Experimental Research on Non-Condensable Gases Effects in Passive Decay Heat Removal System

LIU Yang, JIA Hai-jun
Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China
Key Laboratory of Ministry of Education on Advanced Nuclear Reactor Engineering and Safety, Beijing 100084, China
liu_yang@tsinghua.edu.cn; jiaha@tsinghua.edu.cn

ABSTRACT

Passive decay heat removal (PDHR) system is important to the safety of integral pressurized water reactor (IPWR). In small break LOCA sequence, the depressurization of the reactor pressure vessel (RPV) is achieved by the PDHR that remove the decay heat by condensing steam directly through the SGs inside the RPV at high pressure. The non-condensable gases in the RPV significantly weaken the heat transfer capability of PDHR. This paper focus on the non-condensable gas effects in passive decay heat removal system at high pressure. A series of experiments are conducted in the Institute of Nuclear and New Energy Technology test facility with various heating power and non-condensable gas volume ratio. The results are significant to the optimizing design of the PDHR and the safety operation of the IPWR.

KEYWORDS
Non-Condensable Gas; IPWR; PDHR; Condensation; Natural Circulation

1. INTRODUCTION

The integral pressurized water reactor (IPWR) has received special attention due to its enhanced safety, improved economics, multi-purpose, and modular features in the past decades [1-2]. Nowadays, some advanced IPWRs [3] are under developing and will be deployed in near future, such as NHR200, ACP100, SMART, mPower, NuScale and ABV.

The 5MWth nuclear heating reactor (NHR-5) is an integrated, water-cooled, natural circulation research reactor which was developed in 1989 and operated for years by institute of nuclear energy technology (INET) of Tsinghua University. In the last twenty years, on the basis of NHR-5, the INET has improved NHR incrementally and the 200MWth NHR200-II reactor is the newest NHR type with inherent safety characteristics and passive safety features [4].

The NHR200-II reactor pressure vessel (RPV) hosts all the components of the primary coolant system: core, control rods drive mechanism (CRDM), gas-steam pressurizer and steam generators (SGs). This integral arrangement of the reactor allows avoiding pressure components outside the RPV, such as SGs, and largely reduces the size and number of the RPV penetrations. The occurrence of the large break loss of coolant accident (LBLOCA) is eliminated inherently and only small break LOCA (SBLOCA) may happen.

In order to mitigate the consequences of the SBLOCA and avoid it turning into severe accident, the passive decay heat removal (PDHR) system is designed for NHR200-II which is shown in figure 1. The

PDHR system removes the decay heat by condensing steam directly through SGs and transfers the decay heat to water tanks by natural circulation**.**

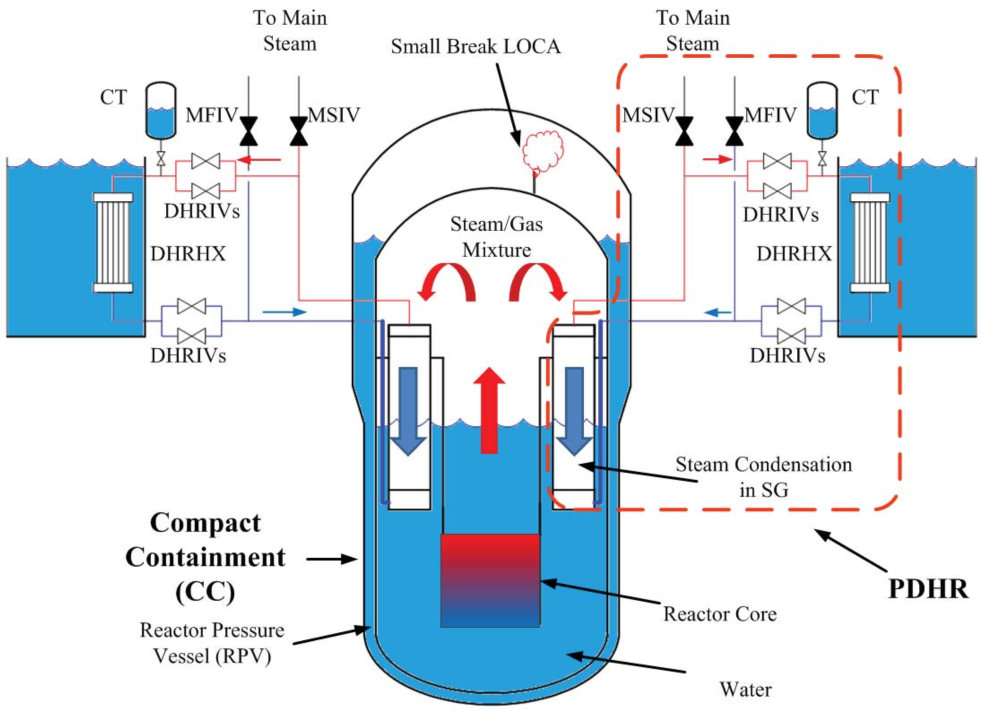


Figure 1. Schematic diagram of CC and PDHR system in SBLOCA.

