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## EXPERIMENTAL CHARACTERIZATION OF CO-CURRENT SUBCOOLED BOILING PHENOMENA IN A RECTANGULAR GEOMETRY

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### ABSTRACT

A subcooled boiling phenomenon is an important safety concern in the nuclear reactor such as in the downcomer of a nuclear reactor during a postulated loss of coolant accident. In order to characterize a subcooled boiling phenomenon, an experiment has been performed for a rectangular geometry of test channel having a rectangular cross-section of 0.3m X 0.25m, and a height of 6.4m. This study has a purpose to generate experimental data in order to develop and validate a two-phase analysis code. To set clear boundary conditions, the water is supplied from the bottom of the test section under a constant outlet pressure by controlling condensation of the generated steam at a returning line to the storage tank. The measured data can be classified into global and local two-phase parameters. Pressures, temperatures and flow rate for the boundary conditions and regional collapsed water level in the test section are global parameters. Two types of local probes were specially developed to measure local two-phase parameters related to the flow dynamics. Steam parameters such as void fraction and bubble velocity are measured by a multi-sensor conductivity probe. In the meanwhile, a liquid velocity is measured by a BDFT (Bi-Directional Flow Tube). The measured local data shows two-phase structure developed from wall nucleation and bulk condensation. The generated data would be utilized in developing and/or validating two-phase analysis codes such as nuclear safety analysis code and CFD codes.

### INTRODUCTION

The APR1400 (advanced power reactor) is an advanced Korean pressurized water reactor which adopts new safety injection features that four mechanically independent safety injection systems with a DVI (direct vessel injection) method that injects ECC (emergency core cooling) water directly into a reactor vessel downcomer instead of into the cold-leg pipes [1]. While it is expected that these improvements will greatly enhance the reliability of the ECC system, some technical issues were addressed in relation to the subcooled boiling in the

downcomer during a reflood phase of loss of coolant accident. When the SIT flow is finished, a significant boiling can occur due to a reduced safety injection flow and a highly maintained structure energy, which can reduce the hydrostatic head and degrade the core cooling capability. The downcomer boiling phenomena include multi-dimensional two-phase behaviour, which is hard to be predicted with conventional safety analysis codes which are used to global system characteristics mostly having one-dimensional behaviour.

Safety analysis using the RELAP5 code showed that the boiling phenomena occurs significantly in the downcomer region. In contrast, a downcomer boiling was not observed in the TRAC-M results. This difference between the simulations was mainly attributable to the adoption of different thermal hydraulics models for the downcomer, especially in the interfacial friction models: RELAP5 uses an interfacial friction model based on the drift flux, whereas TRAC-M uses a modified Blasius friction correlation [2]. Euh et al.(2008) investigated performance of three safety analysis codes, which are RELAP, MARS and TRACE for the downcomer boiling phenomena. They found that most safety analysis codes should be improved for the multi-dimensional subcooled boiling showing in the large gap of flow channel although the results were improved by using multi-node model for the gap of downcomer.[3] The studies show that the thermal hydraulic models of the existing best estimate (BE) codes should be evaluated for the successful application to the downcomer boiling phenomena. To improve the hydraulic models, experimental database for the multi-dimensional boiling phenomena are essential with a well defined boundary conditions. However, the downcomer boiling phenomena was not an important issue in previous cold-leg injection systems, and thus there have been few studies on a downcomer boiling.

Sudo(1982) performed a separate effect test on downcomer boiling phenomena. The test was performed using a slab geometry, in which the channel gap and height were 0.2 and 6.5 m, respectively. Also it was performed in a transient condition, and it showed the possibility of a degradation of the hydrostatic

head of the coolant due to a downcomer boiling. Since the purpose of the experiments are to address the system behaviour during a transient condition, local two-phase flow parameters such as the local void fraction and the interfacial friction factor, which provide information on an internal flow structure, were not measured in the test.

