

# THERMAL-HYDRAULIC TESTS AND ANALYSES FOR THE APR1400'S DEVELOPMENT AND LICENSING

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The program on thermal-hydraulic evaluation by testing and analysis (**THETA**) for the development and licensing of the new design features in the APR1400 (Advanced Power Reactor -1400) is briefly introduced with a presentation on the research motivation and typical results of the separate effect tests and analyses of the major design features. The first part deals with multi-dimensional phenomena related to the safety analysis of the APR1400. One research area is related to the multi-dimensional behavior of the safety injection (SI) water in a reactor pressure vessel downcomer that uses a direct vessel injection type of SI system. The other area is associated with the condensation of steam jets and the resultant thermal mixing in a water pool; these phenomena are relevant to the depressurization of a reactor coolant system (RCS). The second part describes our efforts to develop new components for safety enhancements, such as a fluidic device as a passive SI flow controller and a sparger to depressurize the RCS. This work contributes to an understanding of the new thermal-hydraulic phenomena that are relevant to advanced reactor system designs; it also improves the prediction capabilities of analysis tools for multi-dimensional flow behavior, especially in complicated geometries.

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**KEYWORDS** : APR1400, THETA, DVI, Fluidic Device, Sparger, IRWST, Multi-Dimensional

## 1. INTRODUCTION

Development of the APR1400, an evolutionary type of pressurized water reactor (PWR), was completed at the end of 2001 and its standard design was approved in May 2002 [1]. Recently, a contract was signed for the construction for the first unit (SKN Unit #3), the commercial operation of which will commence in 2013. The APR1400 has a capacity of 4,000 MWth with a 2x4 loop arrangement of the reactor coolant system (RCS) and a designed lifetime of 60 years. In addition, the APR1400 incorporates many advanced design features to enhance its safety. The new design features include the following: four trains of the safety injection system (SIS) with a direct vessel injection (DVI) mode and a passively operating safety injection tank (SIT); an in-containment refueling water storage tank (IRWST); and a safety depressurization/venting system (SDVS). Each SIS train has a high-pressure safety injection pump and an SIT with a fluidic device (FD).

The new design features were evaluated successfully to ensure they enhanced the APR1400's performance and safety. Relevant experimental activities were conducted over several years on some selected items during the licensing review process at the Korea Atomic Energy Research Institute. The experimental works, which was government -

supported and industry-sponsored, have been performed within the framework of the program on thermal-hydraulic evaluation by testing and analysis (**THETA**) of nuclear systems and components [2]. And a subsequent evaluation has been done focused on various multi-dimensional phenomena closely associated with the new safety systems [3].

The separate effect tests and analyses performed under the THETA program can be categorized into two parts. The first part is focused on multi-dimensional phenomena relevant to the design of the new safety systems, such as the DVI type of SIS and the IRWST. The second part is associated with the development of new safety components, such as an FD as a passive SI flow controller and a sparger to depressurize the RCS. Research items for the first part include tests for the emergency core cooling (ECC) water bypass and the wall boiling in the reactor pressure vessel (RPV) downcomer. These tests are relevant when evaluating the performance of the ECC system in the case of a large break loss-of-coolant accident (LBLOCA) for the DVI mode of a SIS. Other items also include tests to simulate a downcomer seal clearing for the formation of a steam vent path in the case of a DVI line break and to simulate a boron mixing in the RPV downcomer. The research items for the second part include tests for developing the

FD as a passive flow controller and tests for verifying its performance; they also include tests of the air clearing loads and the condensation-induced hydrodynamic loads, the aim of which is to evaluate the performance of the IRWST and the sparger.

We briefly explain how the THETA program is relevant to the development and licensing of the APR1400. In particular, we discuss our research motivation and objectives, the experimental and analytical methods, and the typical results obtained from the tests and analyses for each item.

## 2. MULTI-DIMENSIONAL BEHAVIOR IN A REACTOR DOWNCOMER

The multi-dimensional behavior of SI water in an RPV downcomer, as schematically shown in Fig. 1, is directly related to the use of a DVI type of SIS in the APR1400. The behavior includes the bypass and the subcooled boiling phenomena of SI water in an RPV downcomer during an LBLOCA reflood phase, the venting behavior of the vapor phase through a DVI line break in an upper downcomer of the RPV during a small break loss-of-coolant accident

(SBLOCA), and the mixing phenomena (or the so-called boron dilution) of borated SI water in both the RPV downcomer and the core inlet regions during a main steam line break (MSLB) or SBLOCA event.

The system analysis codes have reached an acceptable degree of maturity. Their reliable application, however, is still limited to validated domains because most of the codes are based on a one-dimensional approach. Qualified codes are requested more nowadays for the purpose of assessing the safety of existing reactors and for developing advanced reactor systems. In principle, new experimental works are needed to improve our understanding of various physical phenomena or processes; to address new phenomena, processes or system behavior; and to provide an experimental database for the development, validation and improvement of the codes. Experimental data are especially needed because of the uncertainty involved in the quantification of existing codes, because of the need to check the scale-up capability to a plant scale, and because of the development of new generation codes or advanced reactor systems.

In fact, advanced reactor systems often adopt new design features, which in many cases, reveal the characteristics of multi-dimensional or multi-fluid thermal-hydraulics.

