# EXPERIMENTS ON THE PERFORMANCE SENSITIVITY OF THE PASSIVE RESIDUAL HEAT REMOVAL SYSTEM OF AN ADVANCED INTEGRAL TYPE REACTOR

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A set of experiments has been conducted on the performance sensitivity of the passive residual heat removal system (PRHRS) for an advanced integral type reactor, SMART, by using a high temperature and high pressure thermal-hydraulic test facility, the VISTA facility. In this paper the effects of the opening delay of the PRHRS bypass valves and the closing delay of the secondary system isolation valves, and the initial water level and the initial pressure of the compensating tank (CT) are investigated. During the reference test a stable flow occurs in a natural circulation loop that is composed of a steam generator secondary side, a secondary system, and a PRHRS; this is ascertained by a repetition test. When the PRHRS bypass valves are operated 10 seconds later than the secondary system isolation valves, the primary system is not properly cooled. When the secondary system isolation valves are operated 10 or 30 seconds later than the PRHRS bypass valves, the primary system is effectively cooled but the inventory of the PRHRS CT is drained earlier. As the initial water level of the CT is lowered to 16% of the full water level, the water is quickly drained and then nitrogen gas is introduced into the PRHRS, resulting in the deterioration of the PRHRS performance. When the initial pressure of the PRHRS is at 0.1 MPa, the natural circulation is not performed properly. When the initial pressures of the PRHRS are 2.5 or 3.5 MPa, they show better performance than did the reference test.

**KEYWORDS** : SMART, Integral Type Reactor, PRHRS, Two-Phase Natural Circulation

## 1. INTRODUCTION

The SMART (System integrated Modular Advanced ReacTor) [1] is a small integral type pressurized water reactor with a power of 330 MWt; it has several enhanced safety features. The primary components of the SMART, which include a core, a pressurizer, steam generators, and main coolant pumps, are housed in the reactor pressure vessel to avoid the occurrence of a large break LOCA (LOss of Coolant Accident). A pilot plant of the SMART, SMART-P, has a rated power of 65 MWt. The SMART and the SMART-P are designed to reach a high safety level by using various passive safety features. Among the safety systems in the SMART-P, the PRHRS is installed to prevent over-heating and over-pressurization of the reactor coolant system during accidental conditions. The PRHRS removes the core decay heat and sensible heat with a natural circulation in emergency conditions when the normal feed water supply and steam extraction are unavailable.

It is necessary to perform design-related experiments to validate the performance capability and sensitivity of the PRHRS. The VISTA (Experimental Verification by Integral Simulation of Transients and Accidents) facility [2] has been constructed to simulate the SMART-P. The VISTA facility is an integral effect test facility and its scaled ratios are 1/1 in height and 1/96 in volume with respect to the SMART-P. Its design pressure and temperature are set to simulate the steady-state and transient conditions of the SMART-P. The PRHRS of the VISTA facility is designed to simulate the operating conditions and system characteristics of the reference system of the SMART-P. During the PRHRS operation, the major thermal hydraulic phenomena are the two-phase natural circulation flow by the hydraulic head, two-phase pressure drop through the loop, condensation in the PRHRS heat exchanger tube, and boiling in the emergency cooldown tank (ECT).

Research into the thermal-hydraulic behaviors of the SMART PRHRS and the VISTA facility has been performed previously. Chung et al. [3] investigated the thermal-hydraulic characteristics of the PRHRS in the SMART by using the MARS code, and showed that the

PRHRS fulfilled its functions in removing the heat transferred from the primary side of the steam generator when the heat exchanger was submerged in the ECT. Parametric studies of the thermal hydraulic characteristics of transient operations of the VISTA facility were also reported by Choi et al. [4] for a design verification of the SMART-P. This research included safety related accidents of a feed water increase or decrease, loss of coolant flow, and control rod withdrawal accidents. Park et al. [5] performed experiments to investigate the characteristics of the natural circulation and pressure drop in the circulation loop to understand the natural circulation performance of the PRHRS in the SMART-P, the heat transfer characteristics of the PRHRS heat exchangers and the ECT, and the overall thermal-hydraulic behavior in the primary system during the PRHRS operation. A comparative experimental study of the SMART PRHRS is also reported by Park et al. [6] and two-phase natural circulation performance of the PRHRS for the SMART-P following a safety related event has been experimentally investigated by using the VISTA facility [7]. A set of experiments has also been performed to investigate the effects of several components of the SMART-P such as the gas cylinder and CT on the performance of the PRHRS by using the VISTA facility [8].

In this paper a set of experiments has been performed to investigate the performance sensitivity of the PRHRS for the SMART-P by using the VISTA facility; the effects of the opening delay of the PRHRS bypass valves, and the initial water level and the initial pressure of the CT were investigated.

## 2. DESCRIPTION OF THE TEST FACILITY

### 2.1 VISTA Facility and PRHRS

The schematic view of the VISTA facility is shown in Fig. 1. The VISTA facility is an integral test facility created to simulate the primary system and secondary system, as well as the major safety-related systems, of the PRHRS. Its scaled ratios are 1/1 in height and 1/96 in volume with respect to the SMART-P. The reactor core is simulated by electric heaters with a capacity of 818.75kW, which is about 120% of the scaled power. Unlike the integrated arrangements of the SMART-P, the VISTA primary components are connected to each other by pipes for easy installation of the instrumentation and for simple maintenance. The primary system of the VISTA facility includes the reactor vessel, the main coolant pump (MCP), the steam generator, and the pressurizer, all of which are connected to each other by pipes. The secondary system has a single train and is simply designed to remove the primary heat source, which is composed of a feed water supply tank (FWST), a feed water pump, a silencer,

