# Investigation of inclination effect on the performance of passive residual heat removal system in a floating reactor during SBO analysis using MARS-KS

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## 1. Introduction

Marine nuclear power plants are being researched for ship propulsion and floating nuclear power plants (FNPP). FNPPs are designed to serve as power sources for remote areas with limited access to electricity. FNPPs are gaining attention due to their zero-carbon generation, modular construction and passive safety systems. Also, FNPPs use seawater for emergency cooling and offer shorter construction times and reduced risks.

However, since marine nuclear power plants operate under ocean conditions, the thermal-hydraulic behavior of their systems is expected to differ from that of land-based reactors. The effects of ocean conditions must be considered, and a safety analysis should be conducted.

In this study, a conceptual small modular reactor was modeled based on the information of SMART to analyze the TH (Thermal-Hydraulic) behavior under ocean conditions. For the TH analysis, MARS-KS dynamic motion model developed by Seoul National University [1,2] was applied. The performance of the passive residual heat removal systems (PRHRS) was evaluated to determine its capability to remove decay heat through natural circulation under station blackout (SBO) with inclination.

## 2. MARS-KS Modelling

### *2.1 Reference Reactor and Passive Residual Heat Removal System*

For this study, a reference SMR was modelled to conduct safety analysis under ocean conditions. The design of the reference SMR was based on SMART [3]. But, as the detailed design parameters are not open publicly, some parameters were determined in the present work considering engineering convention. Fig. 1 shows the configuration of the SMART-like reference SMR and Table 1 presents detailed design specifications of the reactor. The reference SMR adopts cassette-type Steam Generators (SG) with four trains. It incorporates passive safety systems of SMART including a Passive Safety Injection System (PSIS) and a PRHRS. In the present modeling, the PSIS was removed focusing on the stand-alone test of the PRHRS performance. To compensate for the absence of the PSIS during accidents, the height of the pressurizer was doubled to maintain its water level.

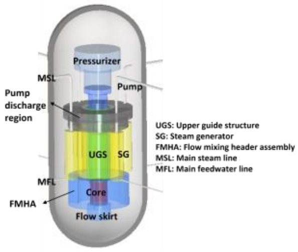


Fig. 1. Reference SMR configuration

The PRHRS is designed to remove residual heat from the primary side during accidents. The lateral length of the PRHRS piping connecting the steam generator and the heat exchanger was shorted to 6 m, which is approximately one-tenth of SMART to consider insufficient space in a barge.

The overall system configuration of the PRHRS single train is illustrated in Fig. 2. The reference SMR includes four PRHRS loops and each is connected to the main steam lines and feedwater lines, which is linked to the SG independently. The PRHRS consists of an Emergency Cooling Tank (ECT) and a condensation Heat exchanger (HX), which is located inside the ECT. The PRHRS operates through natural circulation, providing long-term cooling without external power. Upon activation of the PRHRS, the decay heat from the primary system is dissipated through the SG, which serves as the heat sink. Within the PRHRS, the heated steam from the main steam line is cooled by the HX in the ECT, and subsequently returns to the main feedwater line. The design of HX and ECT is based on the SMART reactor, with the ECT level set as 60 % to prevent spill-over due to inclination angle under ocean condition.

Table 1. Parameter of the SMART-like SMR design specification

| | |
|---|---|
| Reactor type | PWR-type SMR |
| Total power | 365 MWt |
| Primary pressure | 15 MPa |
| Secondary pressure | 6.4 MPa |
| Cassette type steam generator | 4 units |
| SG primary inlet / outlet temperature | 316.4 ˚C / 290.5 ˚C |
| Secondary system degree of superheat | 32.88 ˚C |

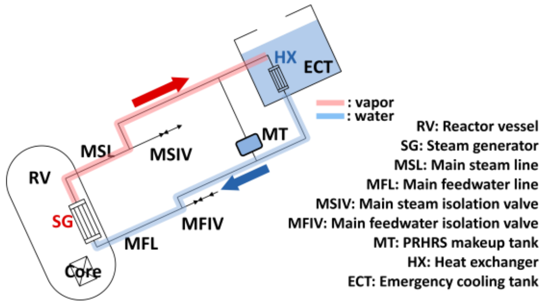



Fig. 2. PRHRS configuration of the reference SMR [4,5]

*2.2 Nodalization and dynamic motion model input*

The core and bypass region are quartered to account for the inclination effect under ocean conditions in Fig. 3-(a). Also, if the model inclines to the left, this direction is defined as '+ direction' in Fig. 2.

