Thermal-hydraulic evaluation of passive containment cooling system of improved APR+ during LOCAs

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1. Introduction

Passive Containment Cooling System (PCCS) gets attention for prolonged station blackout in conjunction with loss of coolant accident. AP1000, ESBWR, and KERENA adopted and validated their own PCCSs and AHWR is developing its unique one. To ensure better safety level and to lower the construction cost, thereby strengthening competitiveness of our NPPs, this passive system is indispensable in advanced NPPs. In Korea, after successful design and validation of Passive Auxiliary Feedwater System (PAFS), PCCS is proposed to be reflected in the next version of APR+. In performance of PCCS, sound operation of PCCS heat exchanger (HX) tubes is vital. To clarify their heat transfer function, various experiments are in progress, involving our group. Furthermore, in case of externally condensed HXs, careful evaluation of flow instability inside HX tubes are of prime importance. In PANDA integral tests targeting HXs of KERENA, a huge oscillation of flow inside tubes is observed [1]. Flow instability is attributed to various reasons and classified into two types: static instability (ex. Ledinegg instability) and dynamic instability (ex. density wave oscillation). The former one is related to multiple stable flow rates at a given pressure drop under equilibrium condition while the latter one involves propagation time and feedback phenomena in transient condition. PCCS tubes correspond to the second type, dynamic instability. The detailed explanations are well documented [2-3].

Our group suggested a PCCS design featuring an air holdup tank (AHT) for removing air near heat exchangers [4]. Based on the design, the thermal hydraulic characteristics of PCCS are explored in this paper.

2. Methods

For our PCCS environment, a system code, MARS, is used to find out adequacy of suggested PCCS and main design parameters that affect stability of inside PCCS tubes.

Figure 1 displays the proposed PCCS schematics. Important values are given in Table 1.

When LOCA occurs and electricity is not available, PCCS works to deliver energy from released coolant and decay heat into water in passive condensation cooling tank (PCCT) disposed outside the containment. Between containment atmosphere and PCCT, PCCS tubes are installed as heat exchangers.

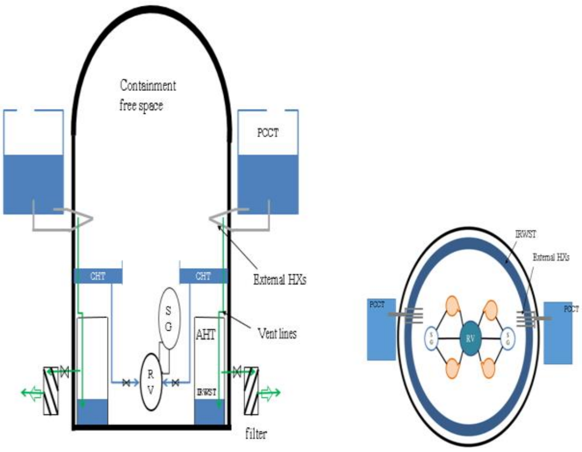

Fig. 1. Schematic for suggested PCCS based on APR+ (left: side view, right: top view)

Table 1: Dimensions on components of PCCS

Parameters		Values
Containment free volume		$79{,}200 m^3$
AHT volume (10% case)		$8{,}800 m^3$
IRWST water inventory		2,692 ton
PCCT water inventory		1,463 ton
Vent line cross-section area		$2 m^2$
PCCS HX Tubes	Inner diameter	0.0448m
	Outer diameter	0.0488m
	Length	8.0m
	Angle	5°

Steam inside containment is condensed on the outer surface of tubes while PCCT water circulates inside PCCS tubes. Since single phase water entering the tube has higher density and two-phase water exiting the tube has lower density, flow circulates naturally. To lower the air mass fraction near heat exchangers, AHT is installed above the IRWST. Due to pressure difference between open containment space and AHT, air is transported into AHT. As a result, steam-air mixture can be effectively condensed on the surface of the tubes.

Figure 2 displays the nodalization of MARS for PCCS. The figure represents the exact number of volumes and connecting junctions for all components as used in simulation. The components are represented as pipes. The containment, AHT with IRWST, and PCCT are made by combining two pipes with junctions in order to avoid erroneous stratification that happens when we use a single pipe. Above the PCCT, a time dependent volume representing atmosphere is disposed. The entrance of HX tubes is connected to the bottom of PCCT and the returning nozzle of HX tubes is

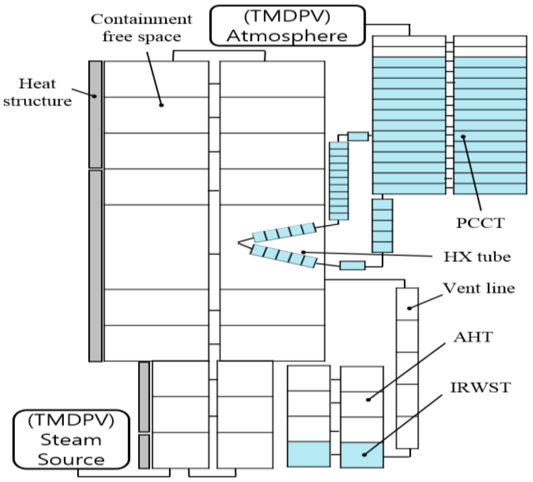

Fig. 2. Nodalization of MARS for PCCS

connected to the middle position of PCCT. The location of returning nozzle is changed to see its effect.

