Proceedings of the Korean Nuclear Society Spring Meeting
Gyeong ju, Korea, May 2003

Preliminary Experimental Results Using the Thermal-Hydraulic Integral Test Facility (VISTA) for the Pilot Plant of the System Integrated Modular Advanced Reactor, SMART-P

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ABSTRACT

Preliminary experimental tests were carried out using the thermal-hydraulic integral test facility, VISTA (Experimental Verification by Integral Simulation of Transients and Accidents), which has been constructed to simulate the SMART-P. The VISTA facility is an integral test facility including the primary and secondary systems as well as safety–related passive Residual heat removal (PRHR) systems. Its scaled ratio with respect to the SMART-P is 1/1 in height and 1/96 in volume and heater power. So far, several steady states and transient tests have been carried out to verify the overall thermal hydraulic primary and secondary characteristics in a range of 10% to 100% power operation. As results of preliminary results, the steady state conditions were found to coincide with the expected design values of the SMART-P. But the major thermal hydraulic parameters are greatly affected by the initial water level and the nitrogen pressure in the reactor upper annular cavity. In the PRHR transient tests, the steam inlet temperature of the PRHR system is found to drop suddenly from a superheated condition to a saturated condition at the end period of PRHR operation.

1. Introduction

The thermal-hydraulic integral test facility, VISTA has been constructed to simulate the SMART-P, which is a pilot plant of the System-integrated Modular Advanced Reactor (SMART), having a rated power of 65 MWt. The SMART is an advanced integral reactor with a power of 330MWt having several enhanced safety features. It contains major RCS components, such as main coolant pumps, steam generators and pressurizers, within a reactor vessel so as to eliminate occurrence of a large LOCA. The basic design of the SMART has been completed in 2002 by KAERI and a prototypic SMART plant, the SMART-P, will be constructed within six years in Korea. ([1] ~ [8])

The VISTA facility is an integral test facility to simulate the primary and secondary systems as well as major safety–related systems. Its scaled ratio with respect to the SMART-P is 1/1 in height and 1/96 in volume. The reactor core is simulated by an electrical heater with the capacity of 818.75kW. The schematic diagram of the VISTA facility is shown in Figure 1. Unlike the integrated arrangements of the SMART-P, the VISTA primary components including a reactor vessel, a main coolant pump, a helical-coiled steam generator, and a pressurizer are connected with pipes each other for easy installation of instrumentations and simple maintenance. The secondary system having a single train is simply designed to remove the primary heat source. Besides these major systems a make-up water system and a chilled water system are installed to control the feedwater supply and its temperature.

Some of safety-related systems to simulate a piping break and the safety injection will be later installed after carrying out the performance tests such as normal operation and operational transients as well as some of accidents.

2. Description of the VISTA facility

2.1 Reactor vessel and core

The primary system of the SMART-P has its function to generate thermal power at the core and to transfer the heat to secondary system through the steam generator by forced or natural circulation. It is composed of main components such as control rod driving devices, main coolant pumps (MCP), steam generator cassettes, internal pressurizers, a gas cylinder and a reactor internal assembly. It also plays a role of the pressure boundary of the coolant which circulates in the primary system under high- temperature and high-pressure conditions.

Table 1. Technical specifications of the pressure vessel of the VISTA facility

Parameters	**Unit**	**Value**
Operating pressure (Maximum)	MPa	14.7 (17.2)
Maximum operating temperature	^{o}C	350
Heating/Cooling rate of primary system	^{o}C/hr	100 / 100
ID (Heating part, Lower plenum)	mm	131.80
ID (Upper plenum)	mm	173.05
Material	-	STS304
Length of lower plenum	mm	560
Height	mm	3677.4
Length of pressure vessel shroud	mm	1400
Centerline distance between heater and SG	mm	1594.3

The main concern of the primary system is the simulation of the reactor performance including startup and heating operation, power increase and decrease, and natural circulation operation of the SMART-P. Therefore, the primary system is designed for several performance tests related to the operation mode and to maintain the minimum function so that the various thermal-hydraulic behavior occurring in the secondary side is not distorted against the transients. As a technical difficulty to install the reactor internals in a single pressure vessel, the primary system of the VISTA facility is simplified to be a loop-type. The SG, the MCP, the pressurizer, and the downcomer are designed to be installed outside the pressure vessel. The core simulator (an electrical heater) inside the pressure vessel is designed to act as a simple heat source. The suction part of the MCP is located at the top of the pressure vessel. The discharge part of the MCP, the pressurizer, the SG, and the downcomer are connected outside the pressure vessel. However, the distribution of the coolant inventory, the core power including the decay heat, the pressure drop of the system and the flow rate during natural circulation, which influences the accident scenario significantly, are preserved according to the scaling law. The technical specifications of the pressure vessel and the core simulating heater rod of the VISTA facility are shown in Table 1 and 2, respectively.

2.2 Steam generator

The SMART-P steam generator (SG) located in circumferential annulus gap in the reactor consists of 12 cassettes. In the VISTA facility, the SG is scaled down as 1/8 with respect to one SG cassette of the SMART-P based on the same scale law applied the other components. It is designed as a single external cassette and located between the main coolant pump outlet and reactor lower plenum as shown in Figure 1.