To identify the downcomer boiling phenomena which are supposed to be happened during a reflood phase of postulated loss of coolant accident for a APR1400, an experimental program has been performed with a newly constructed test facility, "DOBO", which has a rectangular geometry of a test section. [5][6] DOBO facility represents a section of annulus formed between core barrel and reactor vessel. The curvature of the section is simplified to rectangular cross section. The boundary conditions are set for the thermal hydraulic conditions when the large amount of SIT flow would be terminated. The safety injection flow from high pressure safety injection system is penetrated a highly interaction region at the cold leg elevation to a lower part of downcomer, where is simulated region in the DOBO facility. The test section of DOBO has an injection port at the higher side of the test section and drain the water at the bottom of the test section which represents a core inlet. The generated steam due to wall nucleation goes upward by buoyancy and vented to top of the section. Therefore, the two-phase flow has complicated boundary conditions, which are not desirable in respect of a development of thermal hydraulic two-phase flow code.

This study focuses on generating experimental data in order to develop and validate a two-phase analysis code. Unlike the previous test, the water is supplied from the bottom of the test section in order to get clearer boundary conditions. The measured data can be divided into two categories: (I) global two-phase parameters such as pressure, temperature, flow rate, and water level, and (II) local two-phase parameters such as a void fraction and steam velocities.

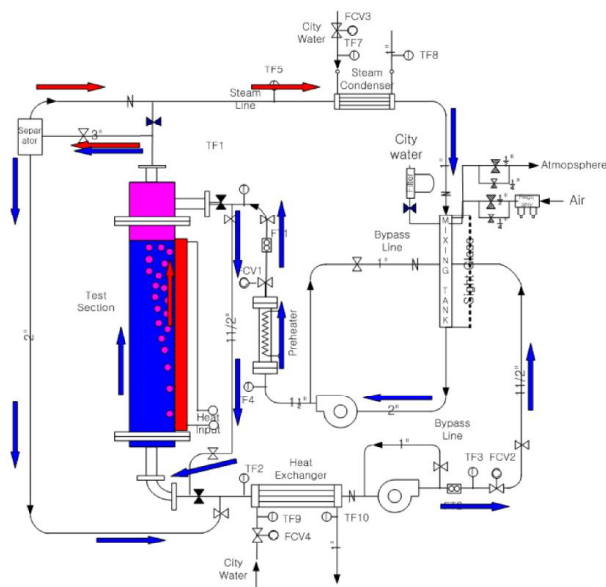


Figure 1 Schematics and flow diagram of test facilities

## EXPERIMENTAL FACILITY

The DOBO (Downcomer BOiling) test facility is designed to simulate the downcomer region below a cold leg in the late reflood phase of a postulated LBLOCA, in which an ECC injection from the SIT is terminated. During this period, most of the thermal hydraulic parameters in the primary system reach quasi-steady-state conditions, and hence the DOBO facility is designed for a steady-state operation.

The DOBO facility consists of a test section, a steam-water separator, a condenser, a heat exchanger, a drain pump, a storage tank, an air injection and ventilation system, a pre-heater and an injection pump, as shown in Figure 1. The maximum operational pressure is 500 kPa. The test section is designed with a slab geometry that simulates the high-temperature wall of a reactor vessel from the cold leg to the flow skirt. However, its length was extended by 1.3 m to allow for an installation of a single DVI nozzle at the top of the test section and to drain water at the bottom but there is no heat input to this region. The width, depth, and total height of the test section are 0.3, 0.25, and 6.4 m, respectively. Only one of the four side walls (which have a length of 5.1 m) simulates a high-temperature reactor vessel wall, and thus the heat transfer area becomes 1.53 m<sup>2</sup>. The heat is generated by 207 cartridge heaters that are inserted in the wall. The maximum available heat flux is 100 kW/m<sup>2</sup>, which corresponds to maximum anticipated value when ECC injection from the SIT is terminated. Glass windows are installed on one adjacent and opposite walls of the heated wall to allow for a visual observation.

