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Prediction of Flow Rate in a Passive Residual Heat Removal System with Various Water Levels

Hun Sik Han [a*], Young In Kim[a], Keung Koo Kim[a]
[a]*SMART Development Division, Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon 305-353*
[*]*Corresponding author: hshan@kaeri.re.kr*

1. Introduction

Safety features of a nuclear power plant concerning a severe accident have been key issues since the Fukushima disaster. SMART (System-integrated Modular Advanced ReacTor), which is a small-sized integral type pressurized water reactor (PWR), has been developed at the Korea Atomic Energy Research Institute (KAERI), aiming at enhancing system safety and reliability [1]. To achieve highly enhanced safety, advanced design features such as incorporating a structural safety improvement and reliable passive safety system have been introduced in the SMART design.

A passive residual heat removal system (PRHRS) is one of passive safety systems that have been adopted in SMART. In the case of an emergency such as an unavailability of the secondary side feedwater supply or a station blackout, the PRHRS passively removes the core decay heat and sensible heat through a two-phase natural circulation, and thus maintains the reactor in a stable condition without any AC power or operator actions.

The PRHRS consists of an emergency cool-down tank (ECT), a condensing heat exchanger (HX), a makeup tank (MT), valves, pipes, and monitoring instruments. Its conceptual diagram is given in Fig. 1. If the passive residual heat removal actuation signal is generated, the PRHRS starts running. Subcooled water in the HX flows into the secondary side of the SG due to the difference in the water level. The feedwater is evaporated by residual heat, and exits the SG cassette nozzle header at a two-phase flow or superheated steam condition. Then, as it flows into the HX submerged in the ECT, the steam is condensed into subcooled water by emitting the residual heat into the cool-down water. Thus, continuous coolant circulation occurs in the PRHRS.

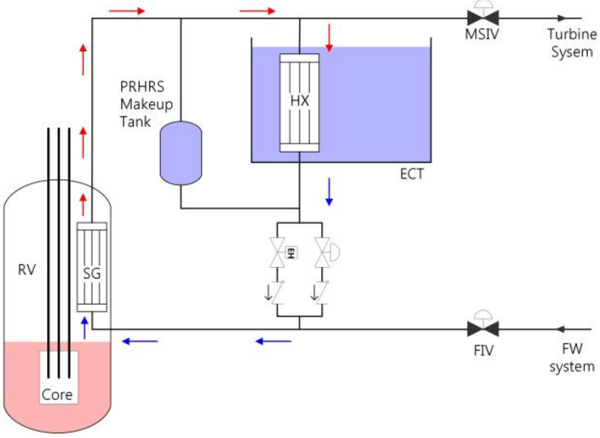


Fig. 1. Conceptual diagram of the PRHRS

Such a natural circulation becomes weakened, however, as the water level and density differences between the HX and the secondary side of the SG dwindle due to the decrease of residual heat. In this study, therefore, the effects of water level in the PRHRS on the flow rate are theoretically examined. To obtain the flow rate variation, the natural circulation in PRHRS is modeled with basic hydraulic theory.

2. Analysis Model

A simplified schematic diagram of the natural circulation in the PRHRS is presented in Fig. 2. The flow rate of the natural circulation is determined at the hydraulic equilibrium point between the driving force of the natural circulation and the hydraulic resistance in pipes, namely

$$\Delta\rho gh - \Delta P_{\text{K-R}(1)} + \Delta P_{\text{K-R}(2)} = 0, \qquad (1)$$