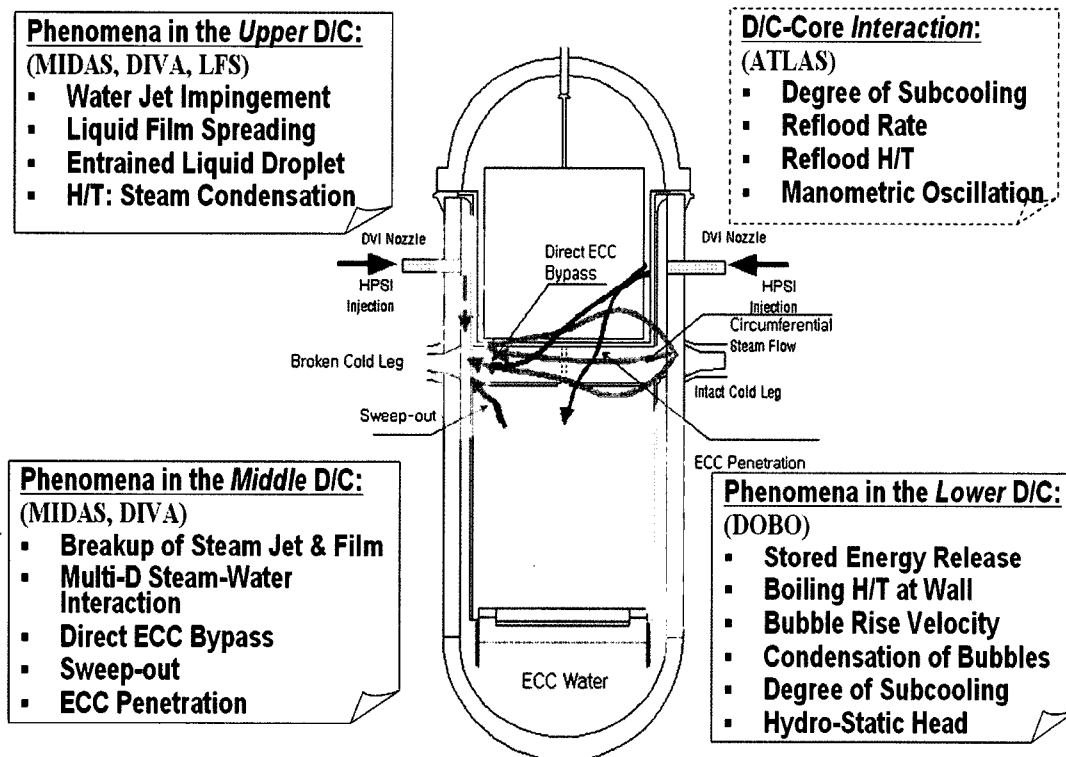


Fig. 1. Major T-H Phenomena in the RPV Downcomer with a DVI Mode during an LBLOCA Reflood Phase

Descriptions of these characteristics can be achievable based either on sophisticated experiments or on more reliable computer codes such as the computational fluid dynamics (CFD) code or the codes of advanced system analysis with the capabilities of analyzing multi-dimensional phenomena.

### 2.1 Bypass of SI Water during an LBLOCA Reflood Phase

The SI nozzles in the APR1400 are located in the upper part of the RPV downcomer, as schematically shown in Fig. 1. Due to this design feature, it seems that in the case of a loss-of-coolant accident, the thermal-hydraulic phenomena in the RPV downcomer may differ from such phenomena in the case of a cold leg injection (CLI), and this difference is believed to govern the LBLOCA reflood phase in the APR1400.

The research objectives of the ECC bypass during the reflood phase of a postulated LBLOCA are as follows: to understand the multi-dimensional flow phenomena at the upper and middle parts of the RPV downcomer; to provide experimental data for evaluating relevant thermal-hydraulic models and correlations in system analysis codes, most of which are currently applicable only to the CLI type of SIS; and to evaluate the contribution of new SI system to safety enhancement. Some experimental data is available on flow behavior in a downcomer with DVI nozzles in

the UPTF facility [4]. However, there is still a need to have additional experimental data on the APR1400 design configuration due to, among other things, the differences in the geometric and thermal-hydraulic conditions between the UPTF and the APR1400.

We performed a systematic investigation of the ECC bypass phenomena in the middle downcomer, as summarized in Fig. 2 and Table 1, by focusing on the multi-dimensional interaction between the phases in the upper and middle parts of the downcomer annulus.

From the preliminary analysis of the UPTF-21D counterpart tests, which used a combination of air and water [4,5], and the CFD analysis of a single-phase flow in an RPV downcomer [6], Yun et al. [5] found the appropriate scaling parameters to describe realistically the ECC bypass phenomena. This finding subsequently led to the development of the so-called *modified linear scaling method*, which is based on the two-fluid model in a two-dimensional flow field [7,8]. By applying this new scaling method to the multi-dimensional behavior in a downcomer, we could adequately preserve the key phenomena pertaining to the ECC bypass during the LBLOCA reflood phase for different scales. The key phenomena include the liquid film spreading width, the direct ECC bypass, and the sweep-out and condensation fraction. The results agree well with each other even when steam-water was used in the MIDAS facility for different scales to simulate the UPTF test [9,10]. Moreover, we have observed the same results

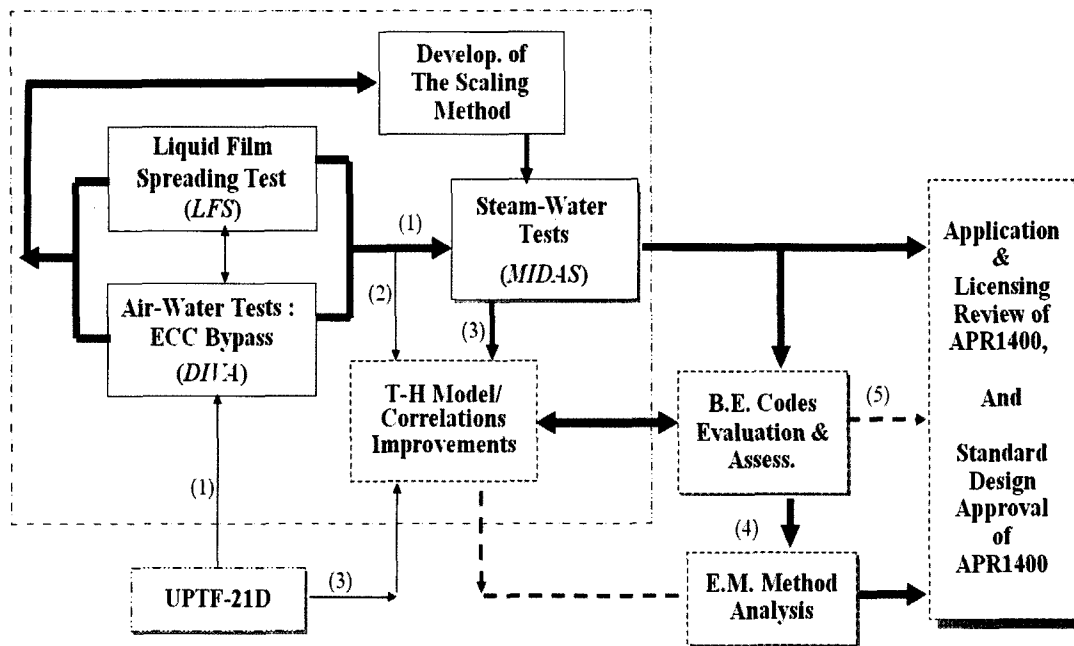


Fig. 2. Systematic Approach for Investigating Multi-Dimensional ECC Bypass Phenomena

**Table 1.** Test Matrix on Multi-Dimensional Phenomena in the RPV Downcomer during the LBLOCA Reflood Phase

No	Test case	Reference reactor	Test scale	Major parameters of interest	Test objectives
1	Liquid film spreading test	APR1400, UPTF	1/7	Liquid film spreading width	Effect of SI velocity, effect of curvature, scalability check
			1/5		
			1/1		
2	Air-water test	APR1400	1/7	ECC bypass mechanism, onset of entrainment (OLE),	Phenomena understanding
			1/5		Condensation effect
		UPTF	1/7	direct ECC bypass (DB),	Scaling law development
			1/4	void height (VH)	Scaling law validation
3	Steam-water test	APR1400	1/5	OLE, DB, VH,	Code validation
		UPTF	1/4	condensation/subcooling	Scaling law validation