The separator is connected to the outlet pipe of the test section for the phase separation of a two-phase flow. The separated water and steam phases are respectively cooled and condensed by two heat exchangers. The temperature of the water in the storage tank is controlled by the heat removal rates of these heat exchangers. The circulating water is injected into the test section at the top and drained at the bottom of the test section by two centrifugal pumps. The mass flow rate required for the DOBO facility during the reflood phase after emptying the SIT tanks is 1.3–1.4 kg/s. The injected water mass flow rate of the test facility is maximally 3.3 kg/s and it is controlled by a control valve. The water level in the test section can be maintained at a fixed value by controlling the drain flow rate at the bottom of the test section.

The water can be heated up to 7°C by a pre-heater at the designed maximum flow rate. The temperature of the ECC water injected via the DVI nozzle can be maintained at a target value by controlling the temperature of the accumulated water in the storage tank and the applied heat of the pre-heater. The system pressure is controlled by an air injection and venting system.

## INSTRUMENTATION

Several kinds of commercially available instruments are installed for the boundary mass and energy flow rates. The location of each instrumentation is shown in Figure 2. The mass flow rates of the circulating water are measured by two Coriolis meters that are installed at the inlet and outlet pipes of

the test section. The estimated uncertainty for a measured mass flow is 0.3% of its read value. The system pressure is measured at the top and bottom of the test section by two SMART-type PTs (pressure transmitter). Seven SMART-type DP (differential pressure) transmitters (LT-1 to LT-7) are uniformly spaced along the two pressure impulse taps of the pressure transmitters for measuring both the water level and the axial void fraction. An additional wide-range DP (LT-8) is installed to check on the measured differential pressure of the seven DP transmitters and to control the water level at the downcomer. The estimated uncertainty of each DP and PT reading is 0.1% of F.S (Full Scale). The fluid temperatures are measured by K-type thermocouples, with their uncertainties estimated at 2.2 °C. These are installed at the inlet and outlet pipes, and also at the top and bottom of the test section. The applied power for the wall heating is measured by a power meter, with a reading uncertainty of 0.35%.

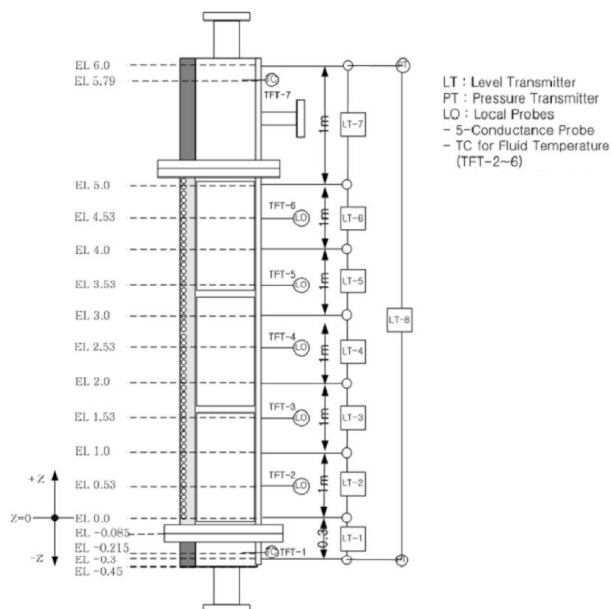


Figure 2 Instrumentation of test section

In addition to the above commercially available instruments, specially developed, 5-conductance probes are installed for a measurement of the local bubble parameters such as the void fraction and 3-dimensional bubble velocity. The detailed design of a 5-conductance probe is shown in Fig.5. Total of five sensors are configured in a probe in order to investigate the multi-dimensional bubble behavior in a highly swirling two phase flow [7]. For the benchmark of a local void fraction and bubble velocity, a separate test was performed in an air-water flow condition. The uncertainty of the void fraction was found to be 7% from a benchmark test. The bubble velocity is measured by the signals from the two-sensors located at the up- and downstreams in the configuration of the sensors. It is benchmarked with a photographic method by using a high speed camera whose deviation is 3.5%. [8] The test showed that

a distortion of the measured bubble velocity due to the other three sensors is negligible up to 1.8m/s of the bubble velocity.