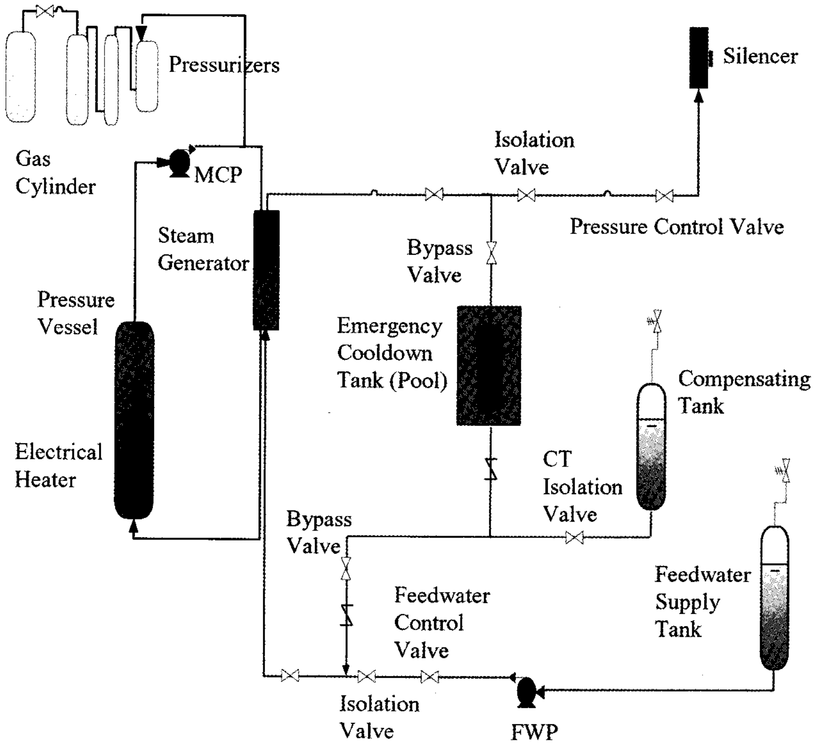

Fig. 1. Schematic Diagram of the VISTA Facility for SMART-P

several valves and related piping. Besides these major systems, a make-up water system and a chilled water system are installed to control the feed water supply and its temperature.

### 2.2 PRHRS of the VISTA Facility

The PRHRS of the VISTA facility is composed of a train for the cooling subsystem, which includes an ECT, a heat exchanger, a CT, several valves and related piping. It is designed to have the same pressure drop and heat transfer characteristics and is arranged to have the same elevation and position as those of the reference system, SMART-P. The VISTA PRHRS is described in previous literature in detail [5]. The technical specifications of the PRHRS of the VISTA facility are summarized in Table 1. The VISTA facility was modified from the original design [5] to perform the sensitivity experiments for the PRHRS performance. In the revised VISTA facility a check valve was additionally installed on the PRHRS condensation line just upstream of the junction to the feed water line of the secondary system and a PRHRS heat exchanger was installed inside the ECT pool. In previous works [5] the inventory in the ECT was circulated by using a coolant circulation pump, while in the present test the ECT barrel was extended to work as a suppression pool. In the present tests the CT is always used during the PRHRS operation. The detailed description of the original and modified experimental facilities is to be found in the previous works [5, 7].

## 3. TEST PROCEDURE AND TEST MATRIX

### 3.1 Test Procedure

The VISTA facility is designed to be operated by a combination of manual and automatic operation. Once the major thermal-hydraulic parameters reach a steady state condition, they are switched over automatically to the control of a PID feedback control logics, which maintains the achieved steady state condition. During the steady-state operation the coolant is circulated by the MCP in the primary loop. In the secondary loop, the feed water is supplied into the SG secondary side by the feed water pump from the FWST, where the water changes into superheated steam that is then vented to the atmosphere through the silencer to eventually maintain the required system pressure. The pressure is controlled by the pressure control valve installed upstream of the silencer.

After reaching a steady state condition and with some delay time, the PRHRS is immediately triggered to start opening the bypass valves that connect the PRHRS to the secondary system and closing the secondary system isolation valves that isolate the secondary system from the feed water supply tank and the silencer. During the

**Table 1**. Technical Specifications of the PRHRS of the VISTA Facility

| Parameters | Unit | Reference Plant | VISTA |
|---|---|---|---|
| Operating pressure | MPa | 3.5 | 3.5 |
| Operating temperature | °C | 242.5 | 242.5 |
| No. of PRHRS trains | EA | 4 | 1 |
| No. of HX tubes/train | EA | 141 | 6 |
| HX: Tube length, ID, thickness | m | 1.2, 0.013, 0.0025 | 1.2, 0.013, 0.0025 |
| HX (including headers): Volume | $m^3$ | NA | 0.00165 |
| HX: Tube material | - | Titanium Alloy | Inconel 600 |
| CT: ID, Height | m | 0.55, 1.5 | 0.0873, 1.5 |
| CT: Volume/tank | $m^3$ | 0.35 | 0.0096 |
| CT surge line: Volume | $m^3$ | NA | 0.00027 |
| ECT (revised): ID, Height | m | NA | 0.4, 3.4 |
| ECT (revised): Volume/tank | $m^3$ | NA | 0.430 |
| SG secondary: Volume | $m^3$ | NA | 0.00567 |
| SS steam line: Volume | $m^3$ | NA | 0.00730 |
| SS condensate line: Volume | $m^3$ | NA | 0.00135 |
| PRHRS steam line: Volume | $m^3$ | NA | 0.00092 |
| PRHRS condensate line: Volume | $m^3$ | NA | 0.00011 |

**Table 2**. Test Matrix for the PRHRS Sensitivity Tests

| Parameter | Test ID | Changes from the Reference Test |
|---|---|---|
| Reference | PRHRS-P-R1 | - |
| | PRHRS-P-R1R | Repetition test |
| Opening time of the PRHRS bypass valves | PRHRS-P-R1-A2 | 10 seconds earlier |
| | PRHRS-P-R1-A3 | 10 seconds later |
| | PRHRS-P-R1-A4 | 30 seconds earlier |
| Initial water level of CT | PRHRS-P-R1-C2 | Initial CT level: 16% |
| Initial pressure of CT | PRHRS-P-R1-D2 | Initial CT pressure: 0.1 MPa |
| | PRHRS-P-R1-D3 | Initial CT pressure: 2.5 MPa |
| | PRHRS-P-R1-D4 | Initial CT pressure: 3.5 MPa |

PRHRS operation the steam generated from the secondary side of the steam generator is transported through the PRHRS steam line and then condensed in the PRHRS heat exchanger, and the condensate water flows into the steam generator again by gravity force through the feed water supply line and the PRHRS condensate line, which forms a two-phase natural-circulation loop.