The reference SMR was nodalized for MARS-KS in Fig. 3-(b). The reference point of motion is set at the lowest point of the reactor vessel, as indicated with a red dot. From this reference point, the centers of each component volume are calculated in terms of cartesian coordinates.

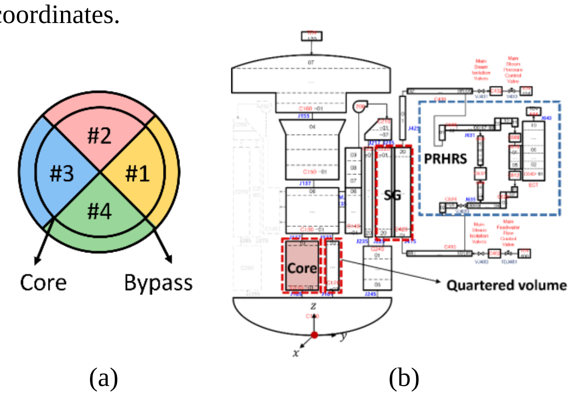



Fig. 3. Modelling of reference SMR – (a) Quartered division of the core and bypass regions in xy plane [6] (b) The MARS-KS node configuration

## 3. Analysis of the performance of PRHRS under vertical and inclined condition

*3.1. Long-term cooling safe shutdown acceptance criteria*

Long-term cooling safe shutdown acceptance criteria with PRHRS are as follows [7,8]: 1) After reactor shutdown, the RCS loop average temperature should reach the safe shutdown state (215.6 °C) within 36 hours and 2) be maintained below this state until 72 hours without operator action and emergency AC power. 3) After 72 hours, operator action and non-safety system support may be used. In the present work, the satisfaction of the first criterion was evaluated with inclination.

*3.2. Evaluation of safe shutdown performance*

An SBO is an accident scenario in which AC power is completely lost as summarized in Table 2: the Reactor Coolant Pumps (RCPs) and turbine trip occur, and offsite power and onsite emergency AC power become unavailable. In this scenario, the heat removal through the PRHRS is the only way to remove decay heat. However, because the PRHRS operates based on natural circulation which is significantly influenced by the relative height difference of heat source and sink, its performance under motion conditions should be evaluated. Therefore, this study investigates whether the PRHRS operates effectively so that the RCS loop average temperature reaches and maintains a safe shutdown state within 36 hours using only the PRHRS without PSIS.

The inclined condition is set to +30˚ inclined to the left. The analysis of vertical condition is also conducted as a reference case.

The results of the accident scenario in vertical and inclined conditions are summarized in Table 2. When an SBO occurs, the control rods are inserted, causing reactor shutdown and the RCPs and turbine trip. Due to the loss of secondary feedwater supply, the PRHRS valves begin to open when the feedwater flow rate drops to 5.9 % of the steady-state flow rate due to a low feedwater flow signal, activating long-term cooling through natural circulation. The main trip events under the inclined condition occurred without delay compared to the vertical condition.

Table 2. SBO accident scenario

| Event | Operation time | | Setpoint |
|---|---|---|---|
| | VT | +30˚ IN | |
| SBO | 10.0 s | 10.0 s | Initial event |
| Control rods insert | 10.5 s | 10.5 s | Equipment actuation delay time 0.5 s |
| MSL / MFL valve closure<br>PRHRS valve open | 15.2 s | 15.2 s | Low feedwater flow rate 5.9 % |
| RCS average temperature reaches the safe shutdown temperature | 39760.0 s (11 h) | 39060.0 s (10.85 h) | |

The following changes occur under inclined conditions. Under the vertical condition, the HX in PRHRS is located approximately 10.93 meters higher than the SG. Under the inclined condition, the HX in PRHRS-1 is located 17.38 meters higher than the SG, while the HX in PRHRS-3 is only 4.48 meters higher in Fig. 4. As the PRHRS is operated by the gravitational head difference as the driving force, the head difference for each loop causes variations in the mass flow rate for each loop as shown in Fig. 5-(a). Under the inclined conditions, the head difference causes a reduced flow rate in PRHRS-3 and an increased flow rate in PRHRS-1 compared to the vertical condition in Fig. 5-(b). After 9 hours, the mass flow rate of PRHRS-1 oscillates and suddenly rises due to the opening of the MT in PRHRS-1 as shown in Fig. 6.