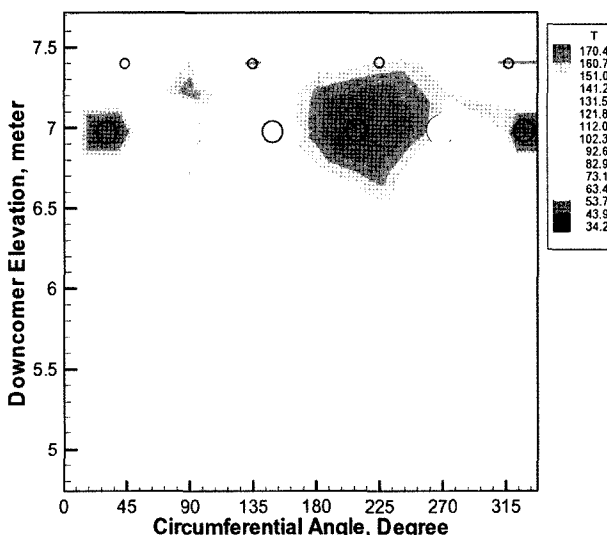
in an air-water counterpart test with both the 1/7 and 1/4 test scales in the same facility [5].

Steam-water experiments on the MIDAS facility, which were designed to simulate an ECC bypass in the downcomer, clearly show a highly complicated multi-dimensional flow pattern for the APR1400 simulation [11,12]. This flow pattern is mainly due to the interaction of the superheated steam injected through three intact cold legs with the SI water injected from the DVI nozzles in the downcomer. The flow pattern is also influenced by the blockage effect of the hot leg nozzles, the interaction of the downward water flow and transverse steam flow, and the direct contact condensation of the steam. The contour of the isothermal lines obtained from the MIDAS test show the multi-dimensional characteristics of the phasic interaction between the steam and water, as typically illustrated in Fig. 3.

This contour clearly shows that the cold SI water is injected by both the DVI-2 nozzle (the farthest DVI nozzle from the broken cold leg) and the DVI-4 nozzle (the nearest DVI nozzle from the broken cold leg) and that the superheated steam is injected into the downcomer through the three intact cold legs (CL-1,2,3). This figure also shows that the relatively colder region around the two hot leg nozzles inside the downcomer indicates a downward flow of the SI water toward the lower downcomer. The experimental data on the multi-dimensional behavior of SI water in the RPV downcomer have been used to evaluate and improve the predictability of the system analysis codes RELAP5, MARS and TRAC.

### 2.2 Subcooled Boiling at the Downcomer during an LBLOCA Reflood Phase

Safety analysis with the best estimate codes shows that the so-called *downcomer boiling* phenomenon may become an important safety issue that affects the thermal-hydraulic behavior in the reactor core during an



**Fig. 3.** Isothermal Line Showing Multi-Dimensional Phenomena in the Downcomer: DVI-2&4 Injection Case

LBLOCA reflood phase for either existing or advanced PWRs. For the APR1400, the RELAP5 and TRAC codes in particular show different behaviors for key parameters [13]. The different behaviors mainly come from the differences in the thermal-hydraulic models, such as the interfacial friction and the interfacial heat transfer.

We performed a subcooled boiling test to identify the two-phase flow behaviour at the lower part of the RPV downcomer during the reflood phase of an LBLOCA under steady-state conditions. The test was performed in the downcomer boiling (DOBO) facility, which simulates a part of the downcomer as a rectangular channel [14]. The test facility was designed with a full-

pressure, full-height, and full-size gap scaling approach, though the circumferential length was reduced by a factor of 47. Another test was done independently by the Korea Advanced Institute of Science and Technology in a reduced height test facility under transient conditions [15]. The boiling at the downcomer wall was simulated by heating only one side of the rectangular test channel in both tests.

The test clearly shows a multi-dimensional flow pattern in the test section, as schematically shown in Fig. 4; it also shows a distinct bubbly boundary layer along the heated wall. Various bubble parameters such as a void fraction, the bubble velocity and the interfacial area concentration were measured with a five-sensor conductivity void probe [16]. The liquid velocity and the fluid temperature were also measured with a local bidirectional flow tube and a thermocouple, respectively. The local distributions of the two-phase flow parameters, as typically shown in Fig. 5, were obtained by traversing the probes over a cross section of the test section at several elevations. [17]

The experimental data is valuable for developing a relevant two-phase flow model. Such a model can be used as an analytical tool for making better predictions of multi-dimensional subcooled boiling phenomena, which cannot be predicted properly with a conventional one-dimensional approach.

### 2.3 Steam Venting through a DVI Line Break (SBLOCA)

One of the technical concerns associated with the DVI concept is whether, in the case of a DVI line break,

the steam coming into the RPV downcomer through the cold legs from the reactor core can escape easily through the broken DVI line, as schematically shown in Fig. 6. A preliminary safety analysis by a system analysis code for this case shows that a core uncover for breaks over 6" in diameter might occur and that loop seal clearing phenomena in the intermediate legs are unlikely to occur even though no core uncover was observed for up to a 10" break [18]. The difficulty of a loop seal clearing is mainly due to the fact that a water plug forms in the upper downcomer between the cold leg and DVI nozzle elevations; subsequently, because of the water plug in the upper downcomer, the vent path of the steam produced in the core throughout the