Several IPWRs have similar design such as IRIS [5] and NuScale [6-7]. The main difference of NHR200-II is the non-condensable gas effect to the condensation in the PDHR system. Large amount of non-condensable gas (nitrogen) exist in the NHR200-II RPV because of integrated gas-steam pressurizer. Previous study indicates that even a small amount of Non-condensable gas existed in the steam leads to a significant reduction in heat transfer during condensation. The non-condensable gas near the condensate film inhibits the diffusion of steam from the bulk mixture to the liquid film. The non-condensable gases effect is one of most concern in PDHR systems. The effect of non-condensable gases on the condensation in low pressure (<0.5MPa) has been extensively studied for the large passive containment cooling system (PCCS) [8~10]. But in order to reduce the coolant loss, the compact high design pressure containment is designed. The equilibrium pressure of the RPV-Compact containment is much higher (>1.0MPa). In this condition, the extensively used empirical correlation, such as Uchida, will get a significant error [11].
In order to investigate the non-condensable gas effects in PDHR system at high pressure, experiments are conducted in the Institute of Nuclear and New Energy Technology test facility with various heating power and non-condensable gas volume ratio. The results are significant to the optimizing design of the PDHR and the safety operation of the IPWR.

2. General description of PDHR

As shown in figure 1, the PDHR system has multi independent trains which can transfer the full decay heat to water tanks by natural circulation respectively. Each train has a heat exchanger, a compensating tank (CT), and connecting pipelines. The decay heat removal exchanger (DHRHX) is submerged in the refueling water tank and located high enough above the SGs to drive a sufficient natural circulation flow. The compensating tank is pressurized with nitrogen gas and can fill up the voids space at the beginning of the cooling process.

When SBLOCA occurs, the RPV depressurizes and loses coolant to containment. Then the reactor will be tripped and PDHR system depressurizes the primary loop of reactor. When water level drops to a level where natural circulation in the RPV is prevented, heat continues to be removed through steam/water being released through the break. Non-condensable gas covers the SGs surfaces and inhibits condensation. The equalization pressure of RPV-CC will not be reached until enough SGs surface can be used for the condensing the steam. Then the losses of coolant will stop.

Through the analysis above, the non-condensable gases effect on the PDHR system is found to be one of most concern to be investigated.

3. Description of the Test Facility

The test facility is composed of three parts: an experimental vessel, a passive cooling loop and water tank. A schematic diagram of the test facility is shown in Fig. 2. The major specifications are listed in Table 1.

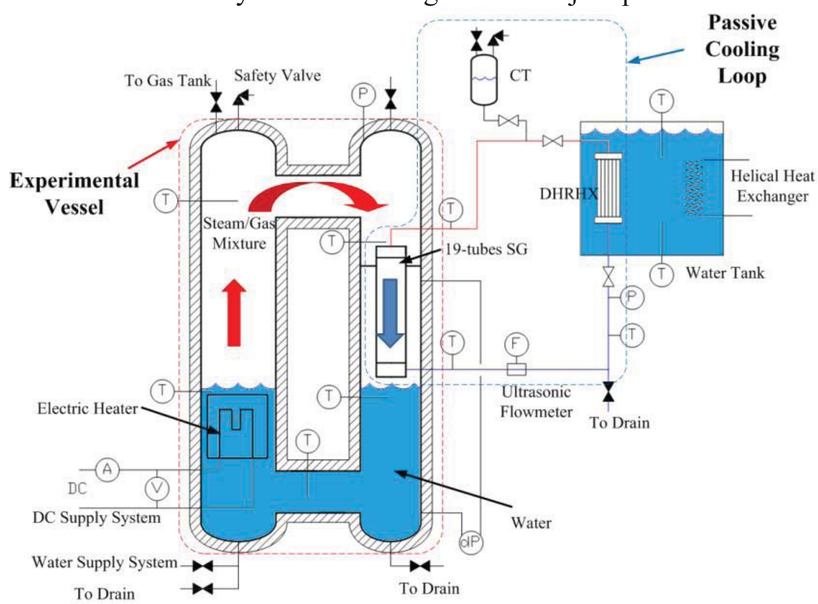


Figure 2. Schematic diagram of the test facility.