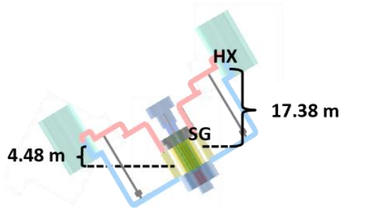
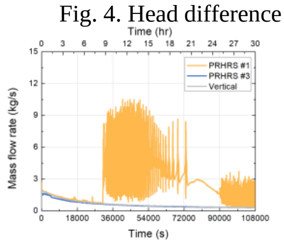
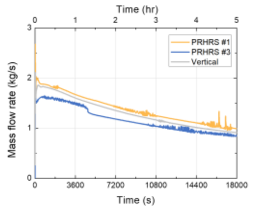



Fig. 4. Head difference between SG and HX




(a)

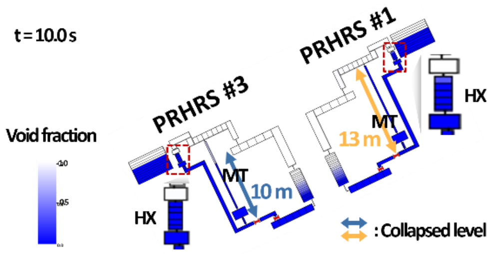



(b)

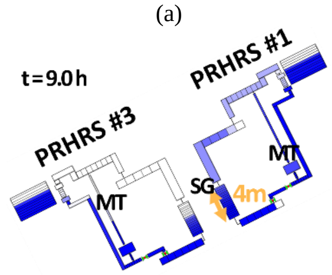
Fig. 5. Mass flow rate of PRHRS under vertical and inclined conditions – (a) Until 100000.0 s (b) Until 20000.0 s

For further analysis of entire PRHRS in inclined condition, the void fraction distributions have been illustrated as shown in Fig. 6. At 10 seconds after the initiation of the accident, the MT line and PRHRS piping act like a manometer because the PRHRS valves have not yet opened as shown in Fig. 6-(a). In PRHRS-3, more water is stored in the HX, while the water level in the MT line remains around 10 meters. In contrast, in PRHRS-1, the water level in the MT line remains at 13 meters, and less water has remained in the HX.

The head difference of PRHRS-1 increases due to the inclination, enhancing natural circulation as shown in Fig. 5-(b). As a result, the increased mass flow rate for the same decay heat reduces the temperature change of water passing through SG, leading to a subcooled condition. When the SG reaches the full water level in Fig. 7, the MT opens and the circulation flow rate of PRHRS-1 increases. Fig. 6-(b) shows two-phase mixture entering the HX of PRHRS-1.




(a)




(b)

Fig. 6. Void fraction distribution of PRHRS under +30˚ – (a) Initial condition (t = 10.0 s) (b) When makeup tank opens (t = 9.0 h)

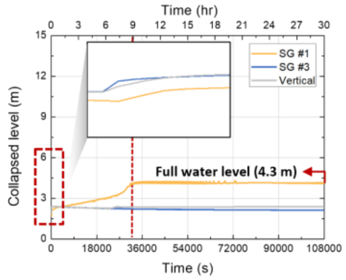



Fig. 7. SG collapsed level under vertical and inclined conditions.

The RCS loop average temperature is calculated as the mean of temperatures measured at the RCP discharge region and the FMHA. Since the reactor coolant system consists of four loops, the RCS loop average temperature is calculated for each loop. Under the inclined condition, more heat is removed compared to the vertical condition, resulting in a slightly faster temperature decrease. In the vertical condition, the safe shutdown temperature of 215.6 °C is reached within 11 hours, as indicated by the red dash line in Fig 8. While under inclined conditions, it is reached within 10.85 hours.

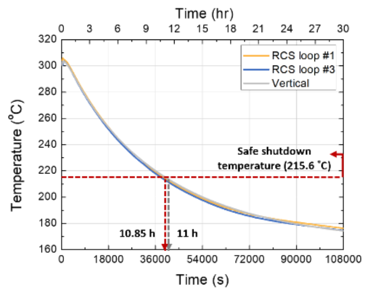



Fig. 8. RCS loop average temperature under vertical and inclined conditions

The total head difference of the four loops under the inclined condition decreases by 12.5 % compared to the vertical condition in Fig. 9-(a). The removed heat of each HX is related to the head difference. The greater the head difference, the higher the heat removal rate of the HX in Fig. 9-(b) and (c). The total removed heat until 60000.0 s of HX under the inclined condition is slightly higher than the vertical condition in Fig. 9-(d). Although the total head difference under the inclined condition is lower than that of the vertical condition, the effect of increased heat removal in PRHRS-1 is higher than that of decreased heat removal in PRHRS-3. As a result, the system reaches the safe shutdown temperature earlier under the inclined condition, as seen in Fig. 8. However, no significant change in total removed heat is observed, given the extent which total head difference has decreased.