Table 2. Technical specifications of the core simulating heater rod of the VISTA facility

Parameters	**Unit**	**Value**
Power (Rating/Maximum)	kW	682.29 / 818.75
Control range of heater rod power	%	0.1 ~ 120
No. of rods (Heating/Non-heating)	EA	36 / 1
Maximum power per rod	kW/rod	22.74
OD and pitch of heater rod	mm	9.5 / 12.7
Arrangement of heater rod	-	Triangular Lattice
Hydraulic diameter of heating region	mm	9.22
Flow rates (Heating region/Shroud bypass)	kg/s	3.5364 / 0.1094
Heat flux of heater rod (Rated power)	kW/m^2	529.19
Flow area of heating region	m^2	0.0029615
Length (Heating/Lower/Upper non-heating region)	mm	1200/560/200
Maximum allowable surface temperature	°C	800
Power supply	-	3P, 440V, Wye

Twelve helical tubes having inner diameter of 12(mm) and outer diameter of 14(mm) are arranged to have the same geometrical pitch as that of the SMART-P.

The primary coolant enters the inlet of the SG and flows through the shell side forming a countercurrent flow with respect to the tube inside coolant. The subcooled feedwater supplied from the feedwater tank is heated in the tube by the primary side. When the feedwater flows into the tube it boiled and finally goes out at a superheated condition. Table 3 shows the detailed design characteristics of the steam generator.

Table 3. Technical specifications of the steam generator of the VISTA facility

Parameters	**Unit**	**Value**
Number of SG	EA	1
Number of Tube	EA	12
Tube Average Length	m	9.75
Tube Vertical/Horizontal Pitch	mm	11.5/14
SG Total Height	m	2
SG Inside Diameter	m	0.184
Tube Diameter(In/Out)	mm	7/10
Tube Material		Inconel 690
Heat Transfer Area	m^2	3.12
Tube Columns	EA	3
Shell Side Flow Area	m^2	0.005
SG Material Except Tube		Stainless Steel
Design Pressure/Temperature		17.2 MPa/353°C

2.3 Pressurizer

The end cavity (EC), the intermediate cavity (IC), and the upper annular cavity (UAC) of the SMART-P are simulated by three independent cylindrical vessels. Each vessel is connected by a separate pipe to simulate the surge flow. The upper annular cavity is connected to the hot leg via a surge line. The volume of each cavity is scaled down at the ratio of 1/96 and the height and the elevation are preserved. The volumes of the connecting line between cavities are designed to be larger than the scaled volume to avoid excessive friction. The available commercial pipe is used for the connecting line. The desired and actual volumes are shown in Table 4. A single row of a helical heat exchanger is installed in the intermediate cavity to control its coolant temperature. The pressurizer is also designed to be connected to safety and auxiliary systems such as the overpressure protection system, the makeup system, the gas supply system, and the drainage and vent system. The outer surfaces of the cavities and the connecting pipes between the cavity and the hot leg are wrapped with heaters and heavily insulated to avoid the heat loss to the environment.

Table 4. Specifications of the Pressurizer System

Item	**Designed volume (*l*)**	**Actual volume (*l*)**
Hot leg to EC	0.050	0.788
EC	18.4	18.4
EC to IC	0.044	0.375
IC	6.0	6.0
IC to UAC	0.053	0.44
UAC	14.0	14.0
UAC to Gas Cylinder	0.027	0.05

2.4 Main coolant pump

It is a main role of the main coolant pump to supply the primary coolant system with the forced convective flow to remove the heat generated from the core. In the SMART-P the MCP operates at two different modes of high and low speed. The MCP supplies 100% flowrate in the high speed mode, but it does 36% in the low speed mode. Only one axial-type canned motor pump is used in the VISTA facility although two MCPs are used in the SMART-P. Therefore, the pump in the VISTA facility must have the preserved pump characteristics especially at two operation modes according to the scaling law. The thermal-hydraulic operating conditions are the same as those of the SMART-P. The pump is designed to operate at pressure of 14.7MPa and temperature of 310^{o}C at the rated power. The pump is also designed to simulate the coastdown curve by the programmable speed control. The elevations of the inlet and the exit of the pump are also preserved to avoid the scaling distortion. The detailed design specifications are summarized in Table 5.

Table 5. Design specifications of the MCP

Parameter	**Unit**	**Prototype (P)**	**VISTA(M)**	**Ratio(P/M)**
Operating temperature	^{o}C	310	310	1.0
Max. operating temperature	^{o}C	350	350	1.0
Operating pressure	MPa	14.7	14.7	1.0
Max. operating pressure	MPa	17.2	17.2	1.0
No. of RCP	Ea	2	1	2.0
Rated volumetric flow per pump	m3/h	972.2	20.25	48.0
MCP flowrate (total)	kg/s	379.7	3.96	96.0
Rated density	kg/m^{3}	703	703	1.0
Rotational speed	rpm	3600/1300	continuous control	
Rated Head @3600rpm	m	6.0	6.0	1.0
Primary side pressure drop (total)	MPa	0.04064	0.04064	1.0