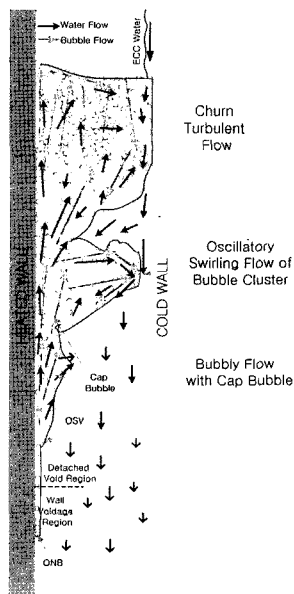
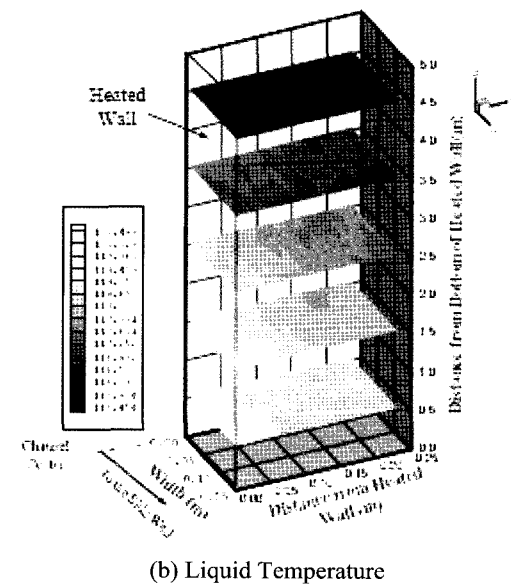
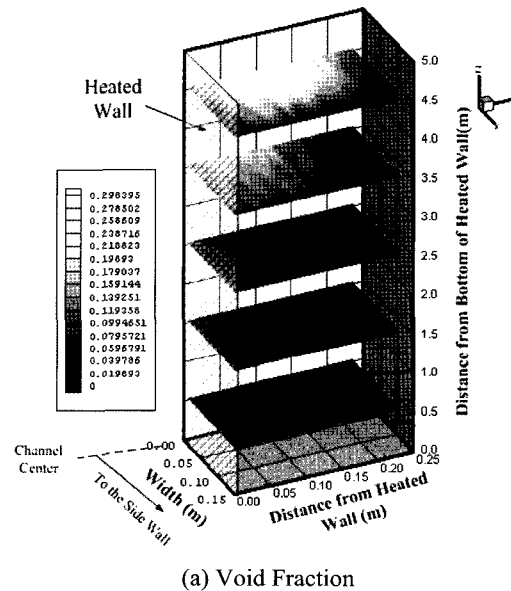
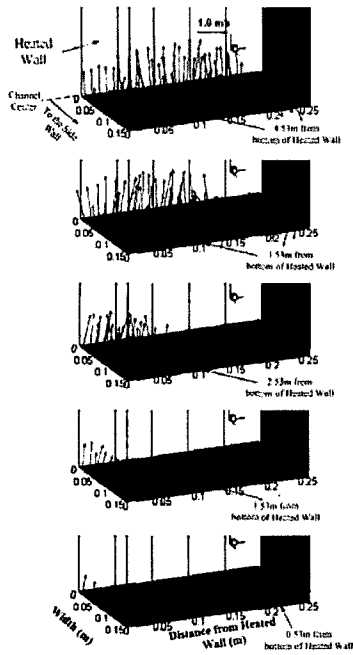
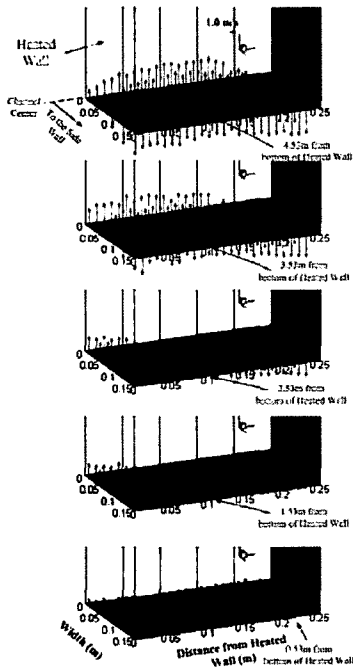


Fig. 4. Schematic of the Subcooled Boiling Phenomena in a Lower Downcomer during the LBLOCA Reflood Phase





(c) 3-D Bubble Velocity



(d) Axial Liquid Velocity

Fig. 5. Local Information on the Downcomer Boiling Phenomena in the DOBO Experiments ( $q''=70 \text{ kW/m}^2$ , 160 kPa)

break can form only when the steam pressure overcomes the hydraulic head.

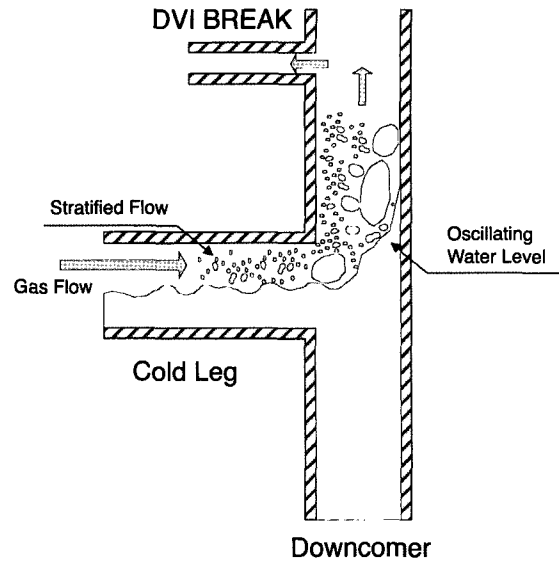


Fig. 6. Multi-Dimensional Phenomena in the Upper Downcomer during a DVI Line Break

To evaluate the prediction capability of the safety analysis codes and to develop a relevant physical model for the flow behavior in the upper downcomer in codes, we performed experiments to visualize the major flow phenomena, namely the flow pattern and the bubble rise velocity in the upper downcomer during a DVI line break. We also performed a flow visualization test, as typically shown in Fig. 7, in an air-water facility (DIVA) with a 1/5 linear-scaled transparent downcomer. The test, which enables us to simulate the conditions of the APR1400, was performed under a steady-state test condition by applying the scaling approach of preserving the Froude and Wallis parameters. These parameters are believed to be the major scaling parameters and they ensure a high degree of similarity in flow parameters such as the ratio of the hydraulic static head of a water plug and the momentum of the steam flow, as well as the flow pattern, the counter-current flow, and the break flow.

From experimental observation [18], we characterized the major phenomena as follows: a bubbly or slug flow in the cold legs; an annular-mist flow in the upper downcomer; and gas venting paths in the upper downcomer, which are formed easily due to a multi-dimensional flow pattern. These observations can be used as backup information for designers who wish to adopt a conservative approach to the easy formation of a gas venting path in an upper downcomer.

## 2.4 Boron Mixing during an MSLB or SBLOCA

The DVI type of SIS can affect the boron mixing behavior in an RPV downcomer during an MSLB or



Fig. 7. Hydraulic Phenomena Observed in the Upper Downcomer ( $v_g=1$  m/s,  $v_l=0.55$  m/s)

SBLOCA event. This effect occurs because the flow path of the borated water injected into the RPV downcomer through the DVI nozzles is quite different from that of the CLI case due to a difference in the location and elevation of the SI nozzles between the two cases.

The core bypass phenomena of the borated water injected by the DVI nozzles during an MSLB with the running condition of the reactor coolant pump (RCP), as schematically shown in Fig. 8, was simulated by means of a two-channel downcomer model with the one-dimensional system analysis code MARS and the three-dimensional CFD code [19,20]. Because of the high RCP flows during an MSLB, the borated water injected through the DVI nozzle flows mainly from the upper downcomer to the upper head of the RPV in the two-channel system analysis model of the MARS code. The CFD analysis results, however, show that the flow pattern in the downcomer is rather three-dimensional. The borated water generally flows to a lower downcomer, as schematically shown in Fig. 9, whereas a part of the borated water flows from the upper downcomer to the upper head of the reactor.

The test program associated with boron mixing in an RPV downcomer can be categorized as follows:

(1) Core bypass of the ECC water by an RCP flow: The typical flow path of the borated ECC water is visualized by a dye injection method to investigate the possibility of a bypass of borated water injected into the upper downcomer to the upper head region, which may be caused by the high RCP.