## 3.2 Test Matrix

Nine comparative experiments have been performed to investigate the performance sensitivity of the PRHRS for an advanced integral type reactor, SMART-P, by using the VISTA facility. The test matrix for the PRHRS sensitivity tests is shown in Table 2. The sensitivities of the design parameters of the performance of the PRHRS are tested to investigate the effects of the opening delay of the PRHRS bypass valves and the closing delay of the secondary system isolation valves, and the initial water level and the initial pressure of the CT. Table 3 summarizes the initial conditions for the reference test, PRHRS-P-R1, which are the normal design conditions for the PRHRS to be operated.

**Table 3**. Initial Conditions for the Reference Test

| Parameter | Initial Conditions |
|---|---|
| The opening times of PRHRS isolation or bypass valves | Simultaneous opening and closing |
| Initial water level of the CT | 80% |
| Initial pressure of the CT | 4.5 MPa |
| Opening of the CT isolation valve | Normally open |
| ECT | Pool-type cooling |
| Initial filling of the PRHRS piping | Filled with water |

During the reference test the reactor core is simulated by an electric heater to which the predetermined power from the programmed ANS-73 decay curve is given. Its initial feed water flow rate was 50% of the rated values and its initial primary flow rate was 100% of the rated flow rate. The scaled 100% flow rates of the primary system are 0.00544 $m^3/s$ at the same pressure and temperature of 14.7 MPa and 310°C, respectively, as those of the reference plant; the scaled 100% flow rates of the secondary system are 0.25 kg/s. In the reference test of PRHRS-P-R1 both the PRHRS bypass valves and the secondary system isolation valves were operated simultaneously; the initial water level of the CT was 80% of the full level, and the initial pressure of the CT was 4.5 MPa. The test of PRHRS-P-R1R is the repetition test for the reference test.

While both the PRHRS bypass valves and the isolation valves of the secondary system actuate simultaneously during the reference test, the PRHRS bypass valves are opened 10 seconds later than the closing of the secondary system isolation valves during the test of PRHRS-P-R1-A3. For the tests of PRHRS-P-R1-A2 and PRHRS-P-R1-A4 the PRHRS bypass valves are opened 10 and 30 seconds earlier, respectively, than the opening time of the secondary system isolation valves. PRHRS-P-R1-C2 is different from the reference test in that it has a different initial water level of 16%, and PRHRS-P-R1-D2, PRHRS-P-R1-D3, and PRHRS-P-R1-D4 are different from the reference test in that they have different initial pressures of 0.1, 2.5, 3.5 MPa, respectively.

## 4. RESULTS AND DISCUSSION

First of all, the results of the reference and repetition tests are explained in detail and then the effects of the opening delay of the PRHRS bypass valves and the closing delay of the secondary system isolation valves, and the initial water level and pressure of the CT, are compared with the reference test.

### 4.1 The Reference and Repetition Tests

Figures 2 through 4 show the comparisons of the natural circulation flow rates, the PRHRS pressures, and the CT water levels, respectively, during the PRHRS operation of the reference and repetition tests. As shown in Figure 2, during the PRHRS operation of the reference test the maximum flow rate of the natural circulation was about 0.023 kg/s (9.2% of the rated secondary flow rate) and the flow rate gradually decreased. During the operation of the repetition test the natural circulation flow rate is low at below 0.017 kg/s (6.8% of the rated secondary flow rate) in the initial period of about 400 seconds; this low level is caused by the lower injection rate of the CT water as shown in Figure 4, and after this the trend for this flow rate becomes similar to that of the rate in the reference test. Compared with the previous experimental results of Park et al. [5], the natural circulation flow rate is lower due to the increased hydraulic resistance caused by an additional check valve. The slower decreasing rate of the natural circulation flow rate is due to the operation of the CT.

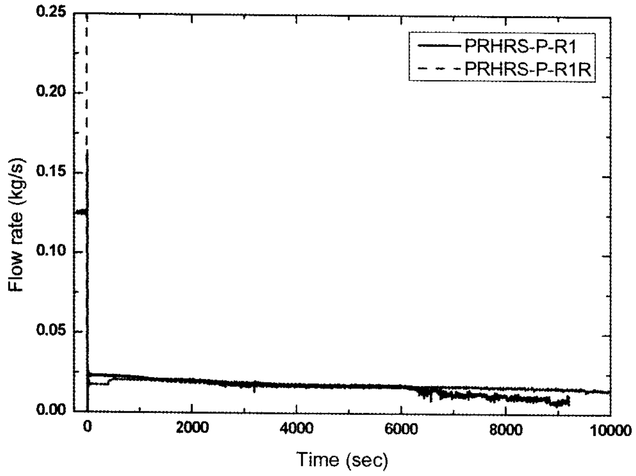

Fig. 2. Comparison of the Natural Circulation Flow Rates between the Reference and Repetition Tests

As shown in Figure 3, the trend of the system pressure is similar to that of the natural circulation flow rate. The initial maximum system pressures were about 5.3 and 5.0 MPa for the reference and repetition tests, respectively, and the system pressure decreased gradually. The difference in these pressures is due to the difference of the initial CT level between the reference and repetition tests. They are lower than 6.2 MPa, which value is obtained without the operation of the CT [5]. However, the decreasing rates of the system pressure are also very small due to the operation of the CT. In the repetition test, the decreasing rate of the PRHRS pressure is slower than that in the reference test. This is due to the higher temperature in the primary system and the greater inventory of the nitrogen gas in the CT with a lower initial water level.

