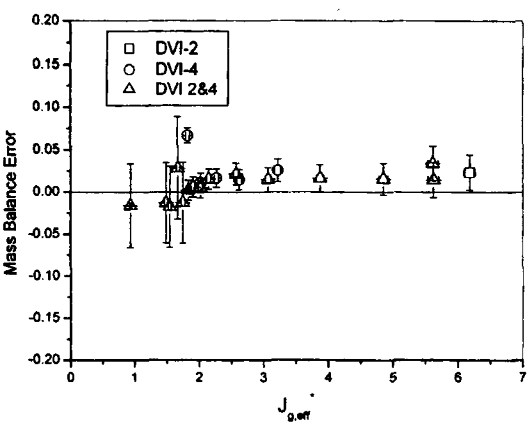


Fig. 5. Mass Balance Error of Tests

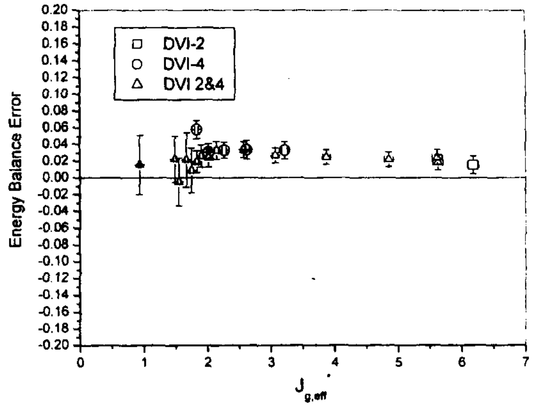


Fig. 6. Energy Balance Error of Tests

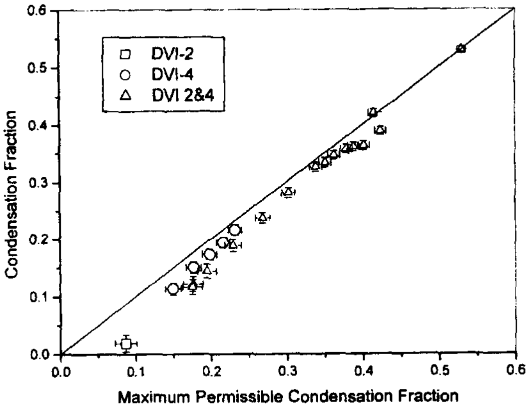


Fig. 7. Condensation Fraction vs. Maximum Permissible Condensation Fraction

Fig. 6 shows the energy balance error for all data. As shown in the figure, the average energy balance error of all measured data is less than 5 %. In this calculation, as stated in the previously, the stored energy in the structures was neglected. These small errors of mass and energy balance confirm that the test conditions are well established and instrumentations are working well during all of the tests.

4.2. Steam Condensation Rate

A large amount of injected superheated steam into the downcomer through three intact cold legs is condensed because of interfacial heat transfer between cold ECC water and high temperature steam in the downcomer. Theoretically, the steam condensation can be continued theoretically until the temperature of ECC water becomes saturation temperature at the system pressure. It can be defined as a maximum permissible condensation rate.

In the present tests, steam condensation fraction is directly calculated from the measured steam flow rates at three intact cold legs and the separator as in Eq.(3).

$$\text{Steam Condensation Fraction} = 1 - \frac{m_{FT\text{-}CL\text{-}401}(t)}{m_{FT\text{-}CL\text{-}101}(t) + m_{FT\text{-}CL\text{-}201}(t) - m_{FT\text{-}CL\text{-}301}(t)} \quad (3)$$

Fig.7 shows that the condensation fraction in the direct ECC bypass tests are slightly lower than maximum permissible condensation fraction. It should be noted that the downcomer water level is maintained at a lower level enough to minimize the sweep-out at the lower part of the downcomer and then it makes increase in the steam condensation rate.

