

An Experimental Study and Numerical Simulation by RELAP5 for the Downcomer Boiling of APR1400 under LBLOCA

Dong Won Lee, Hee Cheon NO and Eu Hwak Lee

Korea Advanced Institute of Science and Technology

Gusong-Dong, Yusong-Gu 373-1, Daejeon, Korea

Tel.: +82-42-869-3857, Fax: +82-42-869-3810, Email: dwlee@nsys.kaist.ac.kr

Seung Jong Oh ¹⁾ and Chul-Hwa Song ²⁾

¹⁾ *Korea Hydraulic and Nuclear Power Co.,*

103-16, Munji-dong, Yuseong-gu, Daejeon, 305-380, Republic of Korea

²⁾ *Korea Atomic Energy Research Institute*

Yuseong-gu P.O. Box 105, Daejeon, 305-600, Republic of Korea

ABSTRACT

The direct vessel injection (DVI) mode of a safety injection system is adopted instead of a conventional cold leg injection (CLI) mode as one of the advanced design features of the APR1400 (Advanced Power Reactor 1400 MW). From the calculation results of RELAP5 with full plant, it is found out that the sudden boiling happens in the downcomer due to heat transfer from the reactor vessel wall and it can affect the reactor safety. In the present study, experimental tests are carried out to observe the actual boiling phenomena in the downcomer and to validate RELAP5. The heated wall of test section has its thickness of 8.2 cm and the same material as the prototype (APR1400) with chrome coating against rusting. From the experiment, we visually observe the vapor jetting near the heated wall with small bubble migration to the bulk region and liquid circulation. The data shows a rapid wall temperature drop generating a large amount of vapor initially. The calculation results of RELAP5 using the three nodal schemes are compared with experimental ones in aspects of water level, void fraction, wall temperatures and phase velocities. It turns out that the double nodal scheme with circulation produces better results than the nodal scheme without circulation to simulate the boiling phenomena in the downcomer. And more, from the measurement of local liquid velocities, the proper gap size is proposed and RELAP5 calculation with it is performed.

I. INTRODUCTION

As one of the advanced design features of APR1400 [1], the DVI mode as a safety injection system is adopted instead of a CLI mode. Several thermal-hydraulic phenomena are expected to happen in the downcomer as shown in Fig. 1. Among them, ECC water bypass by high-speed steam and sweep-out were investigated in the previous work [2]. From the calculation results of RELAP5 with full plant, it is found out that the sudden boiling happens in the downcomer due to heat transfer from the reactor vessel wall and it can cause a rapid increase in the void fraction and also the sudden drop of gravitational head in the downcomer. This makes the core level lower causing the reheating of the fuel rods in the core. Finally, it can affect the safety of reactor significantly. Therefore, the Emergency Core Cooling (ECC) water boiling in the downcomer by heated vessel wall during the LBLOCA reflood phase should be investigated.

In the present study, the experimental facility is installed to observe the real phenomena with the heated wall of 8.2 cm thickness and of the same material as prototype (APR1400). And also, the downcomer boiling is simulated using RELAP5 to understand it and to identify which phenomena govern it. The comparisons between the experimental data and the calculation results show that 1-D treatment of RELAP5 has the limitation to simulate the downcomer boiling. Therefore, the calculation of RELAP5 is performed according to the typical and proposed nodal schemes in the present study. This study is performed as a preparation of the real scale experiment preserving the same thickness (21 cm) of reactor vessel wall.

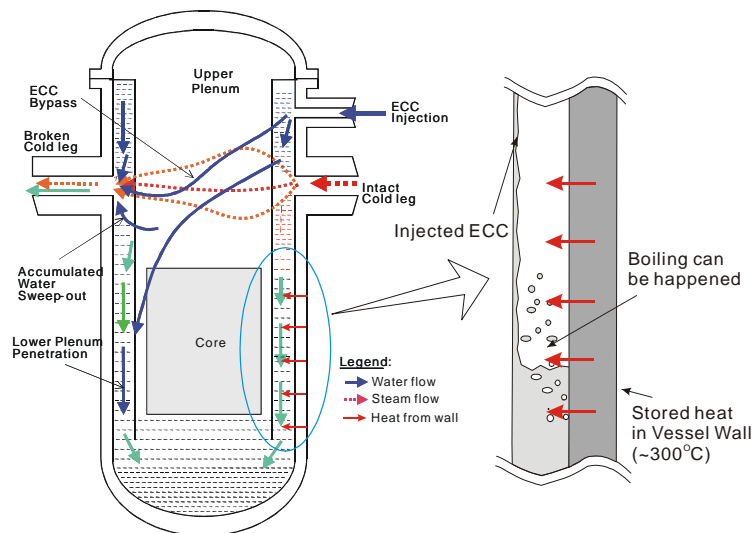


Fig. 1 Expected phenomena in the downcomer of APR1400 during the LBLOCA reflood phase