Additionally, the same calculation was repeated with the original lateral piping length of SMART PRHRS (61 meters). The total head difference was 12.5 %, the same as the previous case in Fig 10-(a). However, due to the longer piping length, the head difference of PRHRS-1 is 52.84 meters, while of PRHRS-3 is -30.98 meters, showing a significant difference from the modified case in Fig. 10-(b) and Fig. 9-(b). PRHRS-3 fails to overcome the head difference, leading to failure in heat removal in Fig. 10-(c). Consequently, the total removed heat under the inclined condition decreases by 7.1 % in Fig. 10-(d). The layout of the PRHRS affects the head difference of each PRHRS. It is obvious that the optimized arrangement of the PRHRS is critical.

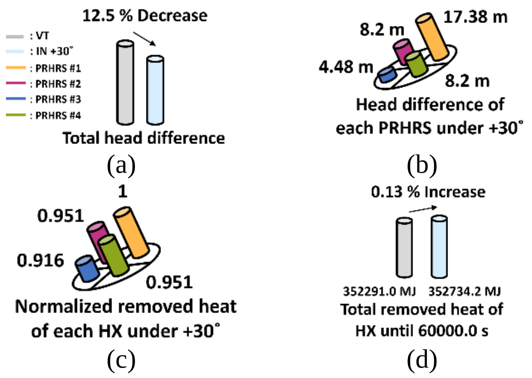



Fig. 9. Head difference and removed heat under vertical condition and inclined condition – (a) Total head difference (b) Head difference of each PRHRS under +30˚ (c) Normalized removed heat of each HX under +30˚ (d) Total removed heat of HX until 60000.0 s

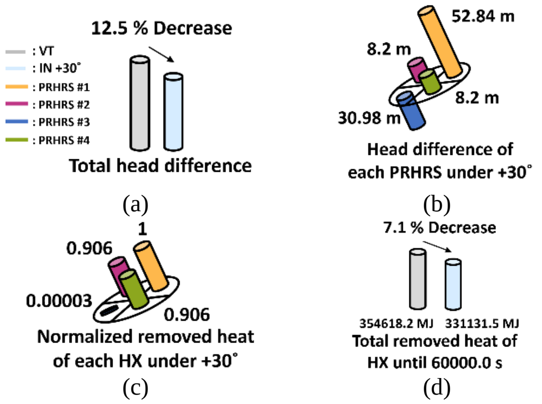



Fig. 10. Head difference and removed heat under vertical condition and inclined condition when applying PRHRS length based on SMART – (a) Total head difference (b) Head difference of each PRHRS under +30˚ (c) Normalized removed heat of each HX under +30˚ (d) Total removed heat of HX until 60000.0 s

Meanwhile, this study uses a simplified one-dimensional model to model the helical coil, condensation HX, and natural circulation in the pool. However, due to the complex structure of the helical coil, its heat transfer performance under inclined conditions can vary depending on inclination [9]. For condensation HX, the filmwise condensation can be affected significantly with tube inclination [10]. For boiling heat transfer in a large water pool, the natural circulation phenomena can be changed largely with inclination angle [11]. These characteristics should be considered in our future work to accurately represent realistic conditions.

## 4. Conclusion

This study conducted the SBO analysis for a SMART-like SMR under vertical and +30˚ inclined conditions. In the inclined conditions, the temperature reached a safe shutdown temperature slightly earlier than the vertical case due to the effect of increased heat removal in PRHRS-1 despite the reduced head difference. It was also clearly shown that the later distance between the SG and PRHRS HX influences the heat removal performance of the system. Consequently, it was emphasized that the position of PRHRS should be considered as an additional factor under ocean conditions. In future work, several heat transfer models, including the helical coil, condensation HX, and natural circulation in the pool, should be refined to better reflect realistic conditions for more accurate analysis. Moreover, the experiments considering these factors should be conducted, and it is essential to incorporate the results of these experiments into the model.

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