4.3. Direct ECC Bypass Rate

The direct ECC bypass fraction is calculated from ECC injection flow rates, steam condensation rate and drain flow rate at lower downcomer as follows

$$\text{Bypass Fraction} = 1 - \frac{m_{FT\text{-}LP\text{-}02}(t)}{m_{Total,ECC,in}(t) + m_{FT\text{-}CL\text{-}1,2,3}(t) - m_{FT\text{-}CL\text{-}401}(t)} \quad (4)$$

To investigate the effect of steam flow rate, the data is presented to the effected steam Wallis number which is defined in the downcomer as follows[8,9,10]

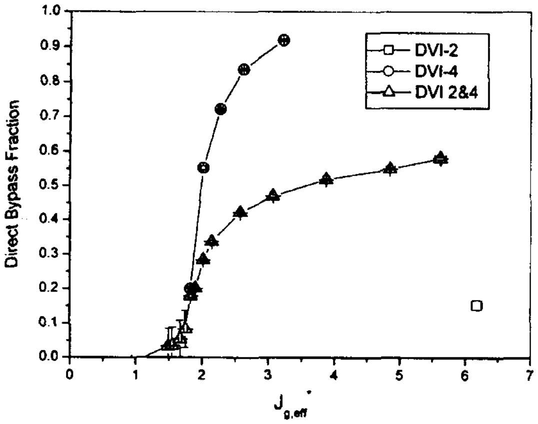


Fig. 8. Bypass Fraction to the Effective Wallis Number

$$j_{g,eff}^{*} = \frac{m_{g,eff}}{\rho_g \cdot A_{Flow}} \left[\frac{\rho_g}{(\rho_f - \rho_g) \cdot g \cdot L_{DC}} \right]^{1/2} \qquad (5)$$

Fig.8 shows the direct ECC bypass fraction to the effective Wallis parameter. Test results show that the direct bypass fraction of ECC water depends significantly on effective steam Wallis number. It is the same result with that of air/water test[4]. Single injection test with the DVI-4 only shows that the direct bypass fraction increases drastically as the effective steam Wallis number increases. The single injection test of DVI-2 shows about 85% of injected ECC water penetrates into the lower downcomer even though the injected steam mass flow rate is five or six times greater than in the case TRAC results of nominal accident condition. It explicitly shows that most of the injected ECC water through the farthest located DVI nozzle from the broken cold leg can be delivered to the lower downcomer region in the LBLOCA.

In the case of both DVI-2&4 injections, the trend of direct bypass fraction follows the combination of those of each single injection tests.

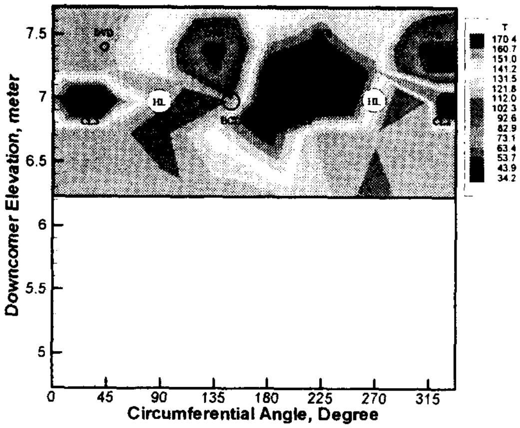
4.4. Temperature Distribution in the Downcomer

To see the behavior of ECC water and steam in the annulus downcomer region, contour plots of temperature for two typical cases of DVI 2&4 injection are presented in Figs.9 and 10. The flow condition of the two data sets simulates that of at 200-260 seconds after initiation of LBLOCA and it is summarized in the Table.3. The test name of Figs. 9 and 10 is 'MIDAS-KM-107' and 'MIDAS-KM-106' , which are for the case of low and medium ECC direct bypass fraction, respectively.