2.5 The secondary system

The secondary system consists of the feedwater supply system and the steam discharge system. Each system is simplified to have single train, although the SMART-P consists of four trains. The feedwater system consists of a feed water supply tank, a feed water supply pump, a filter, a feed water heat exchanger, a main feed control valve, a flowmeter, an orifice, an isolation valve, and the lower plenum of the steam generator. It supplies the demineralized water of pressure of 4.55MPa and the temperature from 40°C to 70°C to the steam generator. The flowrate of the feed water can be controlled by a feed water pump, a main feed water control valve, and a bypass control valve. The steam discharge system consists of the upper plenum of the steam generator, an isolation valve, a flowmeter, a main steam control valve, and a steam dump line to atmosphere. In the steam discharge system, there is a branch point which the passive residual heat removal (PRHR) system starts from. Also, in the feed water supply system, there is a branch point which the PRHR connects to. When the PRHR starts to operate, the steam generated at the steam generator goes to the PRHR system and it condenses at the emergency cooldown tank (ECT) and flows back to the feed water system in the liquid phase. The performance of the PRHR is very important for the design the PRHR in the SMART-P. Therefore, the scaling law applied to the closed loop in the secondary system which consists of the steam discharge pipeline after the steam generator, the PRHR system, and the feed water pipeline before the steam generator. The steam discharge line to which the scaling law is applied is designed to have the same pressure drop as that of the SMART-P. The internal volume of the steam discharge line to which the scaling law is applied is reduced according to the scaling ratio. Also, the same scaling criteria are applied to the feed water line for the pressure drop and the internal volume. The pipelines to which the scaling law applies are designed to have the same elevation as that of the SMART-P. The detailed design specifications of the pipelines to which the scaling law are applied is summarized in Table 6. The feedwater supply tank is designed to supply the feedwater to the steam generator for an hour even though the water supply from the auxiliary system is terminated.

Table 6. The detailed design specifications of the secondary pipeline

	Feed water line	Steam discharge line	Remarks
Piping	1/2” SCH. 160	1-1/4” SCH. 160	
Inner Dia. (inch)	0.466	1.16	
Piping length (m)	10.97	7.88	To the branch of the PRHR
Inventory (m^3)	0.00121	0.00538	To the branch of the PRHR
Pressure (bar)	0.49	1.81	To the branch of the PRHR
Elevation (m)	2.830	4.930	Based on the bottom of the core

2.6 Passive residual heat removal (PRHR) system

The PRHR system is the system installed to prevent over-heating and over-pressurization of the boiler system in the case where the accident occurs. The PRHR system of the VISTA facility is composed of a single train of the cooling sub-system, which includes an emergency cooldown tank (ECT), a heat exchanger (HX), a compensating tank (CT), several valves and related piping. The maintenance cooldown tank (MCT) is also installed to cool the boiler system under normal operating condition. The PRHR system of the VISTA facility is designed to have the capability to simulate both passive and active cooling of the SMART-P. It is connected to both feedwater and steam lines of the secondary system to get a flow path of natural circulation. Enough cooling water is supplied to the ECT from the component cooling water system (CCWS) to remove the heat from the internal heat exchanger efficiently, and enough water and nitrogen gas should be supplied to the CT from the makeup water system (MWS) and the nitrogen supply system (NSS), respectively. It is necessary to perform safety-related experiments to validate the performance of the PRHR system. The PRHR system of the VISTA facility is designed to operate at the initial temperature and pressure of 242.5°C and 3.5MPa, respectively. It is also 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 SMART-P. The diameter, thickness, pitch, and orientation of heat exchanger tubes of the VISTA facility are also preserved. Figure 1 shows the detailed arrangement of main components. In the design stage, the location of the components, pressure drop characteristics, and heat exchanging capabilities are properly calculated and reflected to have the same natural circulation capability with the SMART-P. The scaling ratios of the number of heat exchanger tubes and trains of PRHRS are 1/96 and 1/4, respectively. As the working fluid and the operating pressure are the same between the model and the prototype, all properties are the same. Also the relationships of several parameters are determined by scaling analysis. The scaling ratios of the heat transfer area and the PRHRS volume are set to be 1/24. The technical specifications of the PRHRS of the VISTA facility are shown in Table 7.

Table 7. Technical specifications of PRHRS of the VISTA facility

Parameters	**Unit**	**Prototype (P)**	**VISTA (M)**
No. of trains	EA	4	1
Operating pressure	MPa	3.5	3.5
Operating temperature	°C	242.5	242.5
HX: No. of tubes/train	EA	141	6
HX: Tube length, ID, thickness	m	1.2, 0.013, 0.0025	1.2, 0.013, 0.0025
HX: Tube material	-	Titanium Alloy	Inconel 600
CT: Volume/tank	m^3	0.35	0.015
CT: ID, Height	m	0.55, 1.5	0.0873, 1.5
ECT: Volume/tank	m^3	NA	0.25
ECT: ID, Height	m	NA	0.4, 2.0
RHRS pump: No. of pumps	EA	2	1
RHRS pump: Flow rate	m^3/hr	15.5	0.5
RHRS pump: head	m	7	10