II. EXPERIMENTAL FACILITY

In order to observe the actual phenomena, the test section is manufactured as shown in Fig. 2. The heated wall of the test section has the thickness of 8.2 cm and the same material (SA508 class III; carbon steel) as the prototype (APR1400) with chrome coating against rusting. The vessel wall of prototype has the surface with the stainless steel cladding, however, this difference in surface is not considered in the present study. The front face and two sides of the test facility have the windows in order to observe and to record the phenomena. The DVI line and the broken cold leg are installed in the upper part of test section to inject the ECC water and to bypass the water and steam, respectively. The water temperature and local liquid velocity in the test section are measured using the K-type thermocouples and pitot tubes developed here, respectively. Vapor velocity in the test section is measured using high-speed camera and its image processing work. In order to insert these sensors, the instrumentation bar is installed at one side in the test section. In the heated wall, the thirty thermocouples (K-type) are inserted to measure the wall temperature as shown in Fig. 3. In order to heat up the wall up to 300 °C, a furnace type heater (10 kW) is used.

Figure 4 shows the schematic of the experimental facility. The water is injected through the DVI lines using the water tank and water pump. A separator is used to separate and measure the amount of water and steam in the mixture through the broken cold leg. Temperature, pressure, and flow sensors are installed in the inlet and outlet regions of each line in order to measure each parameter. The video camera is prepared in order to observe the ECC water boiling in the test section through both of the side and front windows. And the high speed camera (KODAK motion coder SR-1000) is used to measure the bubble velocity through the image processing. In the instrumentation, the uncertainties of major measured parameters are summarized in Table 1.

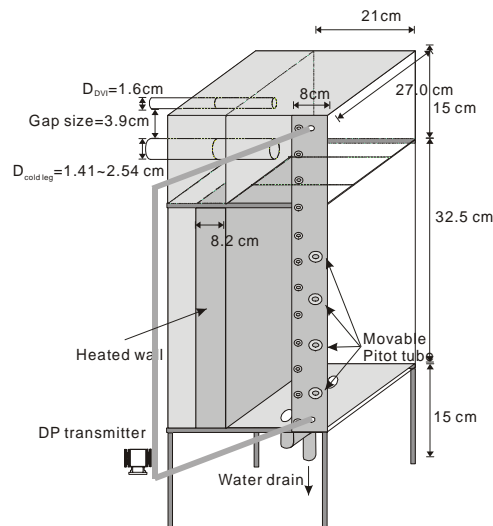


Fig. 2 Schematic of the test section

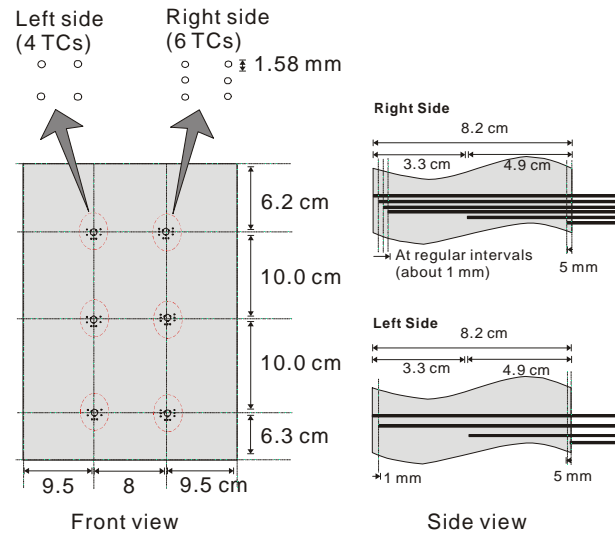


Fig. 3 Installation of thermocouples for measurements of heat flux and wall temperature