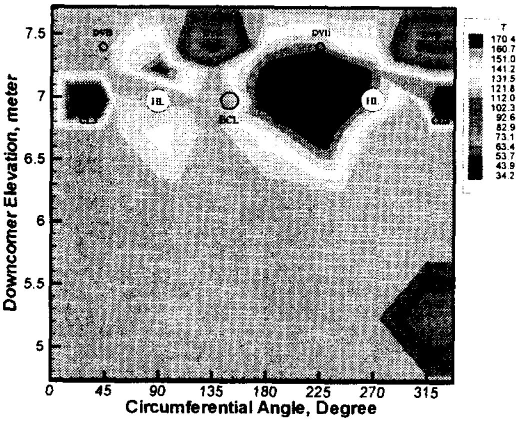
The figures show complicated flow patterns in the downcomer region, as also found in the air/water test[4]. We found from the air/water test when the ECC water is injected into the downcomer annulus through the DVI nozzles it forms a round jet and impinges and spreads out on the core barrel wall[4]. Figure 9(a) and 10(a) confirm the water film formation of ECC water on the core barrel wall as found in the air/water test. It shows that the water temperature increases rapidly by steam condensation and most of the steam condensation occurs in the near the CL-2 nozzle located opposite side of broken clod leg.

Table 3. Flow Condition of MIDAS-KM-105 & MIDAS-KM-107

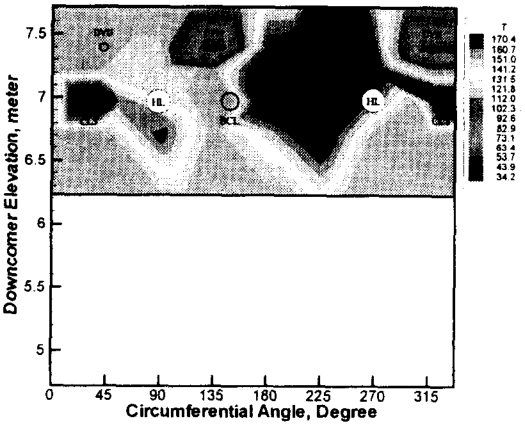
Parameter	MIDAS-KM-105	MIDAS-KM-107
Steam Injection Flow Rate (kg/s)	0.309 x 3(ea)	0.27 x 3(ea)
Bypass Fraction	0.337	0.083
Condensation Fraction	0.326	0.362