2.7 Instrumentation and data acquisition system

The data acquisition system provides data collection functions for the VISTA facility. The system consists of a computer, a display terminal, the VXI C-size mainframe and terminal panels residing in the control room. They are connected through an industry standard IEEE 1394 (Firewire) serial control and the date interface. The data acquisition system is isolated from the control system by using several types of signal distributors. The computer provides the display, and data storage functions. It has the capability of displaying and saving all process variables such as various rod and fluid temperatures and mass flow rates and pressures of each component during experiments. The computer collects and saves data from the various instruments measuring pressure including differential pressure, level, flow, pump speed, and temperature. The instrumentation part of this system consists of an industry standard VXI mainframe from Hewlett-Packard (E8403A), and the firewire controller interface card (E8491B with option 001), and several (currently four) state-of-the-art data acquisition A/D card (E1413C) with several types of functional signal conditioning plug-ins (SCPs). The terminal panels provide the isothermal reference junctions needed for the accurate temperature measurement. The four cards can be synchronized to perform the scanning simultaneously. The maximum A/D conversion rate on each E1413C card is normally 100kSample/sec, but is controllable according to the user requires. The normal data-scanning rate is set to 100Hz, but the data saving rate is 2Hz with the mean values of the 50 scanning data. Table 8 shows the number of instruments.

Table 8. Instrumentation of the VISTA facility

Instrument type	Number of instruments
Pressure	23
Temperature	117
Flow rate	6
Level	9
Differential pressure	18
Heater rod power	22
Etc	26
Total	221

3. Results and discussion

3.1 Test matrix

As mentioned before, the VISTA facility has been designed and fabricated to have a volume scaling ratio of 1/96. The volume scaling law strictly applied to the design of each component of the primary system and the passive residual heat removal system. Therefore, as the first step of experimental work, the overall and individual performance tests of the VISTA facility are carried out under the steady state condition ranging from 10% to 100% power.

A test matrix undertaken for the performance verification of the VISTA facility under the steady state condition is shown in Table 9. The experimental test ID is designated as H-Pxx-Qyy-zzzz. The numeric number “xx” indicates a power percentage, and the “yy” a feedwater flow percentage for the scaled values, respectively. The word “zzzz” means serial numbers of the tests carried out or special test conditions like PRHR operations. As can be seen in the Table 9, the feedwater flow rate is increased from 25% to 100% for each power condition in order to cover the full spectrum of the test conditions. Table 9 shows the measured total powers and the feedwater flow rates.

Table 9. Test matrix for steady state operation

Test #	Test ID	Power		Flow	
		(kW)	(%)	(m^3/hr)	(%)
1	H-P10-Q25	83.7	10	4.9	25
2	H-P10-Q36	87.2	10	6.9	36
3	H-P10-Q50	81.1	10	9.8	50
4	H-P10-Q75	90.1	10	14.7	75
5	H-P10-Q100	90.1	10	19.6	100
6	H-P25-Q50	187.6	25	9.8	50
7	H-P25-Q75	196.1	25	14.7	75
8	H-P25-Q100	198.6	25	19.6	100
9	H-P36-Q50	267.5	36	9.8	50
10	H-P36-Q75	271.3	36	14.7	75
11	H-P36-Q100	276.2	36	19.6	100
12	H-P50-Q50	374.2	50	9.8	50
13	H-P50-Q75	376.0	50	14.7	75
14	H-P50-Q100	377.7	50	19.6	100
15	H-P75-Q75	541.7	75	14.7	75
16	H-P75-Q100	544.0	75	19.6	100
17	H-P100-Q100	726.1	100	19.6	100

In reaching a steady state condition for a given power, the PRHR system is triggered to start by opening the bypass valves which connects the PRHR system to the secondary system and closing the secondary system isolation valves which isolate the secondary system from the feedwater supply tank and the silencer. The valve opening time interval between the isolation and the bypass valves is set to about 0.5 seconds. A test matrix for the PRHR operation is summarized in Table 10. Six tests in total are carried out so far. When a PRHR start button is pressed, the electrical heater and the RCP are switched off immediately, and the valve control signals are generated with a certain time delay. The decay heat was not simulated for the present tests.

Table 10. Test matrix for PRHR operation

Test #	Test ID	Power (%)	Flow (%)	Remarks
1	H-P10-Q36-PRHR	10	36	0.5 sec time delay
2	H-P25-Q50-PRHR	25	50	0.5 sec time delay
3	H-P36-Q100-PRHR	36	100	0.5 sec time delay
4	H-P50-Q100-PRHR	50	100	0.5 sec time delay
5	H-P75-Q100-PRHR	75	100	0.5 sec time delay
6	H-P100-Q100-PRHR	100	100	0.5 sec time delay

3.2 Heatup process

For a given power, the initial conditions of the primary and the secondary system are adjusted to meet the design values. The coolant level of the upper annular cavity was set to about 34%. The primary system is pressurized by a nitrogen gas to about 50bar. The feedwater supply tank, which provides water to the steam generator, is also pressurized by a nitrogen gas to 30bar. The feedwater temperature is automatically controlled by a controller to maintain a setting temperature in a range of 40°C to 70°C. The core power and the feedwater flow rate are simultaneously controlled until the thermal-hydraulic conditions of the primary and the secondary systems reach the design values given by Figure 2.