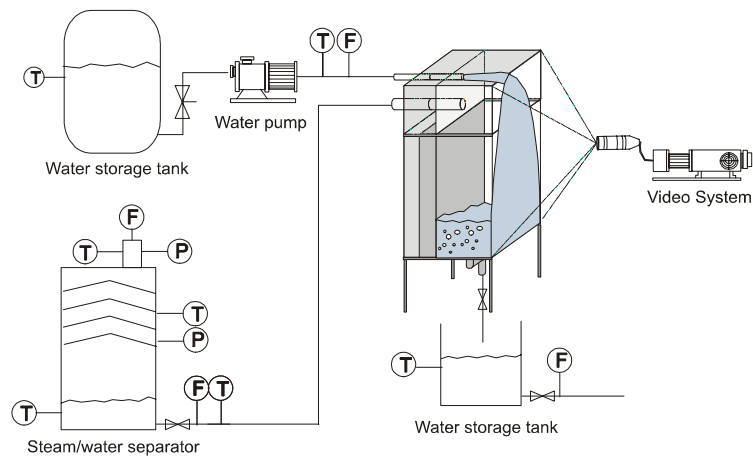


Fig. 4 Schematic of the experimental facility

Table 1 Uncertainties of major measuring parameters

Parameters	Instrument	Accuracy	Measurement Error
Temperature [K]	K-type thermocouples	0.4 %	$\pm 3\text{K}$
Pressure [Pa]	Pressure transmitter	0.1%	0.14%
Level [m]	DP transmitter	0.075 %	0.13%
Steam flow rate	Vortex flow meter	1.0 %	1.1%
Water flow rate	Turbine flow meter	0.5 %	0.52%

III. RESULTS AND DISCUSSION

III.A. Experimental results

From the pre-calculation of RELAP5 with full plant and previous experiment [2], the following conditions are determined: the wall temperature is around 300 °C and injected water temperature is over 95 °C, respectively. In order to observe the actual phenomena, the water is injected for 30 sec without drain to the bottom, which means that the level oscillation by the core does not consider in the present study. The water level in the test section reaches an axial location of 32 cm from the bottom of the tank by the water injection. The tests are performed with atmospheric pressure. These conditions are used in the calculation of RELAP5 in the same way.

Figure 5 shows the experimental photo and the simple schematic of this phenomenon. From the visual observation, the bubbles jet near the heated wall and do not spread to the bulk region except small migration. And also, the water near the heated wall moves upward and circulates in the test section.

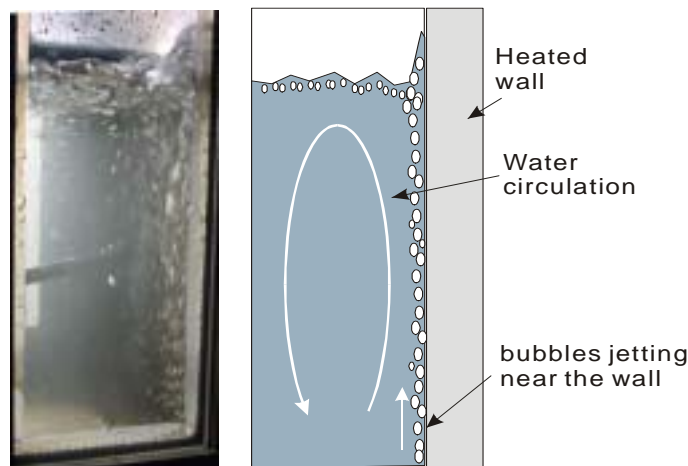


Fig. 5 Experimental photo of boiling phenomena in the downcomer

III.B. RELAP5 analysis according to the nodal schemes

In order to analyze the experimental results with RELAP5, three nodal schemes are composed as shown in Fig. 6 [3]. A single nodal scheme is the typical one to calculate with RELAP5. In this nodal scheme there is no radial pass to flow the water and the vapor through the gap. As a result, there is no liquid circulation in the gap. In order to avoid the problem, the double nodal scheme is proposed to make radial flow passes for each phase as shown in second one of Fig. 6. It causes migration of bubbles generated at the heated wall into the bulk region of the gap. In the experiment, few bubbles exist except near the heated wall. Finally, the double nodal scheme for circulation is proposed to

prevent bubbles generated at the heated wall from migration into the bulk region of the gap while it allows the water to circulate in the gap. The calculation results using these nodal schemes are compared with experimental data.

