Passive X Cooling for Innovative SMR Safety System

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1. Introduction

The Passive X safety system [1] is one of the most important design feature that can assure the inherent safety and passive operation of a nuclear power plant free from severe accident. Recently, newly developed design concepts of small and medium sized reactors (SMRs) of mPower and NuScale [2, 3] have aimed to enhance both inherent safety and competitive economics. However, it is not easy to resolve both contradictory needs at the same time.

To find a successful path toward solving these problems, it is necessary to simplify the system and unify the diverse safety functions. In this paper, verification of thermal hydraulic concept of Passive X cooling as a safety system has been conducted. And this will contribute innovative safety system design and passive operation of SMR.

2. Two type of natural circulation

The initial concept of Passive X was first introduced in 2016 under the name PX. Here, from the concept of Passive X (hereinafter abbreviated as PX) to the practical application, it has been described. Traditionally, the heat exchange method by the natural circulation on the vertical loop as shown in Figure 1(a) is Clock Wise direction (CW) when cooling and heating are started at the same time from the initial static condition in Figure 1(b). Another circulation is Counter Clock Wise (CCW) as shown in Figure 1(c).

Up to now, the reason for using CW direction is thought to be that the advantage of the CCW circulation method has not been found. However, if CCW circulating for the heat exchange is performed, the pressure of the loop is relatively low, and the upper part of the loop is still in a liquid state, which means that the latent heat of the liquid upper part can be used for the heat exchange once again. In other words, it means that boiling by heating and condensation by cooling are possible at the upper region. This could increase the heat exchange capability by the CCW circulation to two times of the CW method. The physical difference between the CW and CCW is that when the CCW circulation is performed, the center of mass in the loop rises, and a syphon phenomenon occurs at the top. In this state, driving force for the

circulation is created by the density difference between the lower right and the left region.
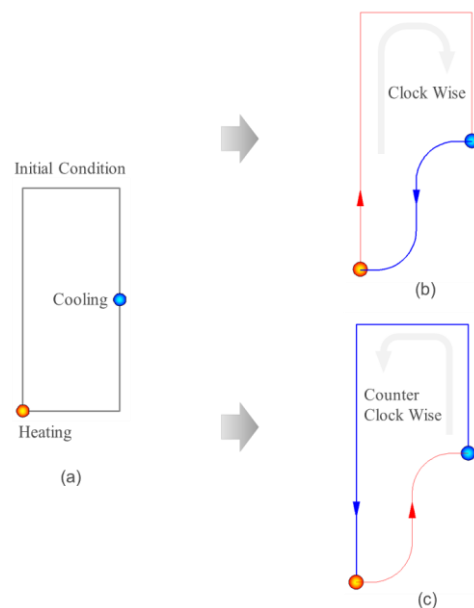

Figure 1. Two types circulation for a heat exchange

3. Single phase calculation result

In order to verify the thermal hydraulics phenomena of Passive X, calculations were performed on the shape shown in Figure 2. The code used in the calculation was MARS1.5, one-dimensional best estimate safety analysis code [4]. The height H of the loop is 2 m, the width d is 1 m, and the pipe inner diameter is 0.1 m. The heating part is located at the bottom and the cooling part is located at 1 m height, and the upper top left of the loop is equipped with a pressurizer for pressure stabilization. As the initial conditions, the loop temperature was set to atmospheric pressure of 92°C, and the power applied to the heating and cooling part were 5kW each. (Here, the letter "O" is indicated as a loop shape). Nodalization of the loop consists of 7 volumes (v1 ~ v7) and 7 junctions (j1 ~j7) including pressurizer, and each volume is divided into 5 sections. Figure 3 shows the circulating mass flow inside the loop for single phase, the pressure at the top and the liquid fraction. In this case, the heating and cooling were made gradually for 500 seconds. The initial mass flow condition is -0.001 for CW and 0.001 (kg/s) for