It was found that the pressure and the temperature of the primary system are very sensitive to both the initial coolant level of the upper annular cavity and the initial nitrogen pressure. Unlike the SMART-P, the VISTA facility has separate pressurizers connected with surge lines. The coolant temperatures in the three pressurizers, upper annular cavity, intermediate cavity and the end cavity, were observed to be lower than those in the SMART-P. Even though tracing heaters were installed on the outer surfaces of the three pressurizers to minimize the heat loss, their heating capacity seems not to be enough to prevent the heat loss. Due to the relatively low temperature of the primary coolant in the pressurizers, it was hard to estimate the final water level in the end cavity caused by the expansion of the coolant volume. Therefore, ad-hoc feed and bleed operations was taken infrequently to match the design values. Further detailed investigations for the performance of the pressurizer are needed as a future work.

The VISTA facility has an open-loop type secondary system unlike the SMART-P, implying the generated steam at the steam generator is dumped to the atmosphere. The steam pressure is controlled by a pressure control valve installed at the main steam line. The steam line thus experiences a subcooled water flow at the initial phase and then superheated steam flows at the later phase during the heatup process. The flow oscillation due to the phase transition was observed in the secondary system. A well-defined operating procedure is required to avoid the flow oscillation in the steam generator.

3.3 Steady state operation

Up to now, the preliminary tests to characterize the overall and individual performance of the facility, such as inventory distribution, pressure drop and thermal-hydraulic behavior under the steady-state conditions have been completed. Table 11 shows the comparison of the steady state conditions under the 100% full power operation. It can be found that most parameters are in conformity with the designed values. The coolant inventory distribution of the major components is summarized in Table 12. The difference between the desired and measured values is negligible as seen in Table 12.

Table 11. Comparison of the steady state conditions under the 100% full power operation

Parameter	**SMART-P**	**VISTA**	**Ratio**	**Comments**
Core power, kW	65,000	726.1	1/90	Including heat loss
Primary coolant flow, kg/s	379.7	4.02	1/94	
RCP head, m	6	2.2	1/2.7	Simplified internal structure
Primary pressure, MPa	14.7	15.2	1/0.97	
End cavity level, %	50	25	1/2	
Core inlet temp, ^{o}C	276.9	278.3	~1/1	
Core exit temp, ^{o}C	310	308.5	~1/1	
Feedwater flow, kg/s	24	0.2499	1/96	
Feedwater temp, ^{o}C	40~70	45	-	
Secondary pressure, MPa	3.55	3.70	~1/1	
Secondary steam temperature, ^{o}C	~300	300.1	~1/1	

Table 12. Coolant inventory distribution of the VISTA facility

Component	Measured volume (m^3)	Desired volume (m^3)	Error (%)
Boiler Pressure vessel(BPV) and MCP	0.04447	0.044934	1.03
The primary side of the steam generator	0.02109	0.021247	0.72
Pressurizer (Upper Annular Cavity)	0.01898	0.0184	-3.17
Pressurizer (Intermediate Cavity)	0.00601	0.006	-0.25
Pressurizer (End Cavity)	0.01393	0.014	0.50
The secondary side of the steam generator	0.00521	0.00567	8.20
Compensation tank (CST)	0.00939	0.00898	-4.59
Emergency cooldown tank (ECT)	0.26020	0.25133	-3.53

The pressure drop across the primary and the secondary system is given in Table 13. The primary side pressure drops were measured between the inlet and the exit of the RCP. The desired pressure drop at a rated condition of the SMART-P is about 60kPa, but the measured value is about 22kPa. It is due to the fact that the internal core structures in the VISTA facility are more simply designed than the SMART-P. An orifice will be installed to match the required pressure drop in the primary side. The third and the fourth columns in Table 13 show the shell and the tube side pressure drops across the steam generator, respectively. The shell side pressure drops in the steam generator did not give great differences in a range of 25% to 100% of the primary coolant flow. However, the tube side pressure drops in the steam generator rapidly increased as the feedwater flow increased. It is attributed to the effects of the orifice installed at the inlet of the feedwater flow.

Table 13. Summary of the measured pressure drop

Case	The primary side (kPa)	The primary shell side of the S/G (kPa)	The secondary tube side of the S/G (kPa)
H-P10-Q25	2.342	2.938	8.7
H-P10-Q36	3.645	3.162	9.6
H-P10-Q50	6.482	3.716	9.1
H-P10-Q75	13.142	5.206	7.9
H-P10-Q100	22.253	7.261	8.3
H-P36-Q50	6.371	3.835	178.3
H-P36-Q75	12.947	5.300	178.3
H-P36-Q100	21.938	7.348	178.0
H-P50-Q50	6.285	3.843	319.0
H-P50-Q75	12.915	5.307	333.7
H-P50-Q100	21.997	7.357	333.4
H-P75-Q75	12.731	5.239	677.8
H-P75-Q100	21.905	7.286	678.3
H-P100-Q100-3	21.007	7.279	1130.4