(a) Inner Wall

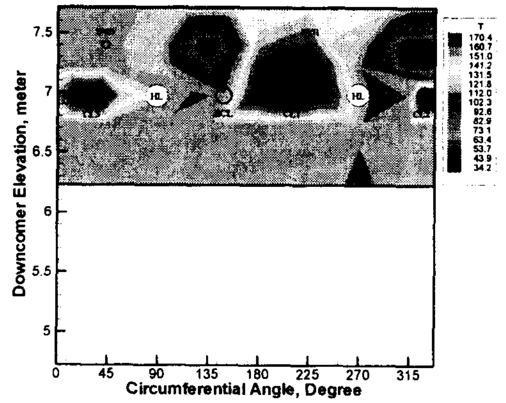


(b) Center Line

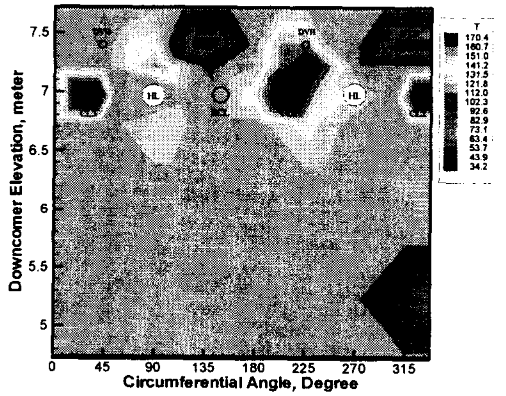


(c) Outer Wall

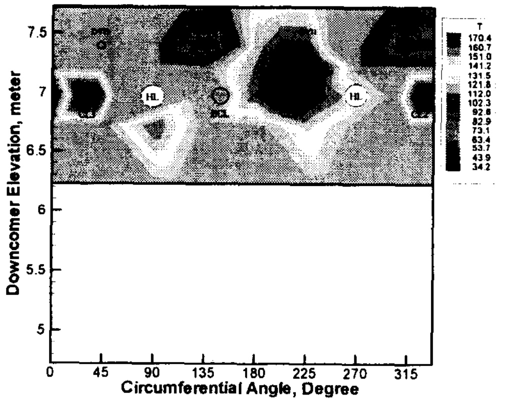
Fig. 9. Isothermal Line in the Downcomer Annulus(MIDAS-KM-107)



(a) Inner Wall



(b) Centerline



(c) Outer Wall

Fig. 10. Isothermal Line in the Downcomer Annulus(MIDAS -KM-105)

However, steam injected from the CL-1 is not condensed abruptly as in the case of CL-2&3. There are local penetration regions around the two hot legs. It plays a roll of flow path of ECC water to the lower downcomer. The local penetration region(cold region) around these two hot leg nozzles, as observed already in air-water experiment[4], results from the blockage effect of them. When a stagnation region is formed around the hot leg nozzles along the steam jet cross flow, ECC water near the stagnation region is penetrated well toward the lower downcomer. Fig.10(a) shows the penetrated water flow rate through them decreases as the steam flow rate increases.

Figs. 9(b) and 10(b) shows most of the ECC water reached to saturation temperature at the elevation of clod leg. It means large interfacial area of ECC water in the center of downcomer gap and thus flow pattern of this region may be annular wispy flow differently with that of outer wall. This flow pattern is also found in the visualized air/water test[4]. A larger cold region below the cold leg-2 nozzle is observed, which is located at the opposite side of the broken cold leg. It tells us again that a high ECC penetration is occurred by a blockage effect of hot leg and relatively weak cross flow effect because this region is located at the opposite side of the broken cold leg.

Figs. 9(c) and 10(c) shows that the temperature distributions near the outer downcomer wall. The flow pattern on the out wall is turned out to be film flow in the air/water test and the thickness of water film is very thin compared to that of inner wall[4]. The plot shows most of the steam condensation near the CL-1 occurs in the core barrel wall and downcomer gap. It is mainly due to the small mass flow rate of ECC water in these regions.

From the experimental observations, a highly complicated multi-dimensional flow patterns are observed in the annulus downcomer where both the superheated steam injected through the cold legs and the ECC water injected from DVI nozzles exist. It was also found that the proximity of ECC injection nozzle to the break and the increase in steam flow result in more ECC bypass. In addition, the hot leg nozzles inside the downcomer play a roll to enhance the ECC penetration into the lower downcomer region.

5. Usefulness and Applicapility of Data

Before the present test, UPTF Test-21-D is the only available data for the DVI mode under the reflood phase of LBLOCA. However, the arrangement and location of DVI nozzles of UPTF are different with those of APR 1400. That is, the number of DVI nozzles is 2 and 4 and their elevation is 0.35 m and 2.1m above from the centerline of cold leg in the UPTF and APR 1400, respectively. These differences result in some differences in the thermal hydraulic phenomena. In the UPTF, ECC water is injected in the jet impingement region of steam injected from cold legs, whereas, in case of APR1400, ECC water is injected in the upper outside region of that of APR 1400. And thus there are more chances to interact between the two fluids in the upper annulus downcomer region of APR 1400.

The present test is carried out in the test facility simulated APR 1400 and thus it gives unique and valuable data on the ECC bypass and steam condensation in the upper annulus downcomer under the DVI mode. The present data can be used for the development and validation of best estimate safety analysis computer codes such as RELAP5, MARS and TRAC. And it can be also used to estimate the direct ECC bypass fraction in the prototype reactor using the modified linear scaling law if the flow condition of APR 1400 is well known.