CCW. As showed in the results, it can be seen that the direction of circulation is determined according to the very small initial direction. In the case of CW, circulation starts faster than in the case of CCW, whereas in the case of CCW, the flow was slowly increased according to heating and cooling, and then the water flow increased as bubbles are instantly generated in the heating part. Finally, the same flow rate (different direction) is reached. The point to note from the results is that when the CCW circulation was performed, the pressure was relatively lower than that of the CW circulation.
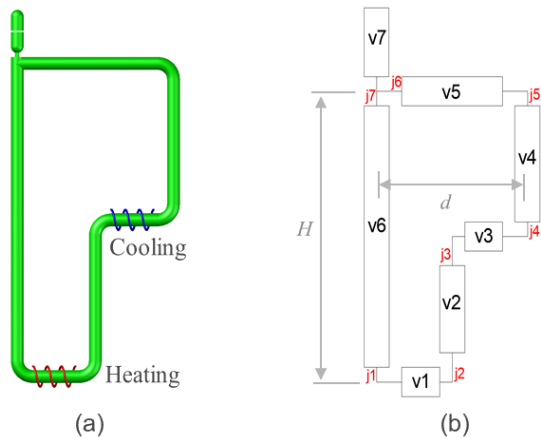

Figure 2. O type loop (a) geometry and MARS code nodalization (b)

4. Two phase calculation result

In Figure 4, the heating and the cooling power were increased to 80kW each for two phase flow circulation. Overall thermal hydraulic phenomenon was similar to that of the single-phase, but there were some differences in the water fraction and circulation flow. In the case of CCW, the flow rate was slightly higher than that of CW due the higher void fraction. The reason is excepted that the pressure of CCW flow is still lower than that of CW flow like the single phase flow.

5. Comparison of 3 types circulation

In order to verify the advantages of CCW circulation mentioned in Section 2, Figure 5 shows selected 3 circulation models such as O Loop, which is a typical circulation loop, and two types of X loop and PX loop corresponding to CWW circulation.
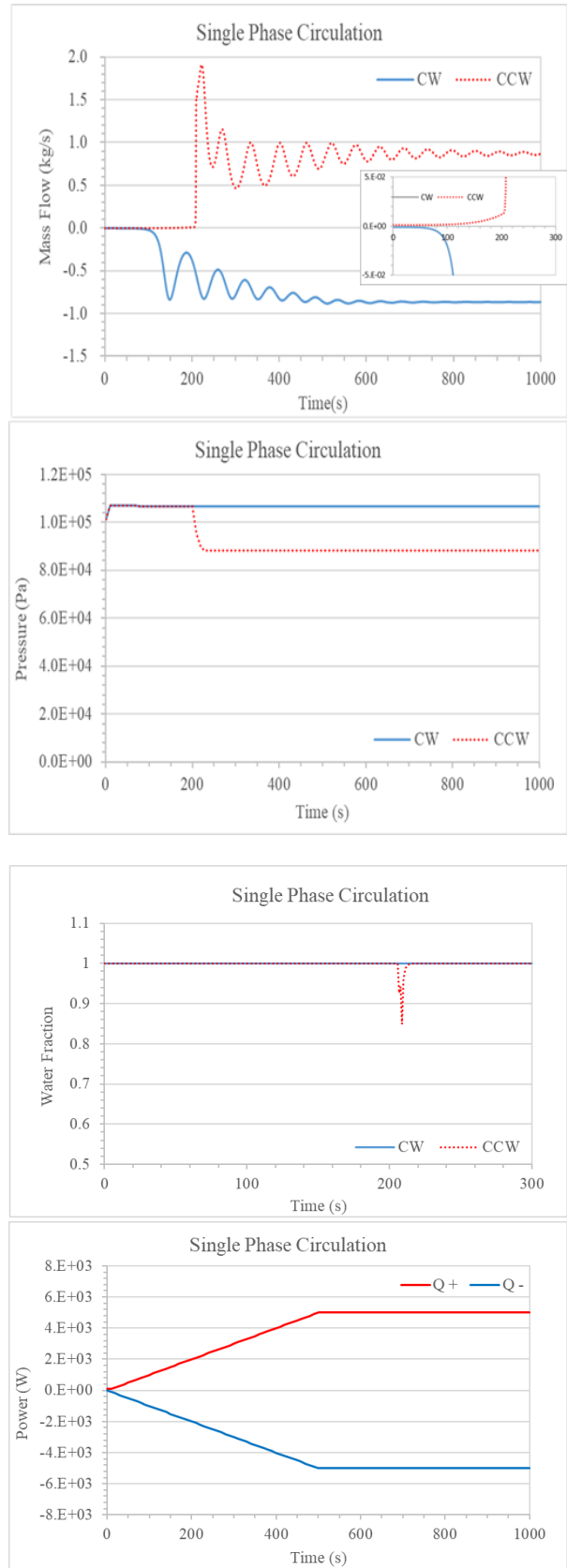