The traversing unit moves the probe in a two-dimensional direction by controlling the radial and rotational components. The probes are installed axially at five elevations of the test section to investigate a propagation of the local bubble flow parameters.

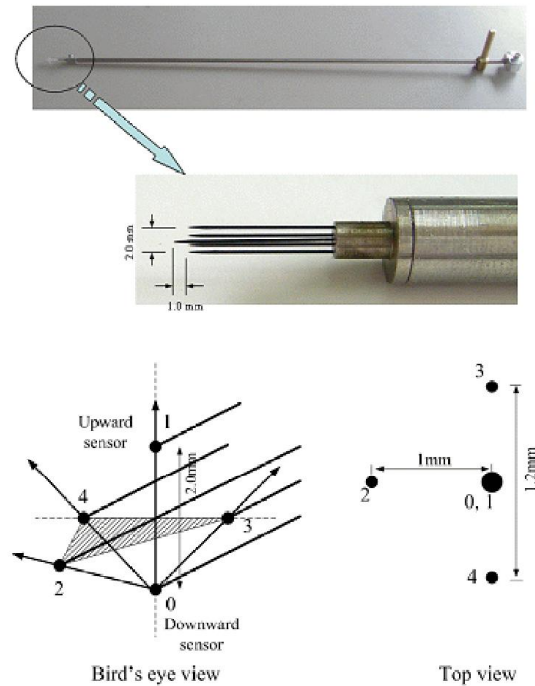


Figure 3 Details of the local 5-conductance probe

## EXPERIMENTAL CONDITIONS

To make boundary condition be clearer, the injection of cooling water was changed from top to bottom of the test section. From the change of cooling water, a co-current two-phase flow can be obtained, which is more suitable boundary condition in order to validate analysis model. The thermal hydraulic conditions at the boundaries were set as those of the downcomer when SIT flow is terminated during a sequence of the LBLOCA. Most of parameters such as temperature, pressure, and flow rate were determined by a simulation with safety analysis code. The test condition is similar to the previous test, R2-1 that simulates the plant condition, except that the water injection is from the bottom. The test was started by injecting heated ECC water from the bottom of the test section. The system pressure is controlled by a heat exchanger located at the steam line by a secondary flow control. The temperature of injected cooling water is controlled by preheater which is placed at the upstream of the cooling water injection line. Data acquisition began after all of the parameters had reached a steady state.

**RESULTS**

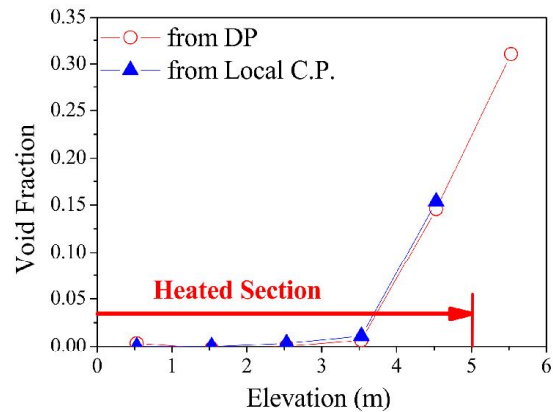
Table 1 summaries the results of measurement for the global major parameters. Pressure is controlled at 161 kPa at the top of the test section. The pressure difference between top and bottom of the test section is mainly contributed by hydrostatic head which can be converted to the average void fraction in the test section. The resultant average void fraction was 7.2% for the overall test section, in the meanwhile, 3.1% for the heated section. The injected cooling water is heated by side wall. As the subcooled liquid flows upward, the temperature of the liquid is increased and a nucleate boiling is started at the heated wall which is called “onset of nucleated boiling”. The nucleated bubble starts to slide along the heated wall and is lifted-off the wall. The bubble which is entered to the bulk region is immediately condensed since the bulk liquid is maintained at subcooled state. The phenomena form a bubbly boundary layer near the heated wall. The thickness of the bubbly boundary layer gradually increased as the liquid temperature is gradually increased. The distinct bubble boundary layer is a typical characteristic of the subcooled boiling flow which occurs in the lower and middle region. In the upper region, a well-mixed bulk boiling occurred while the bubbly boundary layer is sufficiently expanded to the opposite wall. Since the liquid is reached a saturated temperature at the bulk boiling region, a flashing phenomenon is also expected in the upper section as the nearly saturated liquid flows upward.