6. Conclusions

Experimental study for direct ECC bypass phenomena has been carried out under the reflood phase of LBLOCA with DVI system. The test is performed in the MIDAS test facility, which is a scaled-down model of APR1400. The experimental condition is determined by 'modified linear scaling law' which has the same geometrical similarity with linear scaling law, however, the velocity and mass flow rate are scaled to the length ratio. To determine the test conditions, pre-test calculation results of TRAC are used.

The test shows that mass and energy balance errors are less than few percent. The injected steam is condensed in the upper annulus downcomer and the condensation fraction is slightly lower than maximum permissible condensation fraction.

The direct ECC bypass fraction of single DVI injection tests show that it is highly dependent on the distance between broken cold leg and DVI injection nozzle. In the test, the direct ECC bypass fraction of DVI-4 is drastically increased as the effective steam Wallis number increases whereas in DVI-2 test most of the injected ECC water penetrates into the lower downcomer region. In case of DVI-2&4 injections, the trend of direct bypass fraction follows the combination of both trends observed from the each single injection test. The temperature contour in the downcomer shows a multi-dimensional thermal-hydraulic behavior in the downcomer annulus region. It is also observed that the downcomer in which both the superheated steam injected through the cold legs and the ECC water injected from DVI nozzles have a highly complicated multi-dimensional flow patterns including a blockage effect of the hot leg nozzles, interaction of downward water flow and *transverse steam flow* and direct contact condensation.

Nomenclature

A : Flow area
e : Power (J/s)
g : Gravity Constant
l_R : Length ratio
m : Mass Flow Rate (kg/s)
$m_{g,eff}$: Effective steam flow rate (kg/s)
L_{DC} : Characteristic length of downcomer
t : Time

Subscript

CL : Cold leg
f : Water
FT : Flow meter
g : Steam
in : In-flow
out : Out-flow

Acknowledgement

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

References

1. 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).
2. K.H. Bae et al., "Pre-test Analysis for the KNGR LBLOCA DVI Performance Test Using a Best Estimate Code MARS", NTHAS2: Second Japan-Korea Symposium on Nuclear Hydraulics and Safety, Fukuoka, Japan, Oct. 15-18, (2000).

3. T.S. Kwon et al., "Basic Design of the KNGR DVI Test Facility (a): Fluid System", 53121-DVI-GEN-RT002(a), Rev. 01, DS-3, KAERI (2000).
4. B.J. Yun, H.K Cho, T.S. Kwon, C.-H. Song, J.K. Park and G.C. Park, "Experimental Observation on the Hydraulic Phenomena in the KNGR Downcomer during LBLOCA Reflood Phase", 2000 KNS Spring Meeting, Korea Nuclear Society(2000).
5. MPR-1329, "Summary of Results From the UPTF Downcomer Injection/Vent Valve Separate Effects Tests: Comparison to Previous Scaled Tests, and Application to Babcock & Wilcox Pressurized Water Reactors" (1992).
6. W.A. Carbiener and R.A. Cudnik, "Similitude Considerations for Modeling Nuclear Reactor Blowdowns", Trans. Am. Nucl. Soc., Vol. 12, p.361 (1969).
7. A.N. Nahavandi, F.S. Castellana and E.N. Moradkhanian, "Scaling Laws for Modeling Nuclear Reactor Systems", Nucl. Sci. & Eng., Vol. 72, pp.75-83 (1979).
8. K. Kim, "Test Conditions for the KNGR DVI Performance Test", Private Communication (2001).
9. B.J. Yun, H.K. Cho, T.S. Kwon, C.-H. Song, J.J. Jeong and G.C. Park, "Scaling of the Direct Bypass during LBLOCA Reflood Phase with Direct Vessel Injection System"", ICONE-9, Nice, France(2001).
10. H.K. Cho, B.J. Yun,T.S. Kwon, C.-H. Song, and G.C. Park, "Scaling Methodology for the Direct ECC Bypass during LBLOCA Reflood Phase with Direct Vessel Injection System : Its Development and Validation", ICONE-10, Arlington, Virginia, USA(2002).