A visualization test (BOMIX-I) for the behavior of borated water was performed, as shown in Fig. 10, with a scaled-down model of the APR1400. The test shows that the borated water injected into the upper downcomer region is passed out easily into the high flow region of the cold legs and flows easily into the lower downcomer. These types of flows differ significantly from the flows predicted by the one-

dimensional system analysis code.

(2) Turbulence intensity in the downcomer: A CFD simulation of boron dilution does not quantify the effects of a turbulence model because the relevant turbulence intensity data are not available from any experiment of boron mixing, especially in the downcomer or core inlet.

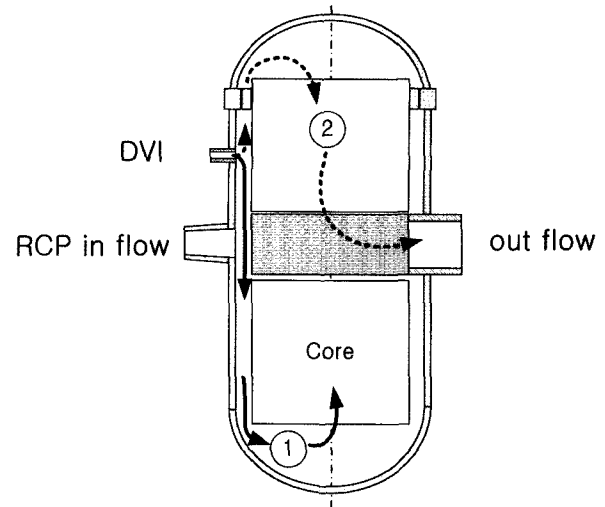


Fig. 8. Flow Path of the Borated Water in the Case of an MSLB with the RCP Running Mode

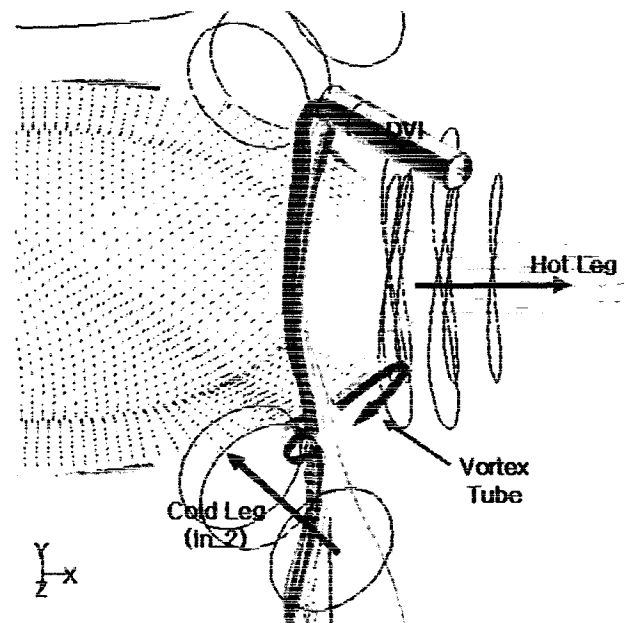


Fig. 9. Downward Flow Path of Borated Water Between the Two Adjacent Cold Legs (CFD Analysis)

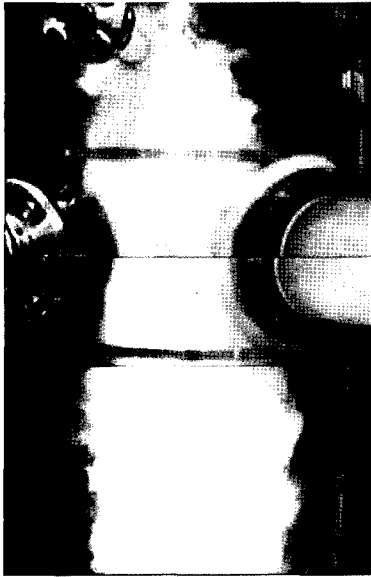


Fig. 10. BOMIX-I Test for a Visualization of the Borated Water Behavior in the RPV Downcomer

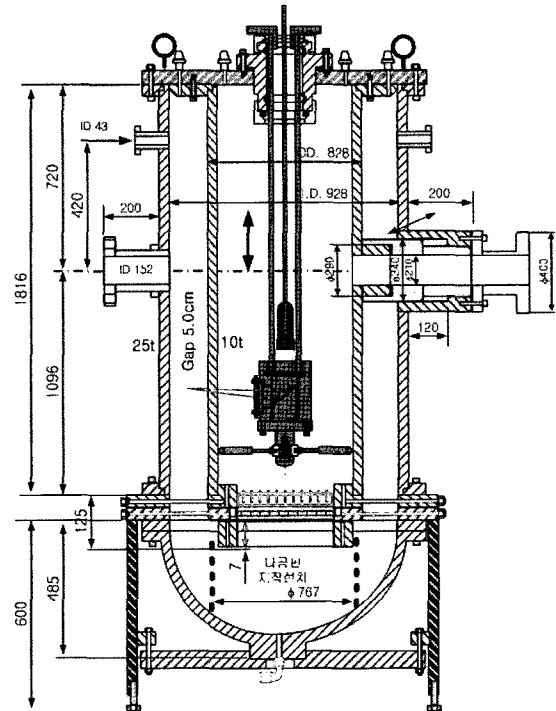


Fig. 11. BOMIX-II Test Facility for Investigating Turbulence Characteristics in the RPV Downcomer

For this purpose, as shown in Fig. 11, another test is being implemented at the BOMIX-II test facility. This test aims to quantitatively evaluate the multi-dimensional behavior by focusing on the effect of the turbulence models selected in the CFD analyses for the flow distribution in an RPV downcomer. In this test, the velocity distribution and the turbulence intensities are being measured at different locations in the downcomer with a laser Doppler velocimetry (LDV), as typically shown in Fig. 12, for a natural circulation or weak forced flow. Measurements are also taken of the concentration of borated water, which is simulated by means of salted water, using the so-called wire mesh technique at the core inlet.

### 3. CONDENSATION-INDUCED THERMAL MIXING IN A LARGE POOL

This subject is associated with the condensation of steam jets and the resultant thermal mixing in a subcooled water pool. The condensation-induced thermal mixing phenomena are major technical concerns, which are directly related to the depressurization system in advanced reactor systems such as the IRWST-SDVS in the APR1400, the ADS-IRWST in the AP600 or AP1000, and the pressure suppression pool in the SWR1000. Along with the SDVS, the IRWST for the APR1400 helps depressurize the RCS by a bleed-feed operation in the case of a total loss of feed water event.