Figure 3. Single phase calculation results for CW and CCW circulations
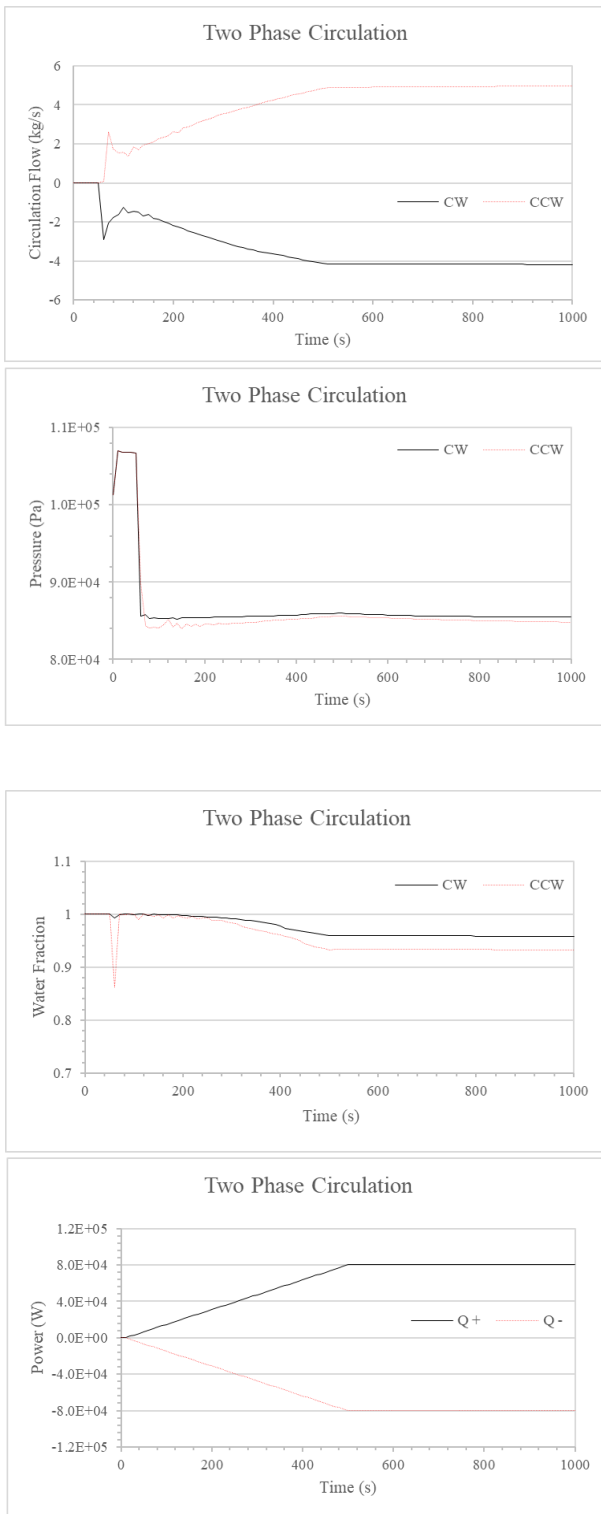
Figure 6 is the three dimensional geometries to calculate MARS code for the loops. Each loop has the height of 24 m, the width of 4 m, the inner diameter of 0.37 m, and the total volume of 6.97m3. The heating parts were located at two points on the left side, 0 m and 12 m high, and the cooling parts were located at 24 m and the middle height of 12 m, respectively. Designating the height of the heating part and the cooling part as a point was set for accurate comparison with the theoretical value (Here theoretical derivation is abbreviated). The reason of setting the heating and the cooling as two point is to represent the region of each adjacent part. For each loop, the height (1/1 ratio) and volume (1/100 ratio) were determined in consideration of the inner volume between the reactor vessel (thermal power: 250 MW SMR) and the safe guard vessel.
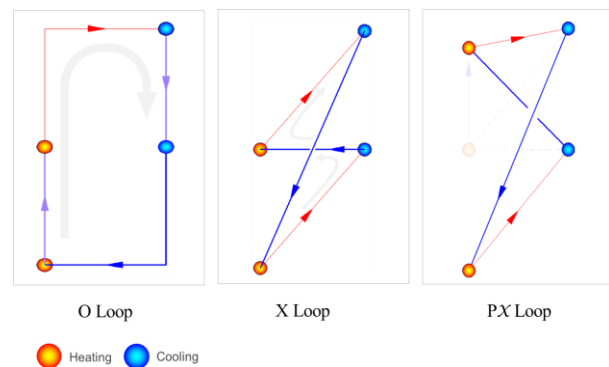