Steam sources by spillage of coolant during blowdown and by steam generation from decay heat are represented with time dependent volumes and time dependent junctions. The break flow rate and flow enthalpy, under the break area of 0.9m^2, were derived from APR1400 report. During 130s, 373 tons of reactor coolants are released giving 680GJ into the containment atmosphere. Decay heat is obtained from the APR+ report. Heat structures are considered based on the APR1400 report: 16 types of structures containing 64,000 tons of concrete with surface area of 45,000m^2 are disposed at adequate locations, such as putting containment dome on the highest location. Due to its large surface area and mass, the heat structures played a significant role as will be shown in the result section.

As initial conditions, temperature and pressure are set to be 300K and 0.1MPa, respectively. In Fig. 2, the blue-painted region represents water while the while-painted region represents air at the initial time.

In our calculation, we considered no PCCT water makeup for the 100-hour simulation. In real application, water can be supplied by external source easily because the PCCT is located outside the containment.

Regarding the heat transfer coefficients, heat transfer models embedded in MARS are used for tube inside and Dehbi's correlation for condensation is adopted for tube outside and heat sink structures by modifying the source code [5]. The Dehbi' s correlation is used due to its broad validity over the range of 0.3m<L<3.5m, 1.5atm<P<4.5atm, 10°C< T∞-TW <50°C. It is applicable to external condensation under turbulent natural flow for a single vertical tube:

$$h = \frac{L^{0.05}\left\{(4.62+35.6P)-(3047.5+572.9P)Log(W)\right\}}{(\bar{T}_\infty-\bar{T}_W)^{0.25}}$$

where h, L, P, W, represent a heat transfer coefficient in W/m2K, a pipe length in m, pressure in atm, air mass fraction, average bulk temperature in K, and average wall temperature in K, respectively.

The correlation does not contain any velocity term and depends only on air mass fraction, pressure, and temperature difference.

First, we evaluated the function of AHT. The volume fraction of AHT relative to total containment free volume is changed from 0% to 20% to see the effect of AHT size. We assessed the required number of PCCS tubes to meet the containment design pressure.

Then, flow instability is checked. Geometry of PCCS HX tubes and their connection to PCCT are varied to clarify the most dominant parameter in terms of flow circulation, or flow instability. The important parameters are displayed in Fig. 3. Six parameters are examined as flexible design parameters: inlet form loss coefficient via orifice plate (Kin), return nozzle height from the bottom of PCCT (Hreturn), downcommer line length (Hdown), tube angle (θ), tube inner diameter (Din), and tube length (L). A parametric analysis is performed using a test matrix, which is shown in Table 2. Conserving other parameters as default values, each parameter is changed to see whether flow becomes more stable or not.

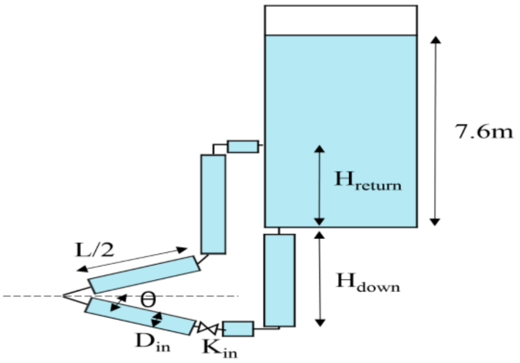

Fig. 3. Main parameters of PCCT and HX tubes to be studied for flow instability4

Table 2: Test matrix for flow instability study inside PCCS HX tubes

	K_{in}	H_{return} (m)	H_{down} (m)	θ (°)	D_{in} (cm)	L (m)
Default	3	3.3	2.5	5	4.48	8
Set 1	30,100	-	-	-	-	-
Set 2	-	2.1,4.5, 5.7	-	-	-	-
Set 3	-	-	1.5, 0.5	-	-	-
Set 4	-	-	-	15, 30, 45	-	-
Set 5	-	-	-	-	2.24 8.96	-
Set 6	-	-	-	-	-	4, 2

3. Results

Based on APR+, thermal hydraulic assessment of suggested PCCS is conducted and flow circulation characteristics inside PCCS tubes are checked.

Depending on AHT volume, the required number of PCCS tubes to meet the design pressure (5.22bar absolute) is lowered as shown in Table 3. Because air mass fraction near PCCS tubes decreases as AHT volume increases, the tube performance is gradually enhanced.

Table 3: Required number of PCCS HX tubes with respect to AHT volume fraction

AHT volume % in containment	number of tubes
0% (no AHT)	500
10%	300
20%	160

Regarding flow instability, mass flux inside PCCS tubes for 10% AHT volume is given in Fig. 4.