Table I. Specifications of the test facility

Item	Unit	Value Range
Primary Loop		
Temperature range of the steam	℃	100~200
Pressure range (gauge)	kPa	90~1500
Non-condensable gas	/	Nitrogen
Vol. ratio of Non-condensable gas	%	3~9
Working fluid	/	Water
Power of electric heater (Max)	kW	50
Number of SG bundle tubes	/	19

Effective condensation area	m^2	1.68
Volume of steam/gas mixture	m^3	0.065
Passive Cooling Loop		
Working fluid		Water
Inlet temperature of DHRHX	℃	110~188
Outlet temperature of DHRHX	℃	21~35
Pressure of the cooling loop (gauge)	kPa	~2300
Mass flow rate	kg/s	0.02~0.06
Water Tank		
Water Temperature	℃	~22
Pressure of the water tank (absolute)	atm	1

3.1. The experimental vessel (EV)

The EV is used to simulate the primary loop of the IPWR. It composes of three parts: pressure vessel, electrical heater and 19-tubes bundle.

The pressure vessel of the test facility is made by two connected vertical pipes. The pipes are made of the SS304 stainless steel. For the left pipe, the inner height of 4970 mm and inner diameter is 110 mm. For the right pipe, the inner diameter is 90 mm. The design pressure of the pressure vessel is 9.5MPa. The outer wall of the test vessel is wrapped up in thermal insulator material.

The electrical heater is installed in the bottom of the left pressure vessel to simulate the reactor core. The rated power is 50kW. The demineralized water in the vessel is heated in the heating bundle and vaporized. The19-tubes bundle installed in the right vessel is used to simulate the condensation function of the SG tubes.

3.2. The passive cooling loop (PCL)

In the PCL, the coolant water is circulated naturally by the fluid density difference. The PCL consists of 4 parts: the secondary side of SG, decay heat removal exchanger (DHRHX), compensating tank (CT) and connecting pipelines.

3.2. Water tank

The water tank contains 0.7t water. The pressure is 1atm and the temperature in the water tank is controlled by a helical heat exchanger.

3.3. Instrument

The temperatures are measured by using calibrated K-type thermocouples with maximum error of ±0.5℃. In the experimental vessel, only steam temperature and condensation water temperature are measured. None of wall temperature of the 19-tubes bundle is measured due to the difficulty of installation.

The pressure is measured by Rosemount 3051 pressure transmitters with a range from 0 to 2.0MPa and maximum error of±0.15%. The water level is measured by differential pressure transmitter.

The heating power is calculated by measuring voltage and current of the DC power supply. The direct current is measured by Hall element with maximum error of ±1.0%.

In the passive cooling loop, the flow rate is very small because of natural convection. The contactless measurement is needed. An ultrasonic flow-meter is installed at the inlet of the 19-tubes bundle.

4. Experimental Procedures and Conditions

4.1. Experimental Procedures

Before starting the experiment, the air in the experimental vessel is purged by the following steps:
1) The water is injected into the experimental vessel and the air above water level is purged out by vacuum pump until the pressure is lower than -90kPa (gauge).
2) Steam is generated in the experimental vessel by the electric heaters installed at the bottom of the experimental vessel. When the pressure reaches 0.5MPa (gauge), open the atmospheric valves at the top of the vessel. The mixture of remaining air and steam is vented out through the atmospheric valves. Close the atmospheric valves when the pressure drops to 0.1MPa (gauge).
3) Continue step 2) for 10 times and the amount of the remaining air can be neglected.

After the purging procession, a set amount of nitrogen is injected into the vessel. The amount of nitrogen injection is quantified by the percentage of system volume at the system temperature and pressure according to the ideal gas law. The redundant water in the vessel is discharged through the drain valve and water level is set to be a little bit lower than the outlet of the 19-tubes bundle. During the warm-up stage, a long period (about 1 h) is taken to heat up the mixture of nitrogen and steam to stabilize operating temperatures and pressures in experimental vessel.

Then, the valve of the passive cooling loop is opened and coolant water is circulated naturally. The power of the electric heater is raised to a group of set values.