O Loop X Loop PX Loop

🔴 Heating 🔵 Cooling

Figure 5. Circulation models for CW and CCW with 2 step heating and cooling (CW : velocity is positive, CCW : velocity is negative)
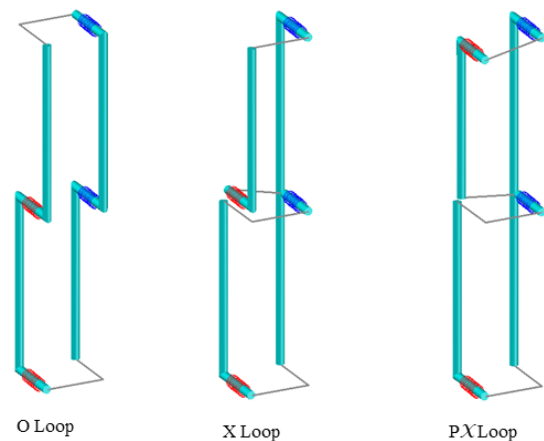

O Loop X Loop PX Loop

Figure 6. Three dimensional circulation models for the nodalizations of MARS code (sky blue is pipe and black line is junction)

Figure 4. Two phase calculation results for CW and CCW circulations

In Figure 5, the arrows are the flow direction, and the difference between the X loop and the PX loop is that the position of the heating part located in the left middle of the X loop has been moved upward.

The calculations were performed by comparing the circulation flow, pressure, and liquid fraction in each of the three loops while heating and cooling under the same power conditions from 6% to 16% of the 2.5MW,

which is 1/100 of the 250MW. Table 1 summarizes the calculation results. In Table 1, the case of O Loop, stable flow occurs until the power reaches 6% (total power of 150kW is sum of two heating parts and the same power is applied on the cooling parts), but when a larger power is applied, superheating occurs from the upper left and the pressure rises rapidly and code calculation is stopped under no superheating condition (Figure 7). This means that the limit of the CW circulation in the heat exchanger capability of O Loop is up to about 6~8% In case of X loop, the capability is up to about 16% that is consistent with the theoretically estimated power ratio ($2\sqrt{2}$). However, the pulsation flow starts to occur from about 8% (Figure 8). In case of the PX, the flow is stable up to about 12%, which can be seen that the heat transfer capability is two times compared with the O loop.