Water level is obtained from the visual observation and compared with the calculation results of RELAP5 according to the nodal schemes as shown in Fig. 7. After injection of water for 30 sec, water level initially reaches an axial location of 32 cm and decreases to 27 cm by 500 sec as boiling progresses. The water level by code calculation is obtained in terms of collapsed level and the comparison results are as follows: the calculated water level using the single nodal scheme agrees well with the experimental one, however, the sudden drop happens around 120 sec, which is not observed in the experiment. Water levels using the double nodal scheme without circulation are much lower than the experimental one in both sides. Water levels using double nodal scheme with circulation are different in both side. Water level at near heated wall is lower than actual one, however, one at far heated wall (component 200 in nodal scheme) agrees well with the experimental one. From the observation and comparison with code calculation results, the double nodal scheme with circulation gives the similar results to the actual phenomena. And also, figure 7 shows the results of void fraction. In the present study, the only numerical results of void fraction are compared because they are not measured experimentally. However, the figure shows that the void is well separated in the code calculation in case of using the double nodal scheme with circulation.

Figure 8 shows the comparison results of local liquid and vapor velocity near heated wall, respectively. The experimental results are local values, however, the numerical results are averaged ones in each node. Therefore, it is difficult to directly compare with them. However, the local experimental values are certainly higher than those of numerical calculation and also, there is such a problem in single nodal scheme and double nodal scheme without circulation that each phase velocity is nearly zero quite differently from the experimental results. It is needed to study more about comparison between the experimental data and predictions of RELAP5.

Surface wall temperature drops rapidly with generating a large amount of vapor initially as shown in Fig. 9 and it also shows the comparison results of wall temperatures according to each nodal scheme. Bold lines with symbol show the experimental results and the thin lines show RELAP5 calculation results. The values represent the distance from the unwetted surface of the heated wall (i.e. 81.5 mm is 0.5 mm from the wetted surface). As shown in Fig. 9, wall temperature using the single nodal scheme has much discrepancy with the experimental ones. It shows that 1-D treatment of RELAP5 has the limitation to simulate the downcomer boiling: lower flow rates than experimental data give different heat transfer from the wall to the water. However, wall temperatures become similar to the experimental ones in case of using the double nodal scheme to make a flow pass. And more, wall temperature using the double nodal scheme with circulation agrees better with the experimental ones than those without circulation as shown.