When the pressure fluctuation in the experimental vessel is less than 0.5% measured pressure and all the temperature fluctuations measured by thermocouples are less than 0.5℃ for more than 20 min, the steady-state conditions are reached. When upon the steady-state, the measurements are made 240 times with 0.5 second intervals.

Between each test case, sufficient time is used for the system to reach a new steady-state condition.

4.2. Experimental Conditions

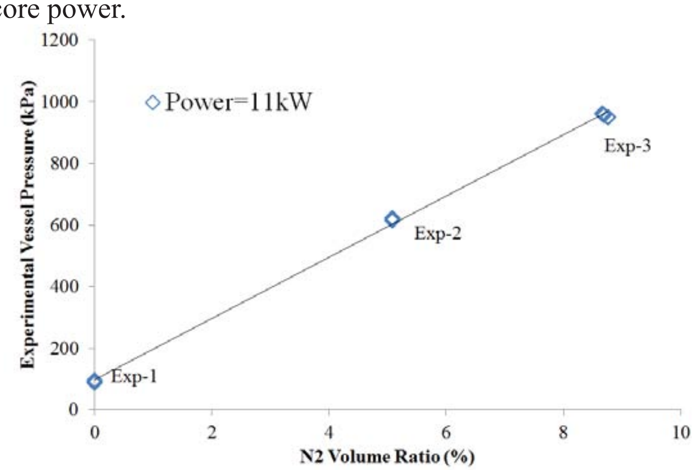
In this study, the heating power is 11~32kW which simulates the decay heat. Three different amount of nitrogen is used to investigate the non-condensable gas effect in the passive decay heat removal system. For the first experiment (named Pure Steam Exp-1), no nitrogen is injected into the experimental vessel. The measured data is used as the baseline. For the second experiment (named N2 Exp-2), the initial nitrogen volume ratio is 5% when power is about 11kW. For the third experiment (named N2 Exp-3), the initial nitrogen volume ratio is 9% at 11kW.

For each experiment, the water tank is used as the ultimate heat sink (UHS) of the heat removal system. The temperature in water tank is almost constant at 22℃ controlled by a helical heat exchanger.

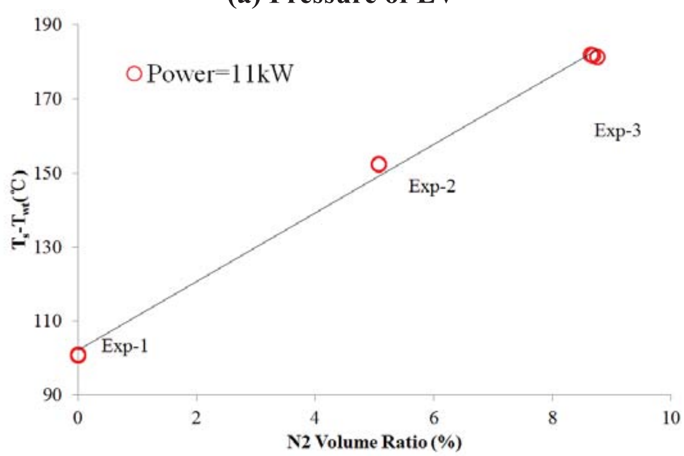
5. Experimental Results and Discussion

The experiment results of three different nitrogen amount are shown in figure 3~figure 9. All the pressure data are gauge pressure.

From the figure 3(a), the nitrogen volume ratio shows strong influence to the pressure of the EV under the same heating power. The higher ratio of non-condensable gas in the vessel the higher pressure is resulted. From the figure 3(b), the non-condensable leads to a significant reduction in heat transfer of passive decay heat removal system. The temperature difference between steam and UHS (water tank) at 9% N2 is 1.8 times than pure steam condition. The higher temperature difference is needed in the heat removal procession for a same core power.



(a) Pressure of EV



(b) Steam-to-water tank temperature

Figure 3. Influence of nitrogen volume ratio at a power ratio.

The figure 4 shows that the pressure of EV decreases as heating power decreases. For pure steam experiment, the pressure at 11kW is 13% of the pressure at 32kW. But for the experiment with maximum nitrogen, the pressure at lowest power just decreases to 64% of the pressure at 32kW. The results show that rate of depressurization is significantly slowed by non-condensable gas.