Table 1. Calculation results of 3 types loop for each power

Power	O Loop	X Loop	PX Loop	$\dfrac{Q_x}{Q_o}$	$\dfrac{Q_{px}}{Q_o}$
6% (150kW)	Stable	Stable	Stable		
8% (200kW)	Dry out	Start Pul.	Stable		
12% (300kW)		Pulsation	Stable		
14% (350kW)		Pulsation	Dry out		~2
16% (450 kW)		Dry out			$\sim 2\sqrt{2}$

6. Advantages of PX loop circulation

In section 5, the calculation results for the three types of loops has been compared. As the results, the X loop has $2\sqrt{2}$ times more heat exchange capability than the O loop, and the PX loop has two times. However, the PX concept is expected to be advantageous in terms of safety and engineering due to its stable flow. Here, the power ratio 2 (Q_{px}/Q_o) means that the volume of the PX loop could be reduced by the same ratio. Figure 9 shows the result of the calculation to confirm this.

The calculation result in the Figure is that the volume of the PX loop is 1/2 less than the O loop (the same height). In this case, the powers were set to 300 kW for each loop. As can be seen from the Figure, the liquid fraction representing the mass distribution and the circulation flow representing momentum are nearly the same. Despite the volume of the PX loop being 1/2, the pressure was rather low. This means that the PX loop circulation is better than the traditional O loop in terms of heat exchange and loop pressure (Figure 10). In particular, when the pressure becomes lower, the thickness of the safety guard vessel becomes thinner, reducing the heat transfer resistance of the material, and the decay heat of the reactor can be dissipated more easily to the final heat sink.
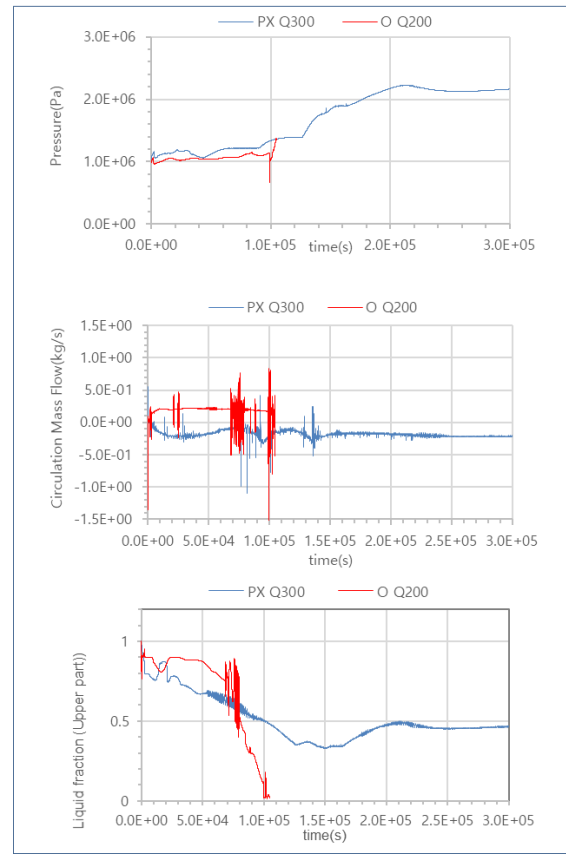

Figure 7. Calculation results for O loop (200 kW) and PX loop (300 kW)
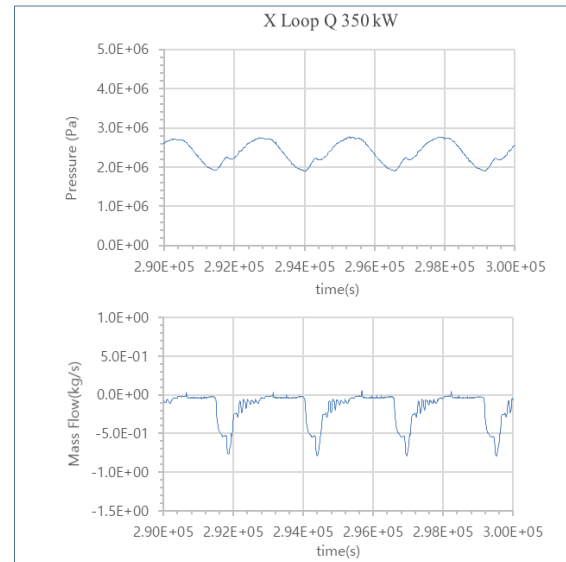