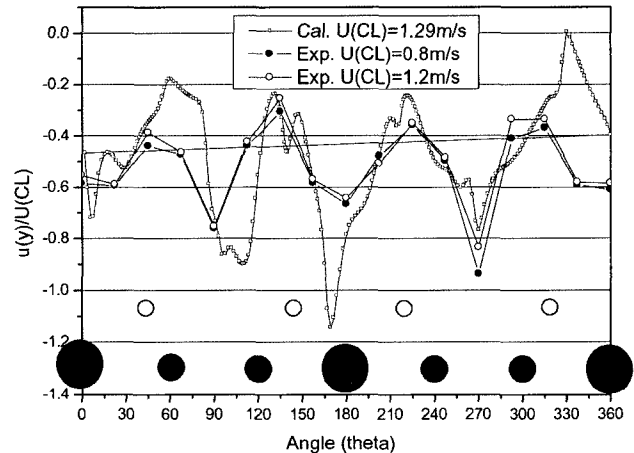


Fig. 12. Typical Results of Velocity Information in the RPV Downcomer: BOMIX-II Test vs. CFD Analysis

### 3.1 Condensation of Steam Jets in a Subcooled Water Pool

We investigated direct contact condensation of steam in a water pool to develop a condensation regime map of



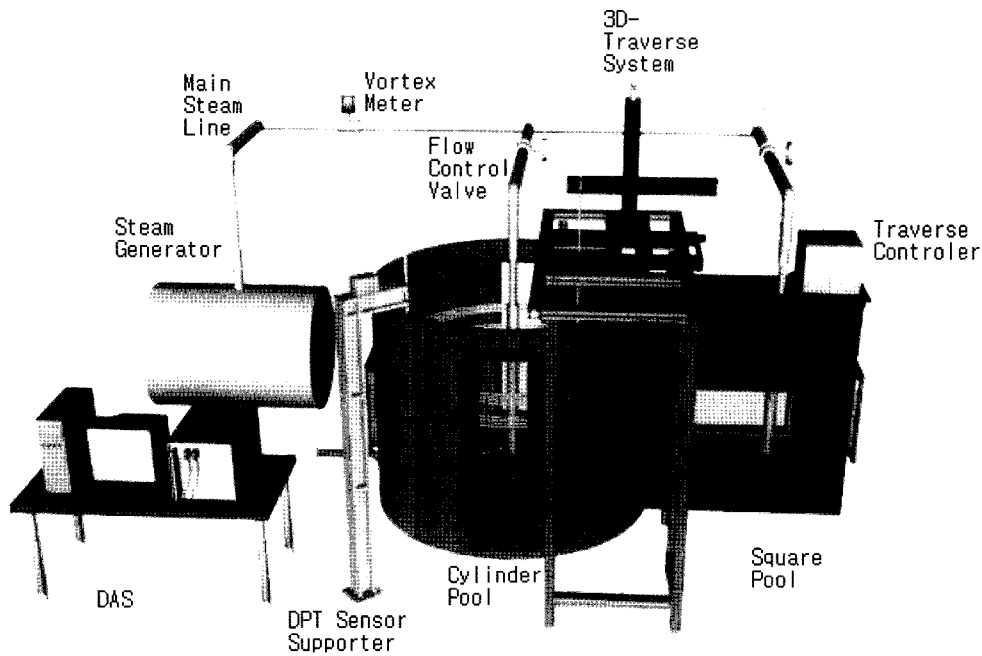


Fig. 13. GIRLS Facility for Steam Jet Condensation in a Pool

the steam jet for simplified spargers. Another objective of this investigation was to produce condensation and thermal mixing models of a steam jet in a water pool. These research items are related to the following: investigating the hydrodynamic load induced by a steam jet condensation; investigating the role of the local temperature in a pool on steam jet condensation behaviors; and producing a turbulent jet model for a steam jet condensation.

As shown in Fig. 13, we performed this experiment in a test facility (GIRLS), which has a steam generation capacity of 0.1 kg/sec under 1.0 MPa and a quench tank of 1.8 m in diameter and 1.5 m in height. The steam mass flux can be widely varied in the range of 0 to 1000 kg/m<sup>2</sup>-s, and the pool water temperature can be varied from 20 to 90 °C. [21]

On the basis of experimental observations [21,22], we have suggested a condensation regime map for a multi-hole sparger, as shown in Fig. 14, to indicate the regime criteria that differ from the case of a single nozzle jet. We have also suggested a model for a condensation heat transfer coefficient and a turbulent jet model for steam jet condensation [23,24].

### 3.2 Thermal Mixing in a Large Pool

Thermal mixing induced by the condensation of a steam jet in a large pool has been one of the major issues to emerge in recent years. This issue is a technically interesting feature of most of the advanced reactor system designs

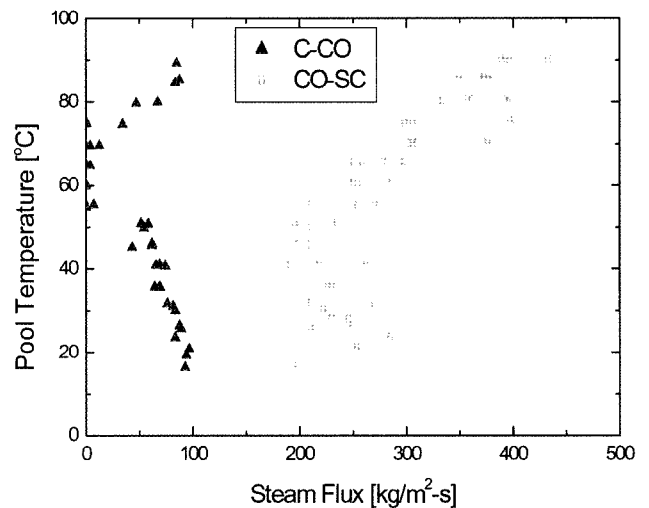


Fig. 14. Condensation Regime Map for a Multi-Hole Sparger

such as the APR1400, the AP600/1000, the EPR, and the SWR1000. The technical aspect involves a combination of steam jet condensation in water and the resultant thermal mixing between hot and cold water. However, the conventional system analysis codes lack the capability of dealing with this multi-dimensional phenomenon, and the

CFD analysis codes of recent interest have not yet been proven to be applicable in the investigation of this mixing issue.

For these reasons, the Korea Atomic Energy Research Institute is conducting experimental and numerical investigations of thermal mixing in a comprehensive way [25,26,27]. An experimental program is being carried out in the B&C loop facility, which consists of a pressurizer, a steam discharge line, a quenching tank and a steam sparger [25]. The steam sparger considered in the work includes both a prototype I-type sparger, as shown in Fig. 15, and a simplified sparger.