Table 14. Summary of the energy balance

Case	MCP flow	FW flow	Q_{heater}	$Q_{balance}$	Heat loss
	(kg/s)	(kg/s)	(kW)	(kW)	(kW)
H-P10-Q25	4.00	0.0247	83.7	64.49	19.21
H-P10-Q36	1.00	0.0258	87.2	68.24	18.96
H-P10-Q50	2.03	0.0253	81.1	66.24	14.86
H-P10-Q75	3.02	0.0246	90.1	64.40	25.70
H-P10-Q100	4.02	0.0249	90.1	64.62	25.48
H-P25-Q50	2.01	0.0602	187.6	163.23	24.37
H-P25-Q75	2.97	0.0622	196.1	168.33	27.77
H-P25-Q100	3.88	0.0622	198.6	167.13	31.47
H-P36-Q50	2.01	0.090	267.5	244.76	22.74
H-P36-Q75	3.00	0.090	271.3	244.65	26.65
H-P36-Q100	3.97	0.0898	276.2	244.36	31.84
H-P50-Q50	2.00	0.1233	374.2	338.13	36.07
H-P50-Q75	3.03	0.1261	376.0	344.87	31.13
H-P50-Q100	4.01	0.1263	377.7	345.09	32.61
H-P75-Q75	3.06	0.1873	541.7	516.58	25.12
H-P75-Q100	4.07	0.1881	544.0	517.94	26.06
H-P100-Q100-3	4.02	0.2499	726.1	687.70	38.40

Table 14 summarizes the energy balances during the steady state operations. The second and the third columns indicate the primary and the secondary flow rates, respectively. The Q_{heater} is the heat input by the electrical heaters simulating the core fuels and is directly measured by the power meters. On the other hand, the $Q_{balance}$ is the power transferred from the primary side to the secondary side through the steam generator. It is calculated from the thermal-hydraulic conditions at the inlet and the exit of the steam generator. The difference between the Q_{heater} and the $Q_{balance}$ is defined as the heat loss because it indicates the unforced heat loss from the hot metal surfaces of the VISTA facility. The heat loss is found to be between 20kW and 30kW. As the total power increases, the heat loss also increases as can be seen in the Table 14.

3.4 PRHR operations

The preliminary PRHR system performance tests were carried out. The total six PRHR tests are performed after steady state conditions are achieved for given powers. After reaching a steady state condition for a given power, the PRHR system was triggered to start by opening the bypass valves connected to the PRHR system and by closing the isolation valves connected to the secondary system with a time delay of 0.5 second.

Figure 3 shows the typical flow rate variation during the PRHR operation. The initial steam flow rate from the secondary system was 0.25 kg/s and it decreased rapidly to about 0.03 kg/s, which is about 12 % of the scaled secondary flow rate. The trend of the flow rate variation during the natural circulation was similar regardless of the initial feedwater flow rate. Figure 4 shows the variation of the system pressure during the PRHR operation. The system pressure increases rapidly after the bypass valves were open and it reached its peak before the superheated steam is condensed in the heat exchanger. As the steam condensed in the heat exchanger, its energy was transferred to the water flowing through the emergency cooldown tank (ECT) and the system pressure decreased. As the heat was removed the primary coolant temperature decreased. Also the temperature of the steam generated in the steam generator decreased and the system pressure decreased rapidly.

The typical temperature variation during the PRHR operation is given in Figure 5. Before the initiation of the PRHR operation, the steam from the steam generator maintains a superheated condition. When a natural circulation was started by the initiation of the PRHR operation, the steam temperature started to fall due to the energy transfer through the heat exchanger in the emergency cooldown tank (ECT). However, the rate of decrease of the steam temperature became large and the steam temperature suddenly dropped to a saturated condition at the time of about 1800 second. It is very interesting result worthy of further investigations.

4. Conclusions and future works

Using the thermal-hydraulic integral test facility, VISTA, several preliminary performance tests were carried out. It is found that the VISTA facility has the capability to correctly simulate the thermal-hydraulic conditions in the SMART-P within an acceptable tolerance. The initial coolant level in the upper annular cavity and the initial nitrogen pressure are found to be the most affecting factors to achieve the steady state conditions.

The thermal-hydraulic behavior of the VISTA facility during the PRHR system was also investigated for the limited cases. The natural circulation flow rate through the PRHR system was about 10 percent at the early phase of the PRHR operation. The system pressure of the PRHR system was affected by the time delay between the opening and the closing of the bypass and the isolation valves installed at the PRHR and the secondary system, respectively. In the near future, the systematic characterization tests for each major component including the MCP, the helical steam generator, and the PRHR system will be performed. In addition to that, more wide range of experimental tests under the normal operation, operational transients, and the postulated accidents will be performed to verify the performance of the SMART-P in greater detail.