As shown in Figure 4, the CT water level increases temporarily as the system pressure becomes higher than the initial CT pressure of 4.5 MPa; it then decreases gradually as the system pressure decreases and the CT inventory is injected into the PRHRS loop. The initial CT water levels are 1.21 and 1.25 kg/s for the tests of PRHRS-P-R1 and PRHRS-P-R1R, respectively. In the repetition test the CT water is slowly injected into the PRHRS loop due to the higher system pressure in the PRHRS loop. As shown in Figure 5, the system pressure is higher in the repetition test than in the reference test throughout the PRHRS operation. The pressures in the primary system decrease to 10.2 and 10.8 MPa for the

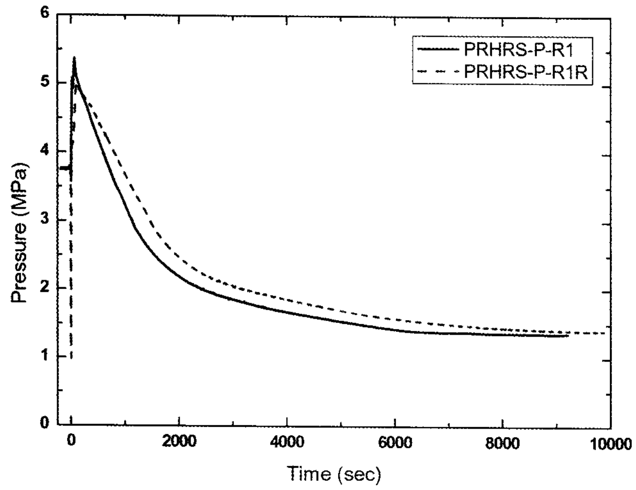

Fig. 3. Comparison of the PRHRS Pressures between the Reference and Repetition Tests

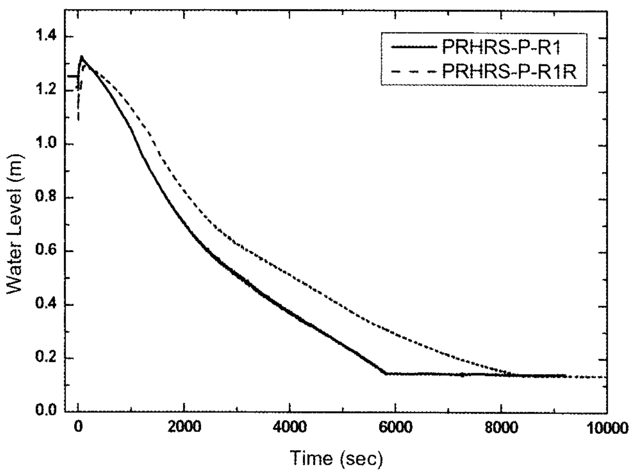

Fig. 4. Comparison of the CT Water Levels between the Reference and Repetition Tests

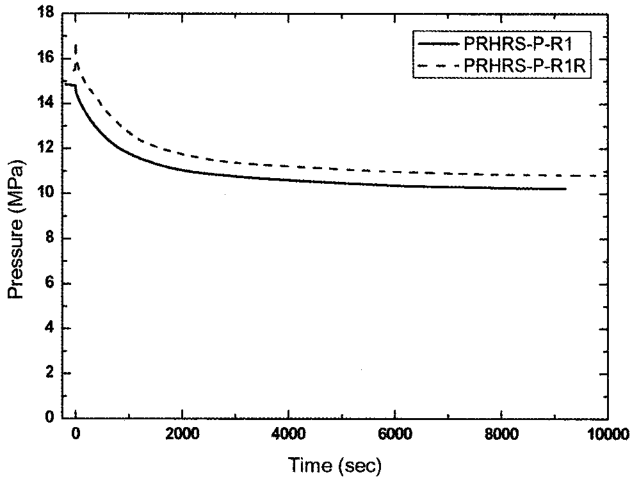

Fig. 5. Comparison of the Primary System Pressures between the Reference and Repetition Tests

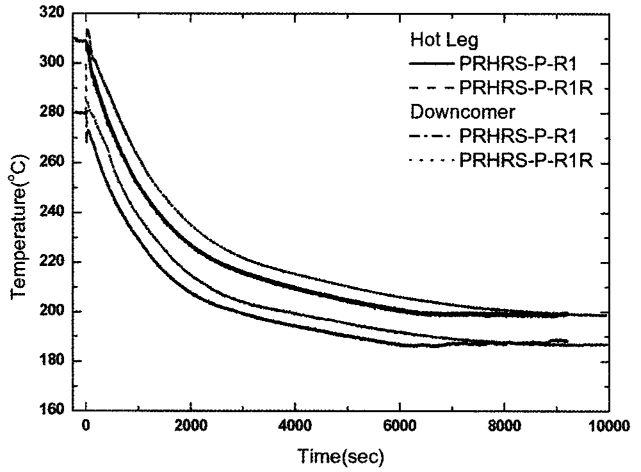

Fig. 6. Comparison of the Primary System Temperatures between the Reference and Repetition Tests

tests of PRHRS-P-R1 and PRHRS-P-R1R, respectively.