The test objectives include the production of an experimental database for evaluating the IRWST of the APR1400 during the bleed-feed operation and the development of an analytical model for a pool mixing analysis with CFD codes [26,27]. Tests have been performed in three cases: first, pool mixing of a transient discharge under a high pressure condition for a prototype I-type sparger, as typically shown in Fig. 15; second, pool mixing of a quasi-steady-state discharge with a high steam mass flux under a medium pressure condition for a simplified sparger [26]; and, third, pool mixing of a quasi-steady-state

discharge with a low steam mass flux under a medium pressure condition for a simplified sparger [27]. These test data were used to understand thermal mixing phenomena in the IRWST.

A CFD analysis was also performed for analyzing pool mixing behavior by comparing with the test data. For this benchmark calculation, we needed a special model for the steam condensation because the CFD codes generally have no model to describe a steam jet condensation in a quenching tank. We therefore developed the so-called condensation region model, where the momentum and the energy of the steam are conserved in the condensed water. In this model, the steam is perfectly condensed to water within the steam penetration length. The penetration length is defined as a function of the steam mass flow, the discharge holes diameter, and the temperature and pressure of the subcooled water. Figure 16 shows a schematic of the condensation region model and we assumed that the condensed water uniformly passes through the boundary of the entire condensed region.

The velocity and the temperature of the condensed water, which we calculated by means of the condensation region model, are used for the boundary conditions of the thermal mixing calculation by the CFD code. The thermal mixing phenomenon in the quenching tank is treated as an incompressible flow. In Fig. 17, which shows a typical temperature distribution in the quenching tank, the distribution varies with time depending on the flow pattern.

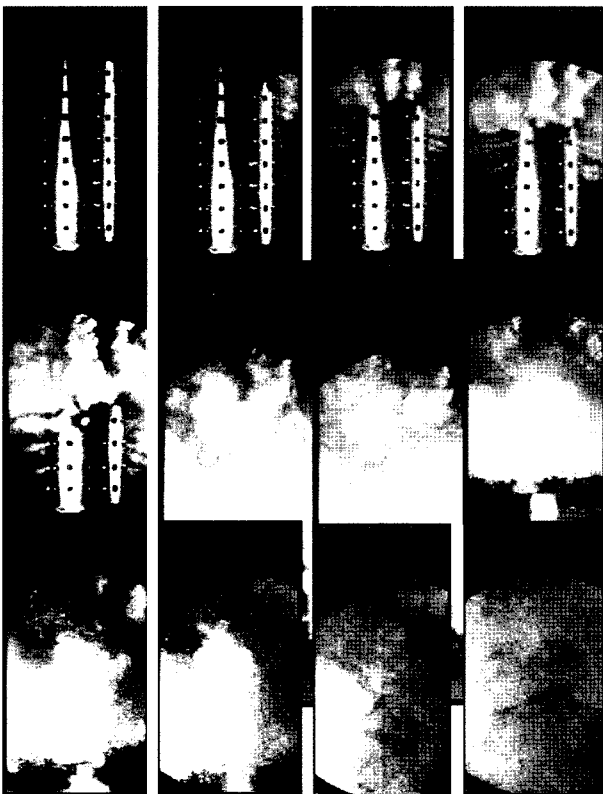


Fig. 15. Blowdown Process Observed in the B&C Facility with a Prototypic Sparger

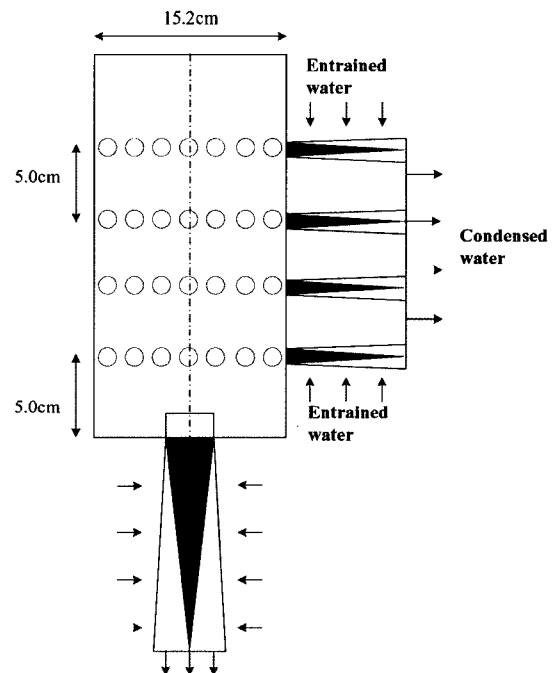


Fig. 16. Steam Condensation Region Model for CFD Analysis

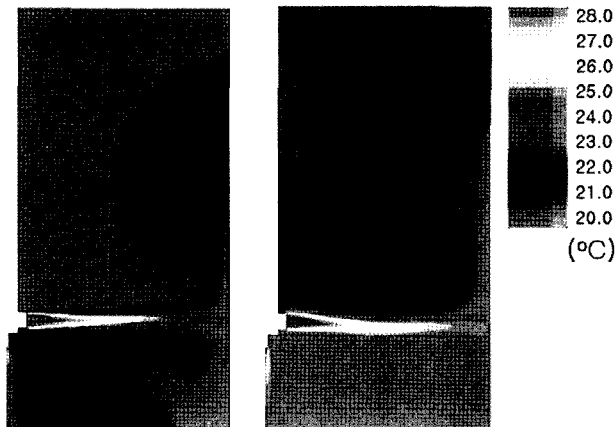


Fig. 17. CFX Calculation Result for a Transient Discharge at  $t=10.5$  sec and 20 sec (Initial Condition: Pzr 100bar, Pool 20 °C)

## 4. DEVELOPMENT OF NEW SAFETY COMPONENTS

### 4.1 Performance Tests for the IRWST and Sparger

To cope with transients such as an RCS overpressure, the APR1400 incorporates the SDVS, which enables a feed-bleed operation capability, and an SIS to maintain the integrity of the RCS and the core. Actuation of the power-operated safety relief valves (POSRVs) results in a transient discharge flow of air, steam or a two-phase mixture to the IRWST through the spargers.

The discharge of these fluids induces complicated thermal-hydraulic phenomena such as a water jet, air clearing, and steam condensation, and these phenomena impose relevant hydrodynamic forces on the IRWST structure and SDVS system. The IRWST structure should therefore be designed so as to withstand these hydrodynamic loads and to maintain its structural integrity as well as the safety functions of the engineered safety features systems.

Hydrodynamic loads on the IRWST wall are induced by air clearing and steam jet discharge through a prototypic sparger of the APR1400. The relevant test of these loads was conducted at the B&C facility [25], as typically shown in Fig. 15. The test was also used to evaluate steam jet condensation and the resultant thermal mixing [25,26].