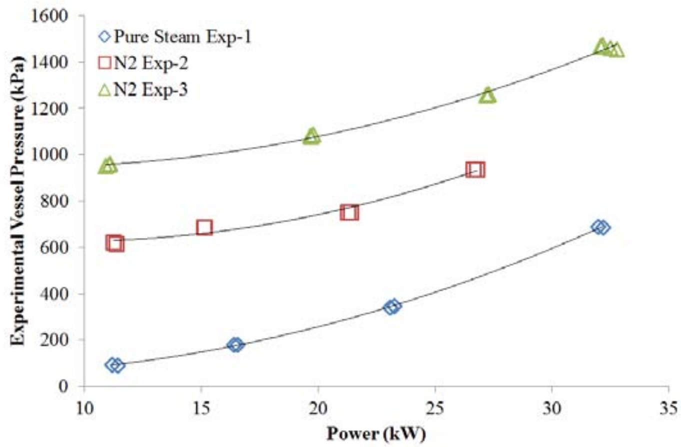


Figure4. Pressure of EV vs. power at different nitrogen amount.

For each experiment, the mass of nitrogen in the vessel is constant. But as decrease of the power, the partial pressure of steam decreases which results an increase of N2 volume ratio. The result shown in figure 5 indicates that during the depressurization of RPV, the N2 volume ratio increases about 40%. The increase of N2 volume ratio will further slower depressurization ratio.

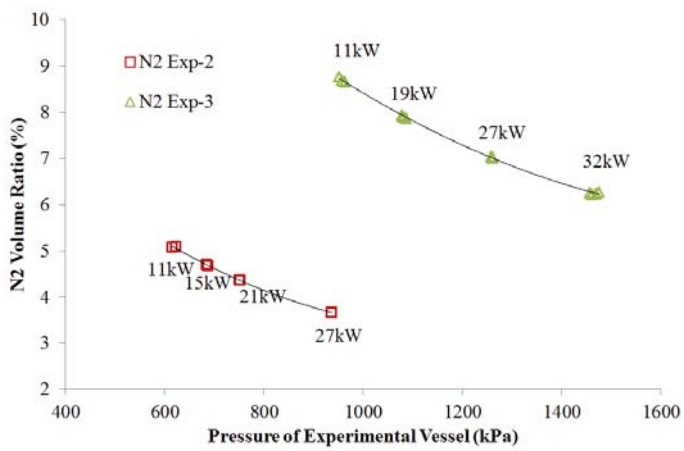


Figure5. N2 volume ratio vs. pressure.

In figure 6, the presence of non-condensable gas reduces the total heat transfer k at the same heating power. And during the power reduction procession, the total heat transfer coefficient k in pure steam condition reduces 53% while 80% reduction is found in the presence of non-condensable conditions.

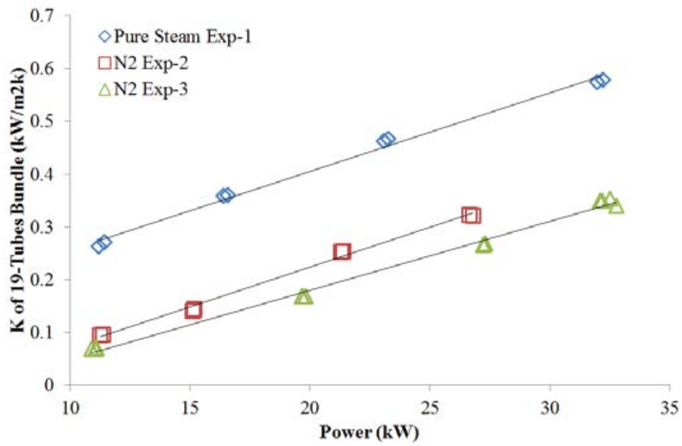


Figure6. Total heat transfer coefficient vs. power.

In figure 7, under the same heating power, a small difference of k leads a large pressure difference in different amount of non-condensable gas condition. Take 27kW for example, 16% difference of k results 35% difference of pressure.

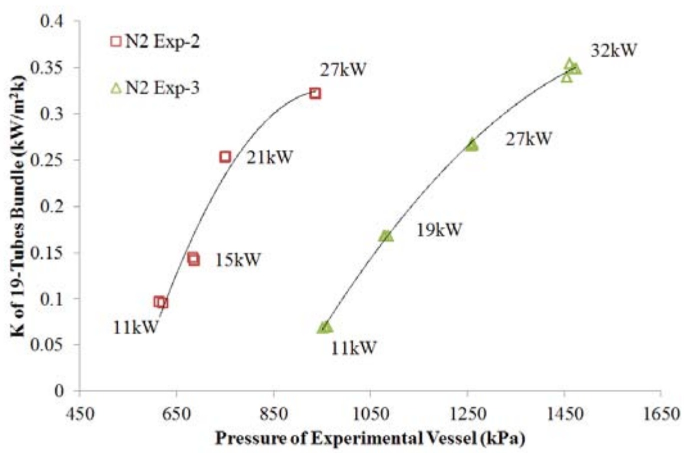


Figure7. Total heat transfer coefficient vs. pressure of EV.