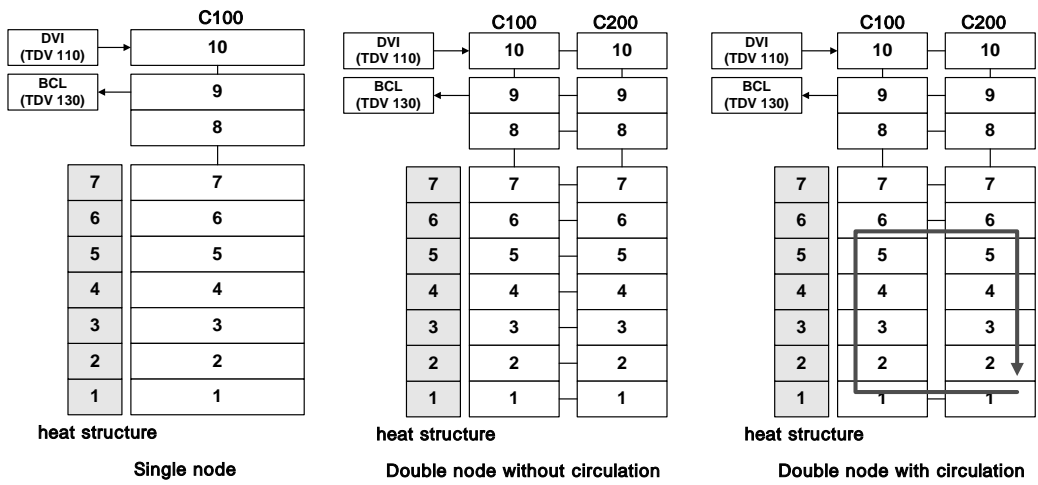


Fig. 6 Nodal scheme of single and double node cases for RELAP5 calculation

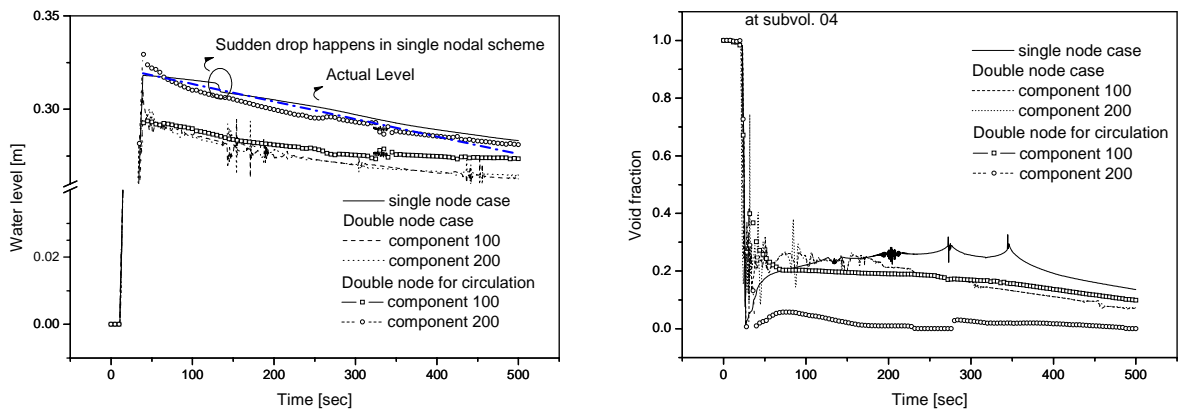


Fig. 7 Water level and void fraction of experimental data and RELAP5 predictions

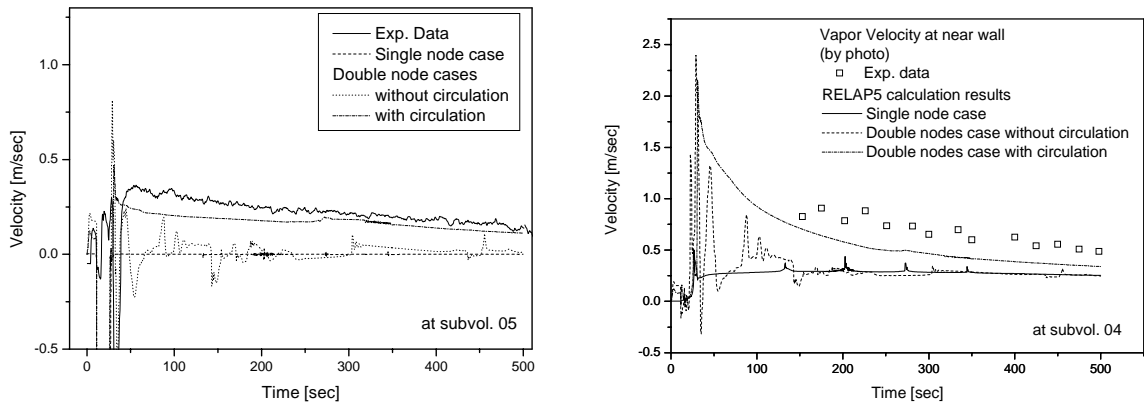


Fig. 8 Local liquid and vapor velocities of experimental data and RELAP5 predictions