As shown in Figure 6, the temperatures in the hot leg decrease to 198 and 199°C for the tests of PRHRS-P-R1 and PRHRS-P-R1R, respectively, and these trends are similar to the trend of the system pressure in the primary loop. As the initial pressure and thus its initial temperatures in the primary loop are a little higher in the repetition test, the detailed parameters of the natural circulation flow rate, the secondary system pressure, and the CT water level show a little difference between the reference and repetition tests. However, the experimental results showed that the overall thermal-hydraulic characteristics were very similar and that the PRHRS operated well for both the reference and repetition tests. Previous test results also showed that the differences of the initial core power, the initial primary flow rate, and the initial feed water flow rate had little effect on the overall thermal-hydraulic behavior in the PRHRS loop. [5]

## 4.2 Effect of the Opening Delay Time of the PRHRS Bypass Valves

Figures 7 through 9 show the comparisons of the natural circulation flow rates, the PRHRS pressures, and the CT water levels, respectively, during the PRHRS operation for the PRHRS-P-R1-A2, PRHRS-P-R1-A3, and PRHRS-P-R1-A4 tests. As shown in Figure 7, the initial feed water flow rates were 0.125, 0.1125, 0.125, and 0.25 kg/s for the PRHRS-P-R1, PRHRS-P-R1-A2, PRHRS-P-R1-A3, and PRHRS-P-R1-A4 tests, respectively. All the feed water flow rates decreased rapidly to about 0.023 kg/s, which is about 9.2% of the scaled secondary

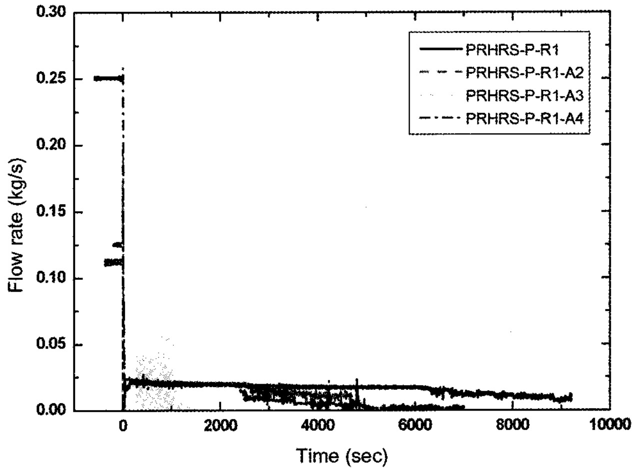

Fig. 7. Natural Circulation Flow Rates for Different Operation Delay of Valves

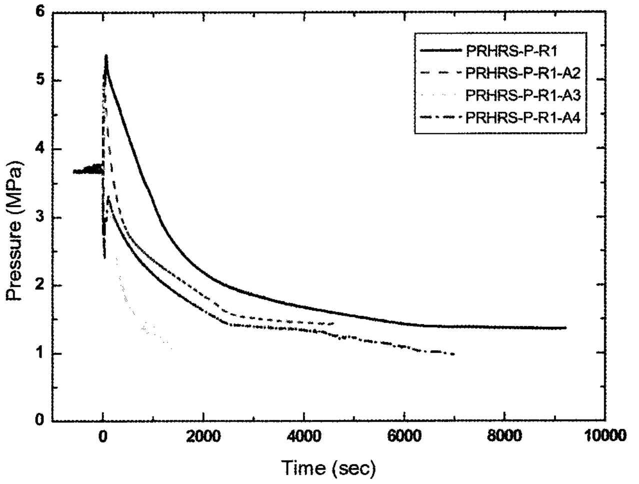

Fig. 8. PRHRS Pressures for Different Operation Delay of Valves

flow rate, even though the initial feed water flow rates were different. When the PRHRS bypass valves were opened 10 seconds later than the closing of the secondary system isolation valves (PRHRS-P-R1-A3), the natural circulation flow rate oscillated with a very high amplitude initially and eventually stopped after an operation of about 1100 seconds as both the CT water level and the secondary system pressure decreased rapidly. When the PRHRS bypass valves are opened earlier than the isolation valves of the secondary system (PRHRS-P-R1-A2 and PRHRS-P-R1-A4), the flow rates begin to oscillate at around 2400 seconds, which coincides with the draining time of the CT. As the water inventory of the CT is drained, the nitrogen gas may be injected into the circulation loop, which inhibits a steady natural circulation.

As shown in Figure 8, the initial maximum system pressures for the PRHRS-P-R1-A2, PRHRS-P-R1-A3, and PRHRS-P-R1-A4 tests were about 4.6, 4.7, and 3.3 MPa, respectively, which were lower than the initial maximum system pressure of the reference test. During the opening delays of the PRHRS bypass valves, which were of 10 seconds duration (PRHRS-P-R1-A3), the water inventory in the CT was drained quickly to fill up the secondary side of the steam generator by the pressure difference between the CT and the secondary system; thus, the liquid level in the secondary side of the steam generator rose high. As there is a large oscillation in the natural circulation flow rate and there is very little steam space in the secondary side of the steam generator, the system pressure decreases very rapidly with the drainage of the water inventory in the CT. During the closing delays of the secondary system isolation valves, which were 10 and 30 seconds in duration (PRHRS-P-R1-A2 and PRHRS-P-R1-A4). The steam is vented through the silencer and the peak system pressure becomes lower than that of the reference test. As the delay time of the valve closing becomes longer, more steam is vented and the system pressure is lowered.

As shown in Figure 9, the draining rate of the water inventory in the CT is very high with the opening delays of the PRHRS bypass valves (PRHRS-P-R1-A3), while it is relatively low with the closing delays of the secondary system isolation valves (PRHRS-P-R1-A2 and PRHRS-P-R1-A4). Similarly to the reference test, the primary system pressure and temperature decreased rapidly with the operation of the PRHRS, and then gradually in the later stages. However, after the water inventory in the CT was drained, the cooling capacity of the PRHRS system was greatly reduced and the pressure and temperature in the primary system stagnated.

In summary, both the opening delays of the PRHRS bypass valves and the closing delays of the secondary system isolation valves have negative effects on the performance of the PRHRS. However, the closing delays of the secondary system isolation valves provide a steadier natural circulation flow rate and lower peak pressure than did those of the reference test, which could be an advantage over the reference test.