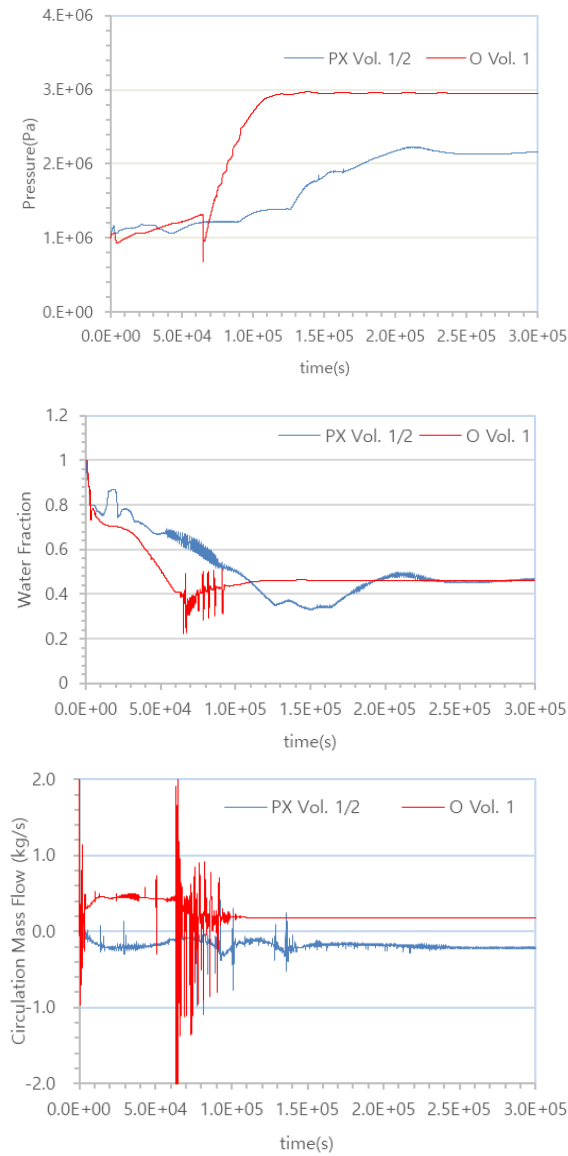Figure 8. Calculation result for X Loop

Figure 9. Comparison of the calculation results for the
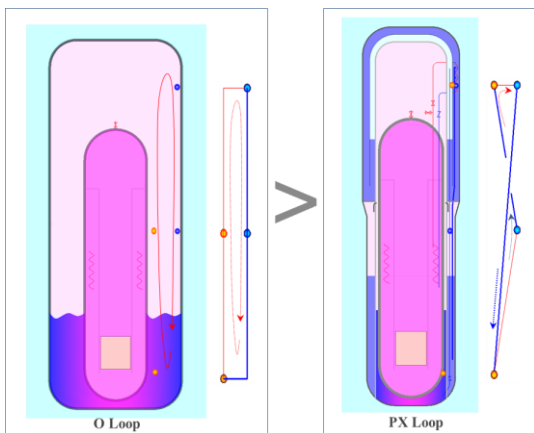volume ratio 1/2 of PX with respect to O loop

Figure 10. Comparison of circulation concepts of two
kinds SMR

7. Conclusion

The PX circulation method newly proposed in this paper has two times heat transfer capability and lower pressure than the traditional circulation O loop type. Therefore, PX circulation concept has a great advantage as the safety system to release the decay heat through the safe guard vessel of SMR.

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