**Table 1** Thermal Hydraulic Conditions of Major Parameters

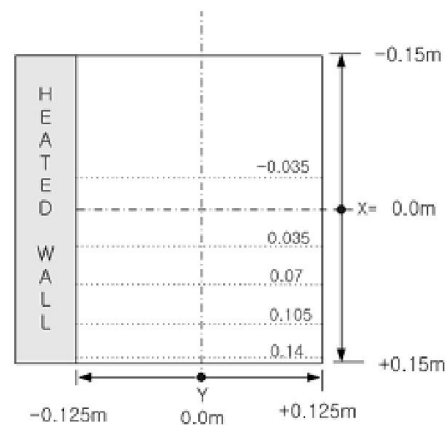
Tag	Values	Comments
PT1, kPa	216.7	Pressure at the bottom of T.S.
PT2, kPa	160.6	Pressure at the Top of T.S.
LT8, kPa	54.31	DP between Top and Bottom of T.S.
FT1, kg/s	1.287	Flow Rate of Injected Water
TFT1, °C	112.9	Inlet Temperature
TFT7, °C	114.1	Outlet Temperature
Power, kW	110.4	
Heat Flux, kW/m <sup>2</sup>	72.2	

Since the channel size is sufficiently large, the pressure drop between each pressure tab is mainly come from the hydrostatic head, which can be easily converted to the void fraction. The average void fraction measured from the DP transmitter was compared by the data from the local conductivity probe as shown in Figure 4. The two void fractions agree well within 5.6% of discrepancy at the 4.5m from the initiation of heated section.

The unheated section starts from the 5.0m from the bottom of heated section. Even if the heated section is finished at 5.0m of elevation, the void fraction is still increased. It means that the liquid is already reached a saturated condition. As flow still goes upward with saturated condition, a flashing is expected, which increases the amount of steam and reflected by increased void fraction as shown in figure 4.



**Figure 4** Profile of Channel Area Averaged Void Fraction



**Figure 5** measured line in a cross-section

Local parameters measured in this study are void fraction and steam velocity. Local conductivity probes are installed at five elevations which were selected for the local measurements along the heated test section. Each measuring plane is located at the midpoint between each DP tab. Five measured lines having 24 points were selected at each measure plane as shown in Figure 5. The distance between each point line is 1.0cm and that between measuring line is 35mm. The data acquiring time of the 5-conductance probe was 30 seconds with a 20 kHz sampling rate at each point.

Figure 6 shows the propagation of the local void fraction along the test section. At the lower elevation where a boiling is initiated, the steam is concentrated near the heated wall. As the generated steam flows upward, the void profile becomes wide and a distinct bubbly boundary layer was found. At the upper part of the heated section, a peaking of the void profile moves to the central region of a measuring plane. This trend reflects the visual observation well, in that the bubbly boundary layer thickness increases rapidly as the elevation becomes higher.

Figure 7 shows a contour plot of local 3-dimensional bubble velocities obtained from a 5-conductance probe. Its comparison with the local void fraction shows that the magnitude of the local bubble velocity follows that of the local void fraction. Moreover, the main direction of the bubble motion is an axial one, and the lateral motion of the bubbles from the heated wall to the opposite cold wall is not so significant. It means that the periodic swirling motion of the bubble cluster, that was observed visually, has a large time period. In addition to this, the bubble velocity is very small or negative near the opposite wall of the heated surface in the upper part of the heated wall region, since the upward bubble motion is suppressed by the downward liquid flow.