## 4.3 Effect of the Initial Level of the CT

Figures 10 through 12 show the effects of the initial water level of the CT. PRHRS-P-R1-C2 indicates the case in which the initial water level is reduced to 16% rather than the 80% of the reference test. Figure 10 shows a comparison of the pressures in the secondary systems. The normal operating secondary pressure is 3.55 MPa. Upon the transient, the pressure suddenly increases from 3.55 MPa to reach a maximum peak value of 5.2 MPa; it then decreases gradually. There is no noticeable difference between the PRHRS-P-R1 and

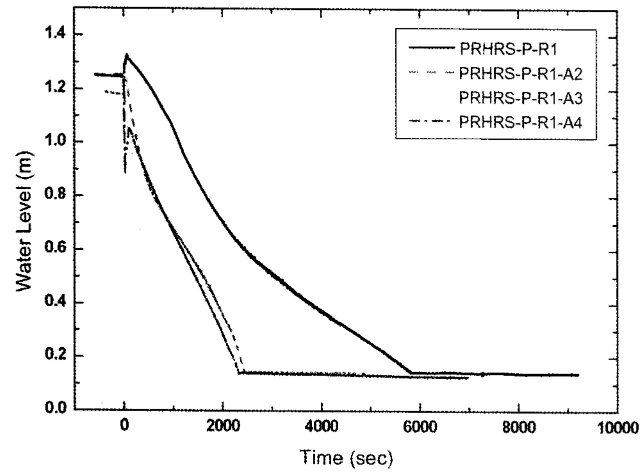

Fig. 9. CT Water Levels for Different Operation Delay of Valves

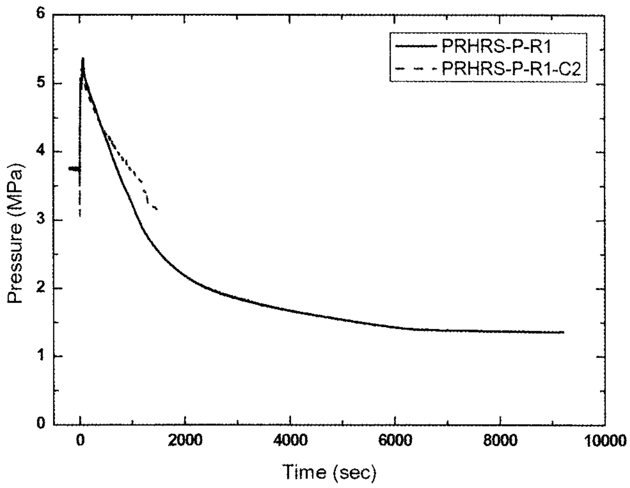

Fig. 10. PRHRS Pressures for Different Initial Water Level of the CT

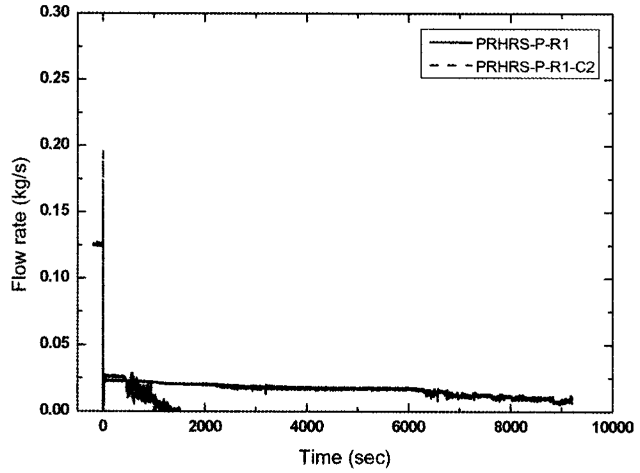

Fig. 11. Natural Circulation Flow Rates for Different Initial Water Level of the CT

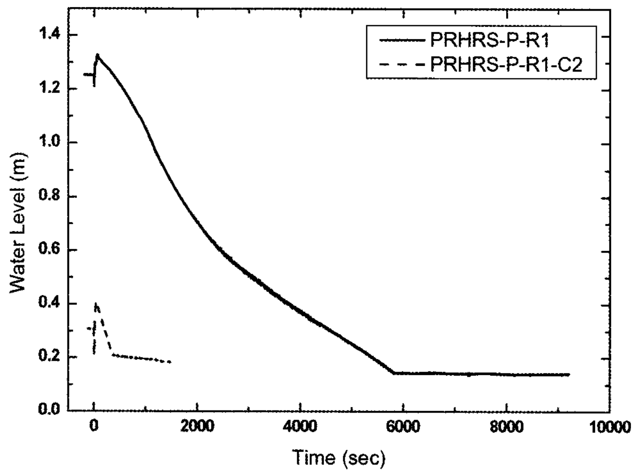

Fig. 12. CT Water Levels for Different Initial Water Level of the CT

PRHRS-P-R1-C2 tests in the earlier stages. However, the decrease of the system pressure in PRHRS-P-R1-C2 becomes slower than that in the reference test as the natural circulation flow rate decreases with an oscillation; the decrease of the system pressure eventually stops at about 1500 seconds after the start of the PRHRS operation.

Figure 11 shows a comparison of the natural circulation flow rates during the PRHRS operation. Upon the transient, the feed water supply is blocked by the isolation valve, and the bypass valve from the steam line to the PRHR system is opened. In the beginning of the transient the PRHRS-P-C2 test shows a natural circulation flow rate of about 0.028 kg/s, which is about 11.2% of the scaled secondary flow rate, under a PRHRS operation similar to the reference case. However, the flow begins to oscillate at around 560 seconds and the natural circulation stops at about 1500 seconds. This time is consistent with the draining time of the CT in Figure 12. Figure 12 shows the comparison of the water levels in the CT. As the initial water level is 16%, the water is quickly drained and finally the nitrogen gas in the CT is introduced into the PRHRS. This results in a failure of the natural circulation flow due to a reduced heat transfer.