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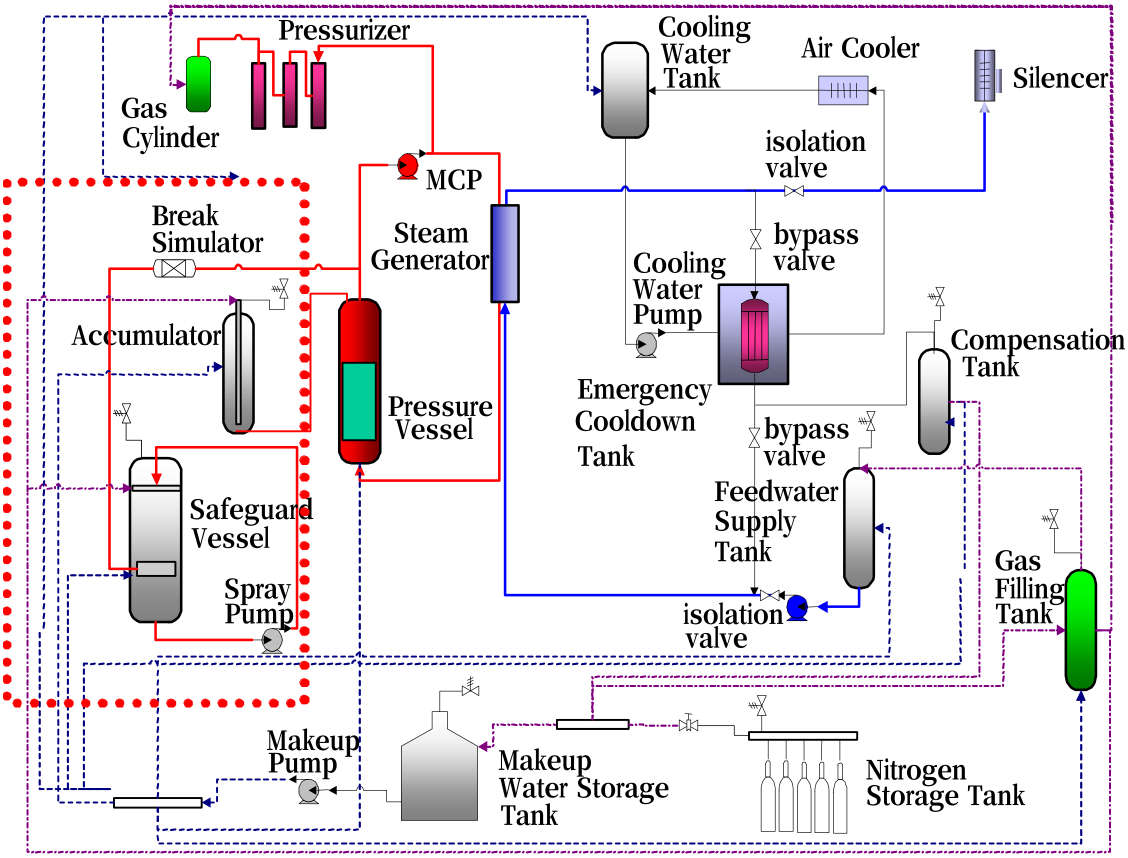

Figure 1. Schematic diagram of the VISTA facility for the SMART-P

(-----   : Safety injection system is to be constructed)