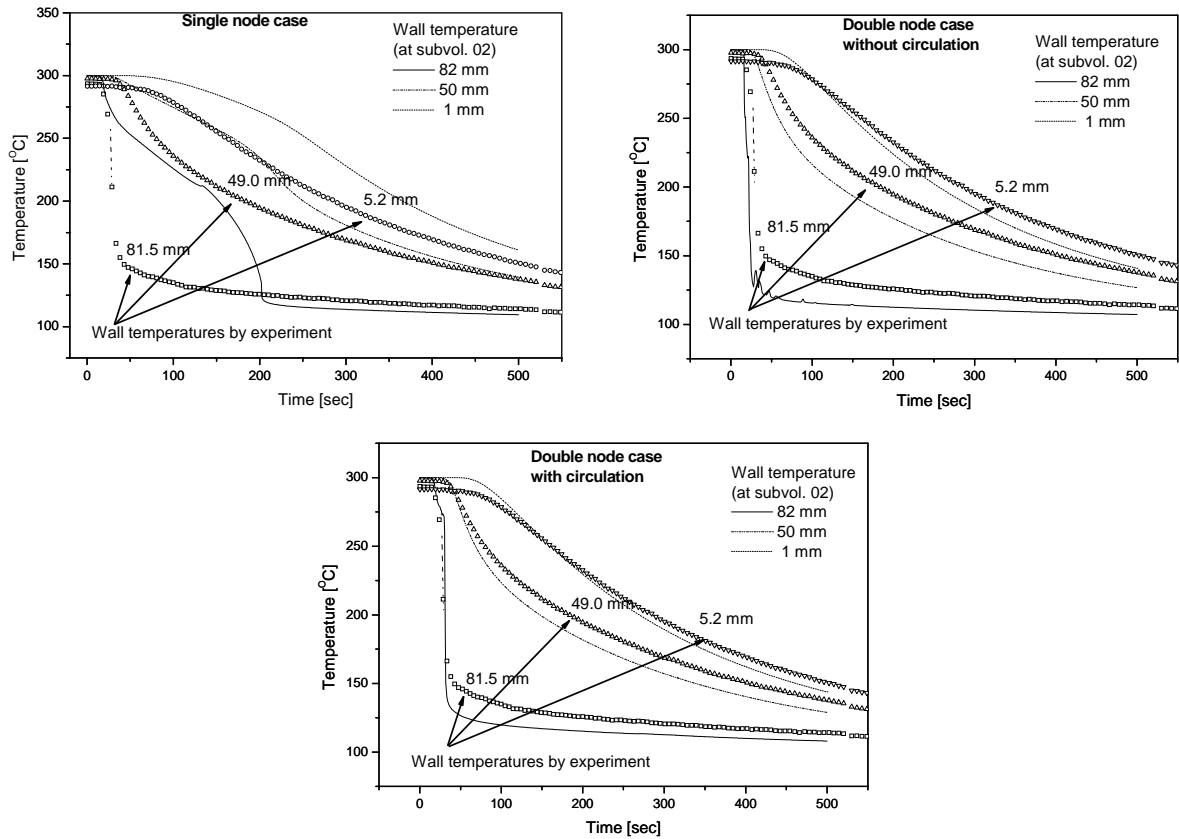


Fig. 9 Wall temperatures of experimental data and RELAP5 predictions using double nodal scheme with circulation

III.C. RELAP5 analysis according to the nodal sizes

As shown in Fig. 6, the downcomer gap is divided into two components for the double node cases and each component represents half of the downcomer. However, the component adjacent to the heated wall is below 20% of the gap width to represent the region containing bubbles as shown in Fig. 5. Since the relative width of the two components would probably affect the void fraction and the fluid velocities, the effect of radial nodalization is investigated in this section.

The liquid velocities are measured according to the distance from the wall with the developed pitot tube. Figure 10 shows the results of liquid velocity measurement and measurement procedure using the pitot tube. From the results, the bubbles exist near the heated wall and the distance from the wall is below 4 cm. Therefore, the nodal size of near heated wall component is determined to 4 cm and the calculation of RELAP5 is performed. Actually, the wall temperature, water level, and void fraction have a little difference according to the radial nodal sizes. However, the local velocities of each phase show higher values than calculation results using half nodal size case as shown in Fig.

11. As mentioned before, the experimental results are local values and it is being investigated to obtain more accurate data.