The main reason for the failure of the PRHRS is the introduction of the nitrogen gas from the CT. Therefore, it is found that the 16% initial water level in the CT results in the deterioration of the PRHRS's performance, and the nitrogen ingression should be blocked in order to secure a stable cooling performance.

## 4.4 Effect of the Initial Pressure of the PRHRS

The CT is a water reservoir that is pressurized by nitrogen gas and is connected to the condensate line of the PRHRS. Therefore, it compensates for the loss of the water inventory in the PRHRS circulation loop during the PRHRS operation. If the CT is installed in the PRHRS loop, the PRHRS can maintain a steady flow rate with its initial water inventory in the CT, and it can maintain a steady pressure condition with its initial gas inventory in the CT. Figures 13 through 15 show the comparisons of the natural circulation flow rates, the PRHRS pressures, and the CT water levels, respectively, during the PRHRS operations of the PRHRS-P-R1-D2, PRHRS-P-R1-D3, and PRHRS-P-R1-D4 tests.

As shown in Figure 13, the initial feed water flow rates are 0.10, 0.125, and 0.25 kg/s for the PRHRS-P-R1-D2, PRHRS-P-R1-D3, and PRHRS-P-R1-D4 tests, respectively. As the PRHRS operation is triggered, the flow rates in the PRHRS loop decrease rapidly. When the initial CT pressure is 0.1 MPa (PRHRS-P-R1-D2), a

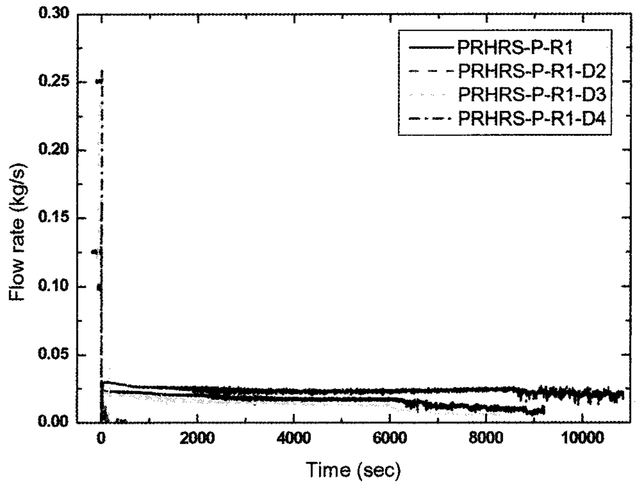

Fig. 13. Natural Circulation Flow Rates for Different Initial Pressure of the PRHRS

natural circulation is not formed in the PRHRS loop. When the initial CT pressures are 2.5 and 3.5 MPa (PRHRS-P-R1-D3 and PRHRS-P-R1-D4), the flow rates are reduced to 0.022 and 0.03 kg/s, respectively. The PRHRS-P-R1-D4 test provides the best performance in terms of the natural circulation flow rate. The flow rate maintains a constant value by the operation of the CT and the flow begins to oscillate according to the time of the inventory loss of the CT.

As shown in Figure 14, the initial maximum system pressures for the PRHRS-P-R1-D2, PRHRS-P-R1-D3, and PRHRS-P-R1-D4 tests were about 0.33, 4.5, and 6.1 MPa, respectively. During the PRHRS-P-R1-D2 test the natural circulation cannot be continued in the PRHRS loop. During the PRHRS-P-R1-D3 test the initial pressure is always lower than that of the reference test; however, during the PRHRS-P-R1-D4 test the initial pressure is higher in the earlier stage and decreases rapidly to maintain, in the later stages, a value lower than that found in the reference test. Figure 15 shows the variation of the CT water level during the PRHRS operation with different initial CT pressures. During the PRHRS-P-R1-D2 test the water inventory in the secondary system flows into the CT and the CT water level rapidly increases to balance the system pressure between the CT and the PRHRS loop. During the PRHRS-P-R1-D3 test the CT water level increases to 1.47 m and decreases gradually. During the PRHRS-P-R1-D4 test the trend of the water level is similar to that in the PRHRS-P-R1-D3 test but its decreasing rate is slower than that found in the PRHRS-P-R1-D3 test.