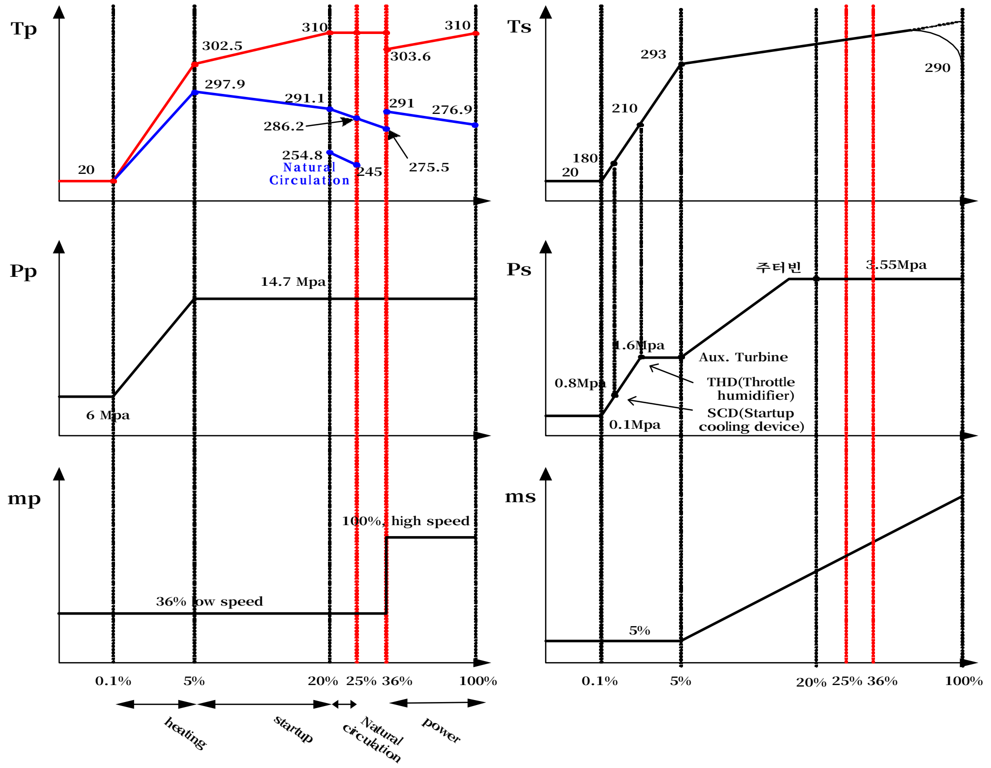

Figure 2. The thermal hydraulic parameters in the primary and the second system

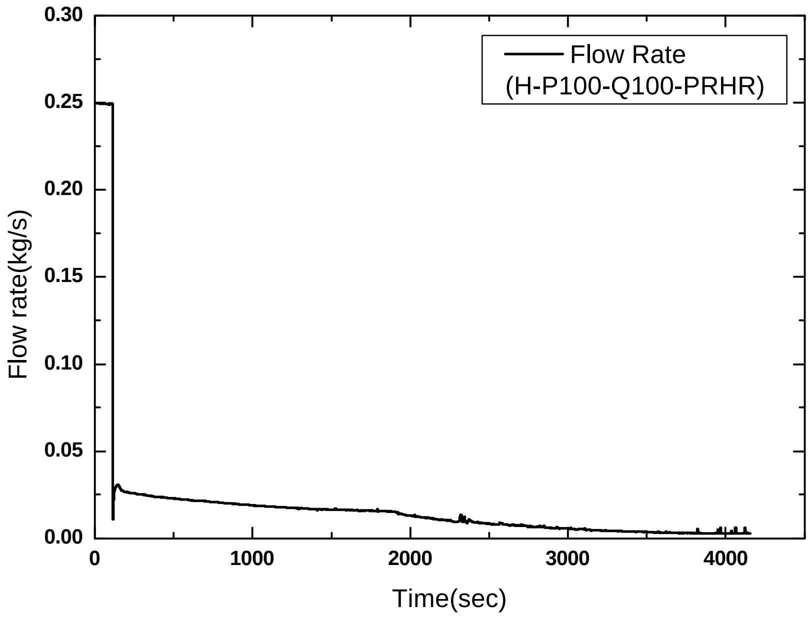

Figure 3. Variation of the flow rate during the PRHR operation (H-P100-Q100-PRHR)

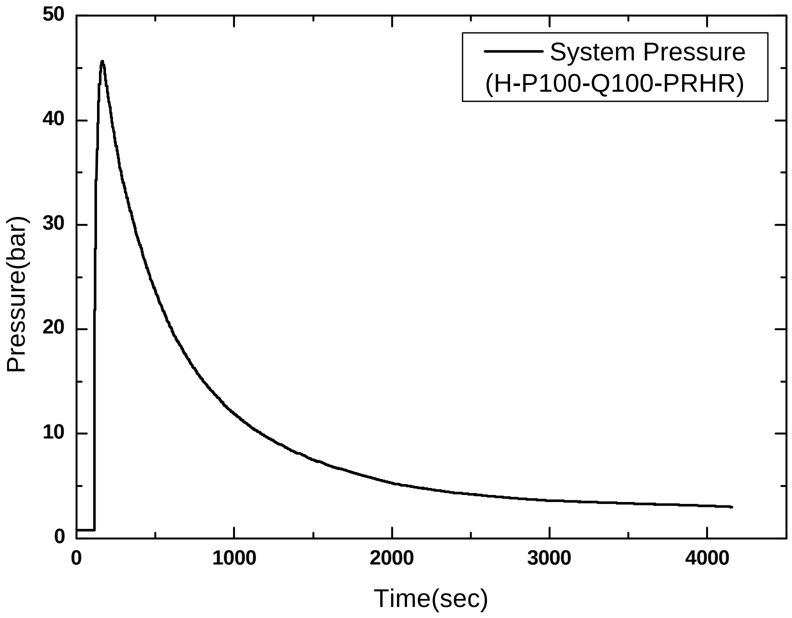

Figure 4. Variation of the system pressure during the PRHR operation (H-P100-Q100-PRHR)

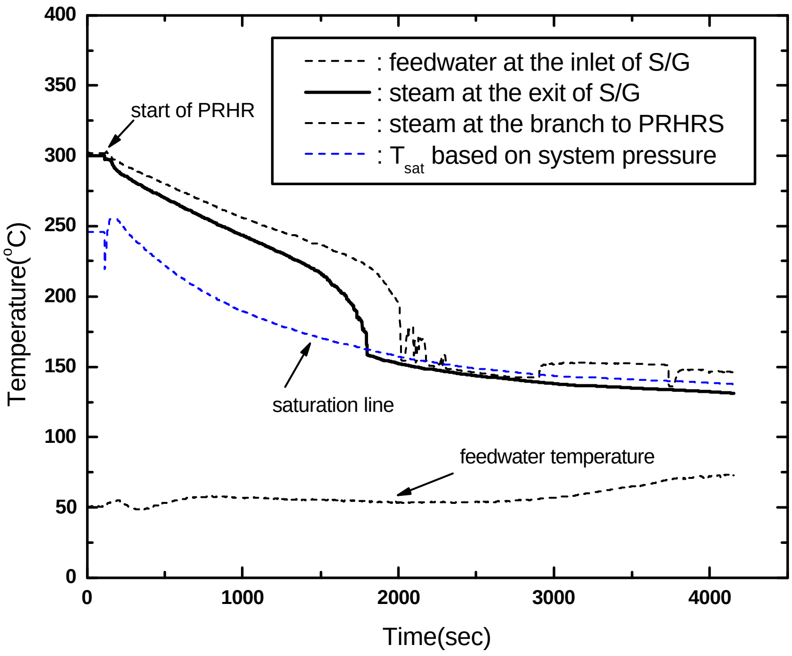

Figure 5. Variation of the temperature during the PRHR operation (H-P100-Q100-PRHR)