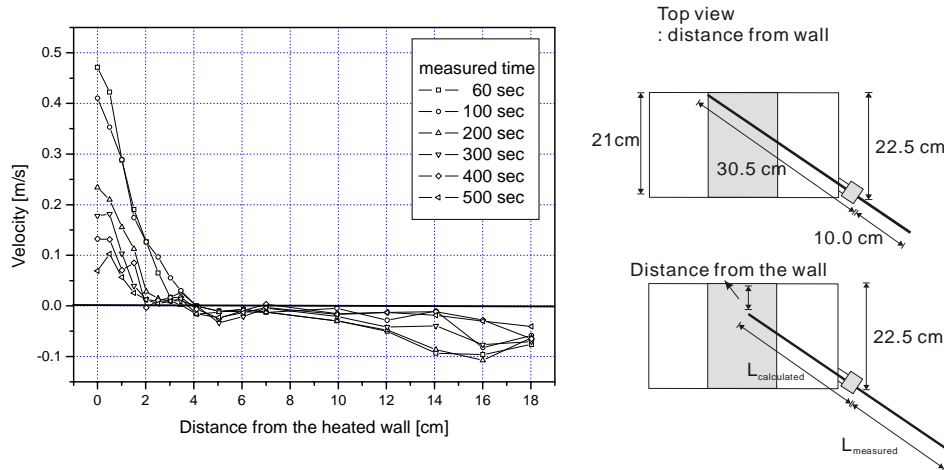


Fig. 10 Liquid velocity measurement for determining the gap size

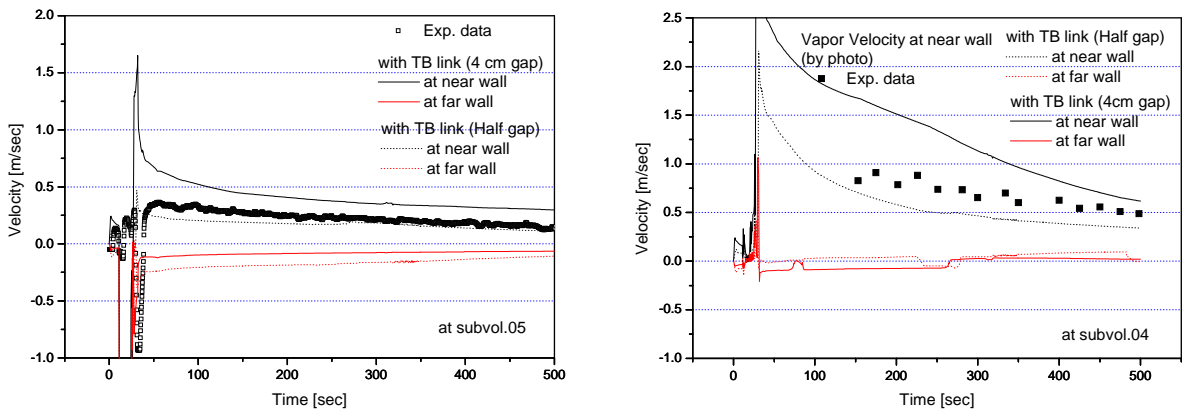


Fig. 11 Local liquid and vapor velocities of experimental data and RELAP5 predictions

IV. CONCLUSIONS

Boiling by reactor vessel wall in the downcomer is investigated using the experimental facility with the heated wall of thickness of 8.2 cm and the same material as the prototype. And also, the test results are compared with the calculation results of RELPA5 to identify it. We visually observe the vapor jetting near the wall with little bubble migration to the bulk region and liquid circulation in the test section. The data shows a rapid wall temperature drop generating a large amount of vapor initially. The calculation results of RELAP5 are compared with experimental ones in terms of water

level, void fraction, wall temperatures and phase velocities. It turns out that the double nodal scheme with circulation produces better results than the single one and double one without circulation because it well represents the actual liquid and vapor flows. From the measurement of local liquid velocity using the developed pitot tube, the gap size is determined to 4 cm and it is used to calculate RELAP5. Comparison results show higher local phase velocities than those of half gap cases. It is more needed to measure the local phase velocities, and to compare with the calculation results of RELAP5.

ACKNOWLEDGMENTS

This work has been supported by Korea Energy Power Research Institute (KEPRI) and Korea Atomic Energy Research Institute (KAERI) through research contract.

REFERENCES

1. Insik Kim and Dong-Su Kim, "APR1400-Evolutionary Korean Next Generation Reactor," proc. of ICON-10, Arlington, Virginia, USA (2002).
2. Dong Won Lee and Hee Cheon NO, "ECC Water Film Spreading, ECC Water Bypass and Sweep-out Phenomena in the Downcomer with DVI of APR1400 under LBLOCA", Proc. of the International Congress on Advanced Nuclear Power Plant (ICAPP), Hollywood Florida, U.S.A., June (2002).
3. The RELAP5 Code Development Team, "RELAP5/ MOD3 Code Manual Volume II: User's Guide and Input Requirements," NUREG Report, NUREG/CR-5535 (1995).