#### 4.1.1 Air Clearing Loads

Following the opening of the POSRVs, the water inside the spargers is discharged and the air inside the SDVS piping and spargers subsequently passes through the spargers into the IRWST in the form of high pressure bubbles. While rising upward, the bubbles expand and compress due to the momentum of the water and an over-

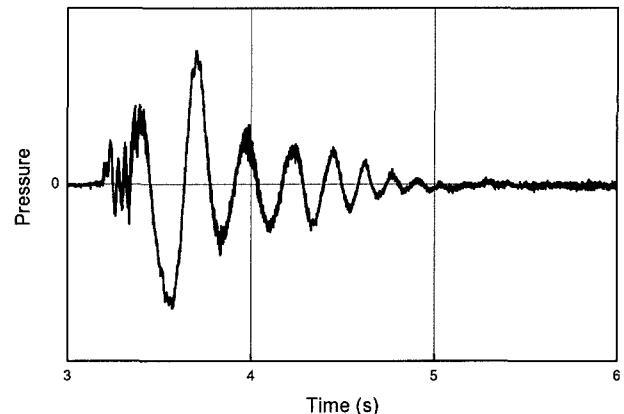


Fig. 18. Typical Dynamic Pressure Signal during the Air Clearing Period

expansion of the bubbles. The oscillation of the bubbles produces an oscillatory load on the submerged portion of the IRWST boundary wall and its internal structures.

There is no established analytical method or clear understanding of the air clearing load caused by the actuation of the POSRVs; furthermore, experimental data for PWR conditions are either rare or unavailable. We therefore conducted a unit cell test with a prototypic sparger to produce thermal-hydraulic load data for the development and verification of an analytical model that can describe the air clearing phenomena [28].

Important parameters for the air clearing phenomena include the air mass in the discharge pipe, the pipe wall temperature, the water temperature in the quenching tank, and the discharged steam mass flow rate. We examined the effect of the valve opening time and the water level in the quench tank. In addition we measured the mass flow rate of steam and air, the pressure and temperature at the discharge pipe, and the dynamic pressure at the bottom and wall of the collection tank [28].

Figure 18 shows a typical trend of the dynamic pressure measured at the IRWST wall during the air clearing phase. The amplitude of the air clearing load depends on the sparger design characteristics such as the type of sparger and the sparger hole pattern. Our test results are prototypic because we used a prototype sparger for the APR1400 in the unit cell sparger test and because of the air mass in the pipe of the test facility and the preservation of the steam pressure and temperature. The data can therefore be used to verify the performance analysis with the aid of the design tools for the IRWST and the SDVS.

#### 4.1.2 Steam Condensation-induced Loads

Following both the water and air clearings from the

SDVS line, a steam or a steam-water mixture is discharged through the spargers into the IRWST and condensed therein. The steam condensation, in general, produces a high frequency, and a low magnitude of an oscillatory loading on the IRWST wall.

After the closure of the POSRVs at the end of the blowdown, the water from the condensation pool rises in a column through the discharge pipe (reflooding phenomena), where condensation of the steam occurs. This phenomenon may produce a big load on the discharge pipe and its supports due to water hammering. The presence of a vacuum valve that enables air to be sucked in can reduce the final level of the water column inside the spargers, thereby greatly reducing the possibility that water hammering will occur. We therefore performed relevant tests with a unit cell sparger to evaluate the hydrodynamic load induced by the steam condensation [25].

#### 4.2 Performance Tests for the Fluidic Device

The APR1400 uses an FD, installed inside the SIT as a passive design feature, to ensure effective use of the SIT water. This design feature enables the APR1400 to achieve the goals of minimizing the ECC bypass during a blowdown, and of preventing a spillage of excess ECC water during the refill and reflood phases of an LBLOCA.

Following a scaled-down model test for developing the FD design for the APR1400, a full-scale performance test was carried out in the VAPER facility to confirm the prototypic performance of the FD designs [29]. The FD design data, which satisfies the performance goal, was obtained from an analysis of the scaled-down model test results.

Figure 19 shows the performance characteristics of the APR1400 FD. The APR1400 FD provides a high discharge flow rate of SI water, when the FD starts to operate, which is required during the refill phase of LBLOCA. When the refill phase is terminated, the discharge flow rate of the SI water drops sharply but is still large enough to remove any heat decay during the reflood phase. Because of the strong vortex motion in the FD, the pressure loss coefficient of the low flow rate period is almost ten times higher than that of the high flow rate period. The difference in the pressure drop helps extend the total duration of the SI water injection and also enables the low pressure safety injection pump to be removed from the SI system.

We performed another test in the VAPER facility to verify the FD performance characteristics of the SKN3&4 reactors, and to confirm the reproducibility of the FD performance in repetitive experiments [30]. From the repeatability tests, we verified that the FD performance satisfies the standard design requirement of the APR1400. In addition, we confirmed the reproducibility of the FD performance with respect to the peak discharge flow rate, the pressure loss coefficient, and the total discharge duration. We strictly applied a quality assurance program

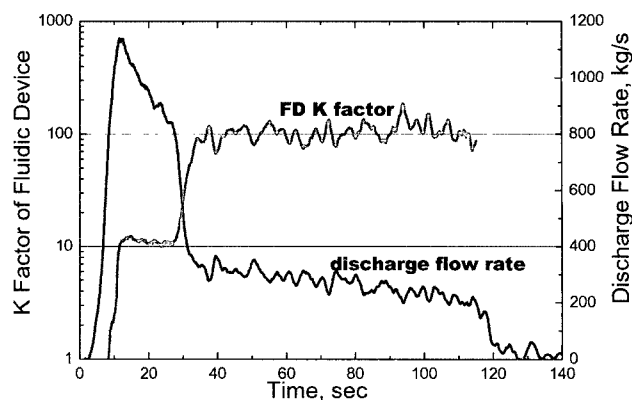


Fig. 19. Example of the Performance of the APR1400 FD

to achieve the experimental results of the highest quality in this test.

#### 5. CONCLUSION

We briefly introduced the THETA thermal-hydraulic experimental program, the aim of which is to develop new design features in the APR1400 and to verify the contribution of the new design features to safety enhancements. We discussed the motivation for the separate effect tests and analyses and illustrated some of the typical results for each item.

The multi-dimensional phenomena that mostly appear in the reactor downcomer annulus and in the IRWST pool were experimentally and analytically investigated in terms of their association with the new safety-related systems. Our aim was to evaluate or validate the prediction capabilities of the analysis tools, particularly the system analysis codes and CFD codes. In addition, we explored the design development and performance verification of the new safety components in the APR1400.

Our results have been used and continue to be used for resolving licensing issues relevant to the standard design approval of the APR1400 and the construction permit of the SKN3&4, particularly with respect to the provision of backup data for licensing. In addition, this work, which is based on experiments and analyses, is believed to be very useful for deepening our understanding of the new thermal-hydraulic phenomena pertaining to advanced reactor system designs.

Aside from the THETA program, we intend to extensively perform integral effect tests with the ATLAS facility in order to verify the safety of the APR1400. Such testing will focus on the transient core-downcomer interaction during the LBLOCA reflood phase as well as on other accidental scenarios related to the new safety design features in the APR1400 [31].

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