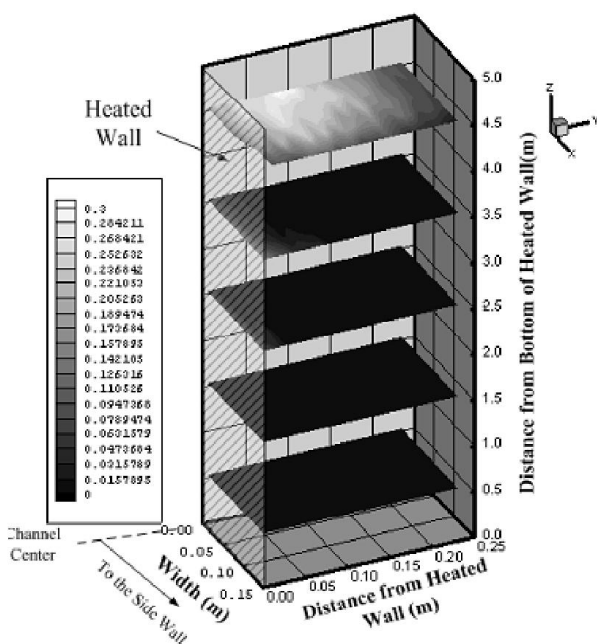


Figure 6 local void fraction in the test section

## CONCLUSION

A subcooled boiling test has been performed with a 0.25m X 0.3m cross-section geometry in order to measure a multi-dimensional two-phase flow behaviour induced by a subcooled flow boiling. The present study focuses on a test under well-defined boundary conditions in order to utilize the data efficiently for a validation of the multi-dimensional two-phase flow analysis code. The flow shows a general co-current flow with a highly swirling flow in the upper part of the test section. After an onset of nucleate boiling point, a distinct bubble boundary layer was found of which the thickness varied dramatically with the applied heat flux.

The data measured in the present test can be classified into two groups: 1) boundary parameters including spatial collapsed water levels and 2) local two-phase parameters for void fraction

and bubble velocity by using a newly designed local 5-conductance probe. The local distributions, of various bubble parameters, reflect the visualization observation well.

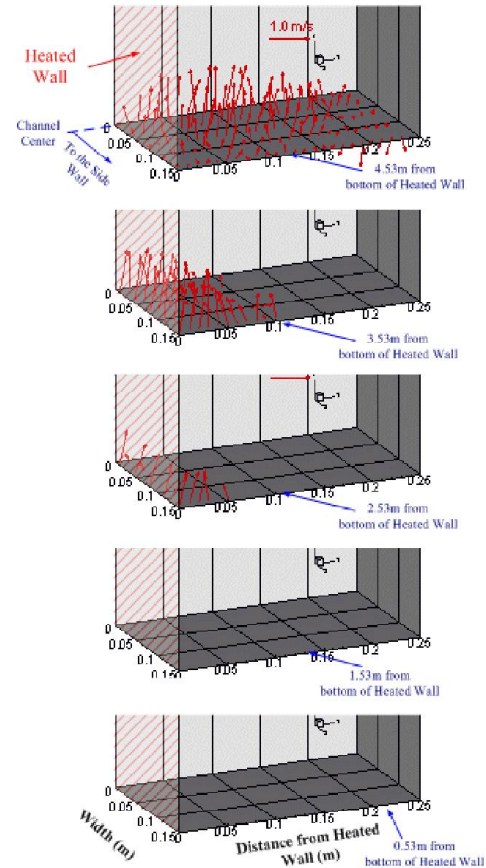


Figure 7 local steam velocity profile in the test section

## ACKNOWLEDGEMENT

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