Another factor for the reduction of *k* is the natural circulation characteristic of the PCL. Figure 8 shows the temperature trend of the PCL during the depressurization. As a decrease of the temperature difference, the driven force of natural circulation decreases and results a reduction of mass flow rate shown in figure 9.

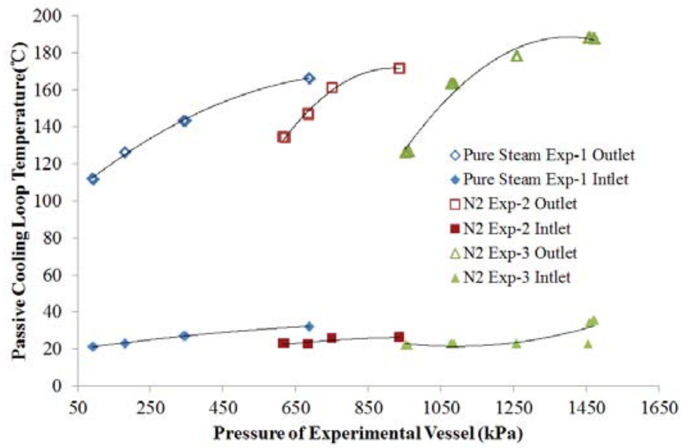


Figure8. Temperature of PCL vs. pressure of EV.

Figure 9 also shows that the reduction ratio of the PCL mass flow rate increases along with the increase of nitrogen volume amount during the depressurization.

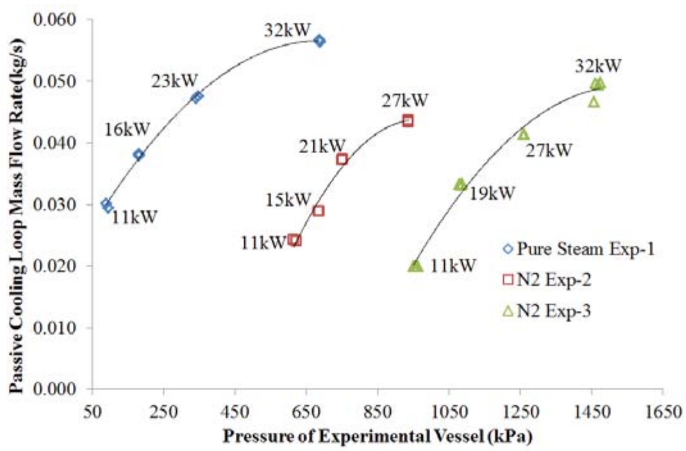


Figure9. Flow rate of PCL vs. power.

6. CONCLUSIONS

The non-condensable gas effect in passive decay heat removal system has been studied by experiment and presented in this paper. The important results are summarized as followed:

1) The presence of non-condensable gas significantly reduces the heat transfer capability of PDHR system. Under the same heating power, the higher amount of non-condensable gas will result a higher pressure of EV and a larger steam/UHS temperature difference in the heat removal procession.

2) As decrease of heating power, volume ratio of non-condensable will increase and higher non-condensable gas volume ratio result a smaller pressure reduction ratio. For the PHDR system, the depressurization capability is weaken by the increasing non-condensable amount.

3) The non-condensation also influences the natural circulation characteristic of passive cooling loop. Higher non-condensable gas volume ratio leads a higher reduction ratio of the PCL mass flow rate during the depressurization.

NOMENCLATURE

CC	Compact Containment
CRDM	Control Rods Drive Mechanism
CT	Compensating tank
DHRHX	Decay heat removal exchanger
EV	Experimental Vessel
IPWR	integral pressurized water reactor
LOCA	loss of coolant accident
LBLOCA	large break LOCA
SBLOCA	small break LOCA
MFIV	Main feed water isolating valve
MSIV	Main steam isolating valve
PCL	Passive Cooling Loops
PDHR	Passive Decay Heat Removal
RPV	Reactor Pressure Vessel
SG	Steam Generator
UHS	Ultimate Heat Sink
k	Total heat transfer coefficient (kW/m^2k)
T	Temperature (℃)
Subscripts	
s	Steam
wt	Water Tank

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