At around 35 hour after the onset of LOCA, two phase flow inside PCCS tubes starts to occur and large oscillation of flow is made. The temperature on the outer surface of tubes is upper bounded by temperatures of containment atmosphere so that thermal oscillation inside tubes is not severe. However, the large flow oscillation may affect the mechanical integrity of tubes. The same phenomena is observed in PANDA experiments [1]. The type of flow instability is thought to be density wave oscillation. The main characteristic of density wave oscillation is that oscillation period (T_{OSC}), which is marked in Fig. 6, is twice the period of mixture transit time ($T_{TRANSIT}$), which is defined as the ratio of water mass inside tubes to inlet flow rate. In our case, the T_{OSC} is around 35 second while the $T_{TRANSIT}$ is around 18 second fulfilling the common condition for density wave oscillation.

It is recommended to avoid flow instability to assure safety of tubes and overall PCCS. The easiest way is to adopt inlet orifice plates. Also, we can change the geometrical values as shown in Table 2. Among six parameters studied, inlet form loss, return nozzle height, and tube angle are found to be most effective. Figure 5, 6, and 7 display their effects. Larger inlet formloss generates larger pressure drop at the tube inlet stabilizing flow. However, when the form loss coefficient is larger than 100, an unstable flow at around 90 hours is noted.

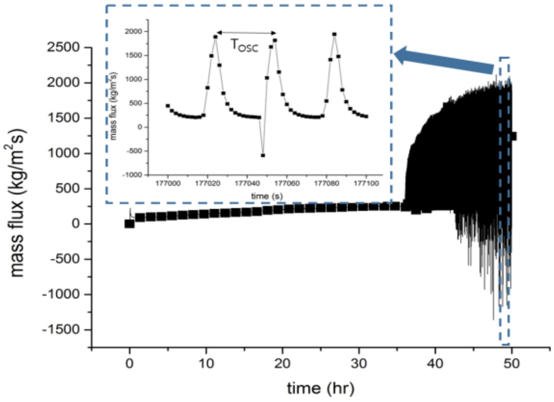

Fig. 4. Circulation mass flux trend inside HX tubes

As concerns return nozzle height and tube angles, there has been no general guide lines or analysis to consult. In our PCCS environment, larger return nozzle and tube angle are definitely preferred. We can say that the large return nozzle height might increase driving force stabilizing the flow while the large tube angle stabilizes the flow with decreased riser height.

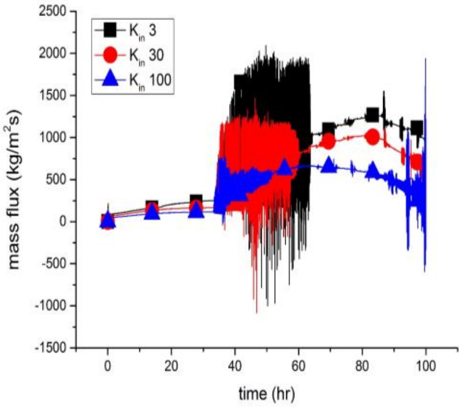

Fig. 5. Circulation mass flux trends inside HX tubes for various inlet form loss coefficients

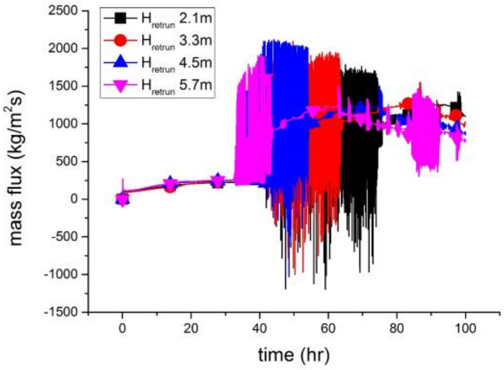

Fig. 6. Circulation mass flux trends inside HX tubes for various return nozzle heights

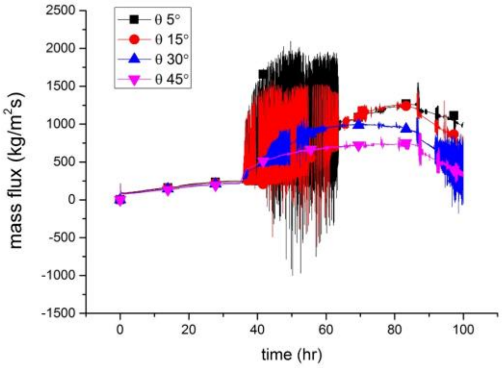

Fig. 7. Circulation mass flux trends inside HX tubes for various tube angles

4. Conclusions

Thermal hydraulic assessment of proposed PCCS is performed using a system code, MARS. Based on APR+, the required number of PCCS HX tubes are calculated with respect to AHT volume. We confirmed that larger AHT is preferred. Flow instability inside PCCS HX tubes are observed. Through sensitivity study, larger inlet orifice plate, return nozzle height, and tube angle are found to be most effective in stabilizing the flow.

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