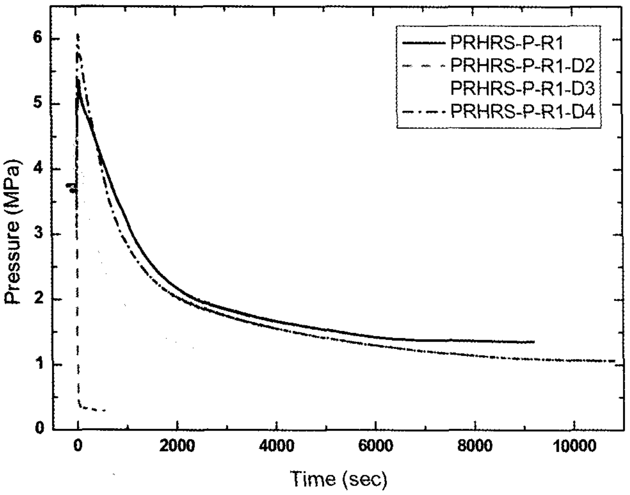

Fig. 14. PRHRS Pressures for Different Initial Pressure of the PRHRS

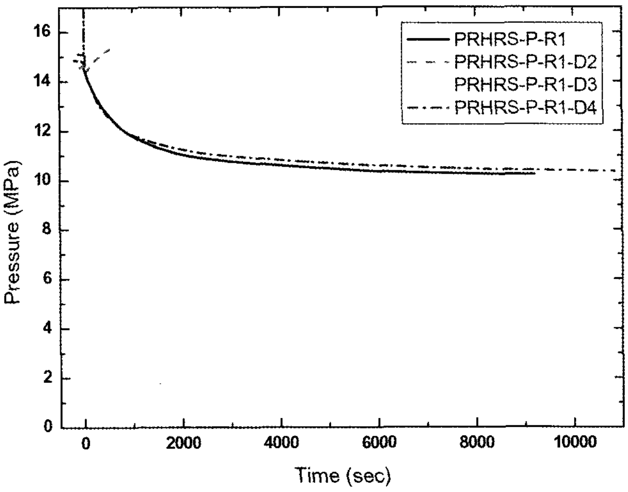

Fig. 16. Primary System Pressures for Different Initial Pressure of the PRHRS

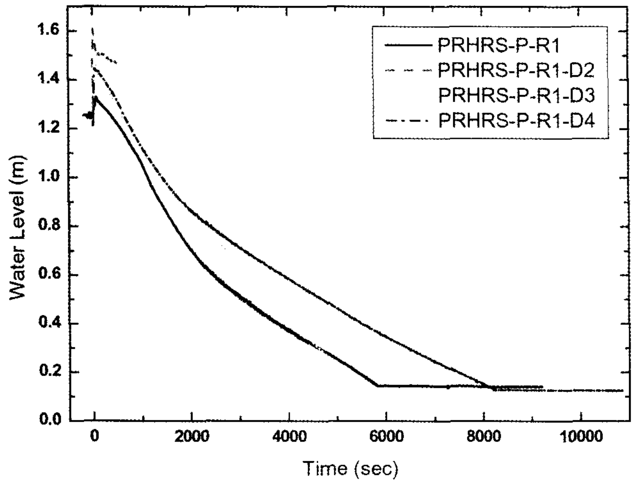

Fig. 15. CT Water Levels for Different Initial Pressure of the PRHRS

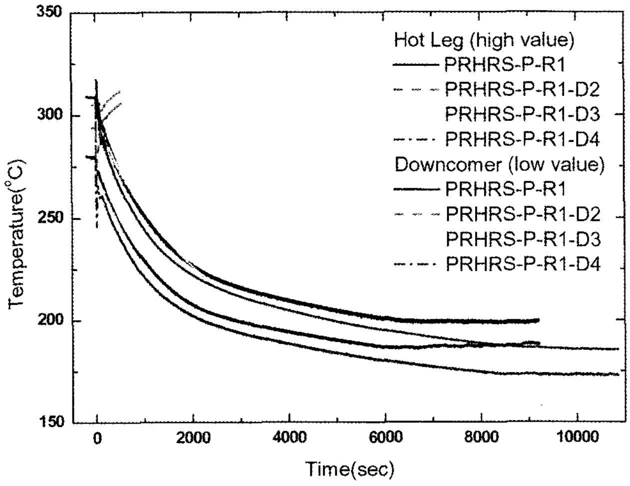

Fig. 17. Primary System Temperatures for Different Initial Pressure of the PRHRS

Figures 16 and 17 show the variations of the pressures and temperatures, respectively, in the primary system during the PRHRS operation. With the operation of the PRHRS both the pressure and temperature of the primary system decrease rapidly in the earlier stages and gradually in the later stages due to a variation of the heat sink capability of the PRHRS. For the PRHRS-P-R1-D2 test both the pressure and the temperature in the hot leg increase; this is due to a failure of the heat removal through the steam generator. The pressures in the primary loop decrease to 9.6 and 10.4 MPa for the PRHRS-P-R1-D3 and PRHRS-P-R1-D4 tests, respectively. The temperatures in the hot leg decrease to 176 and 185°C for the PRHRS-P-R1-D3 and PRHRS-P-R1-D4 tests, respectively. During the PRHRS-P-R1-D2 test the natural circulation fails. The water level stays at a level higher than 80% throughout the test, or the water is not supplied from the CT to the secondary side of the steam generator, in which case only the single-phase steam is heated by the decay heat transferred through the steam generator helical tube. As the decay heat is not removed by the failed operation of the PRHRS, both the pressure and temperature of the primary system increase gradually. During the PRHRS-P-R1-D3 test the maximum peak pressure in the PRHRS loop is lower but the natural circulation flow rate is slightly smaller than those of the reference test; however, during the PRHRS-P-R1-D4 test the maximum peak pressure in the PRHRS loop is higher but the natural circulation flow rate is a little larger than those in the reference test.

## 5. CONCLUSIONS

A set of experiments has been performed to investigate the overall performance sensitivity of the PRHRS of the VISTA facility, which simulates the SMART-P. The thermal-hydraulic characteristics, such as the natural circulation flow rate, secondary system pressures, CT water level, and pressure and temperature in the primary loop, have been experimentally investigated by using the VISTA facility. In this paper the effects of the opening delay of the PRHRS bypass valves and the closing delay of the secondary system isolation valves, and the initial water level and initial pressure of the CT, were investigated experimentally. The following conclusions were derived.

1. During the reference test a stable flow occurs in a natural circulation loop that is composed of a steam generator secondary side, a secondary system, and a PRHRS; this is ascertained by a repetition test. That is, a two-phase natural circulation flow is properly achieved in the PRHRS loop to remove the decay heat from the primary system.
2. When the PRHRS bypass valves are opened later than the secondary system isolation valves, the primary system is not properly cooled. When the secondary system isolation valves are closed later than the PRHRS bypass valves, the primary system is effectively cooled but the inventory of the PRHRS CT is drained earlier.
3. When the initial water level of the CT is very low, the water in the CT is quickly drained, and the nitrogen gas is introduced into the PRRHS. A nitrogen ingression results in the deterioration of the PRRHS's performance and stops the natural circulation in the PRHRS. Therefore, a nitrogen ingression should be prevented in order to secure a stable PRHRS operation.
4. When the initial pressure of the PRHRS is at atmospheric pressure, a natural circulation is not performed properly. When the initial pressures are 2.5 and 3.5 MPa, the system shows better performance than the reference test in terms of the maximum system pressure and the natural circulation flow rate, respectively. When the normal operating pressure of the secondary system is 3.5 MPa, it is recommended that the initial pressure of the PRHRS be set at the operating pressure of the system or somewhat lower than that.

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