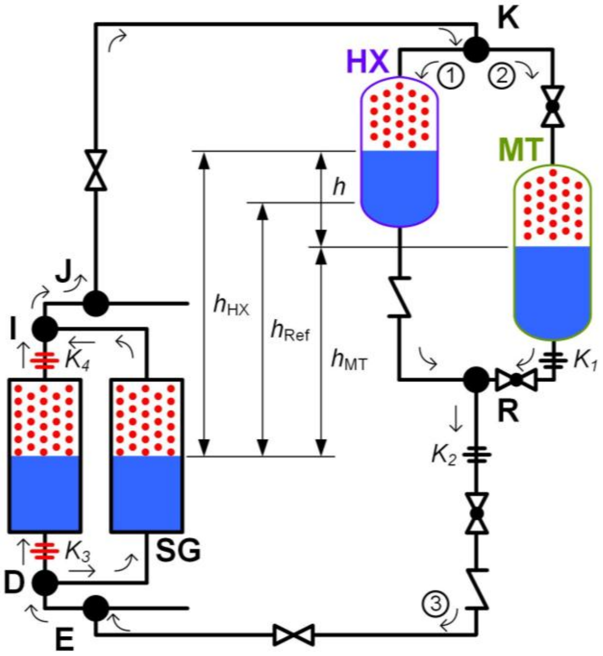


Fig. 2. Natural circulation model of the PRHRS

$$\Delta\rho g h_{\mathrm{HX}} - \Delta P_{\mathrm{R\text{-}K(3)}} - \Delta P_{\mathrm{K\text{-}R(1)}} = 0$$
$$(\text{or } \Delta\rho g h_{\mathrm{MT}} - \Delta P_{\mathrm{R\text{-}K(3)}} - \Delta P_{\mathrm{K\text{-}R(2)}} = 0), \qquad (2)$$

where $\Delta\rho$ is the density difference between subcooled water in the HX (or MT) and steam in the SG, g is the acceleration of gravity, and ΔP is the pressure loss in the pipes. Subscripts K and R indicate the pipe junctions, subscripts (1), (2) and (3) represent the flow paths, and h, h_{HX} and h_{MT} denote the water level differences, as sketched in Fig. 2.

In the above, the driving force is given as a gravity force of the density and water level differences, and the pressure loss is the sum of the friction loss and the minor loss, namely

$$\Delta P_{i-j} = \sum_{i}^{j}\left[\left(f\frac{L}{D}+K\right)\frac{\rho V^2}{2}\right] = \sum_{i}^{j}\left(K_e\frac{\rho V^2}{2}\right), \qquad (3)$$

where f, L, D, K, K_e, ρ and V are the friction factor, the pipe length, the pipe diameter, the loss coefficient, the equivalent loss coefficient, the fluid density and the cross-stream averaged velocity, respectively. The friction factor in the turbulent pipe flow (Re>4000) is expressed as [2]

$$f = \left(1.8\log\frac{\mathrm{Re}}{6.9}\right)^{-2}. \qquad (4)$$

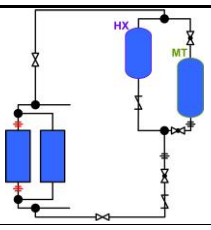
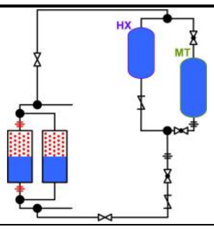
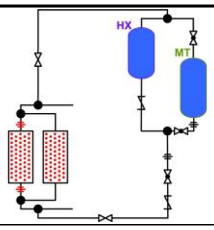
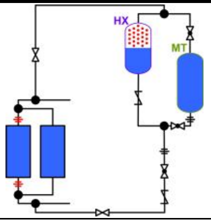
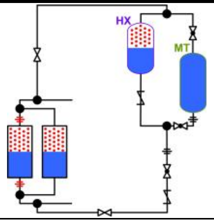
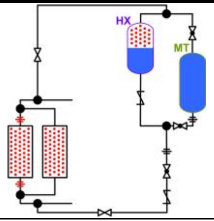
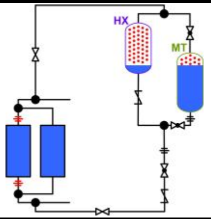
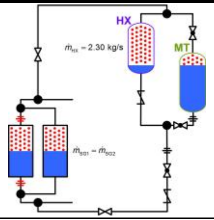
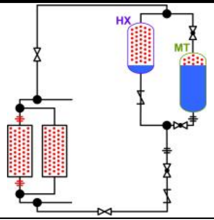
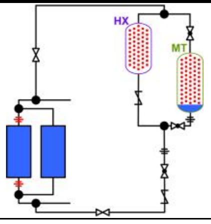
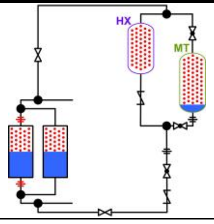
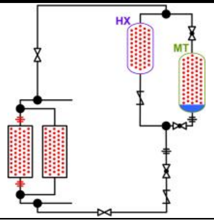
Here, $\mathrm{Re} = \rho VD/\mu$ is the Reynolds number, and μ is the dynamic viscosity. The loss coefficient K in Ref. [3] is used to calculate the minor loss.

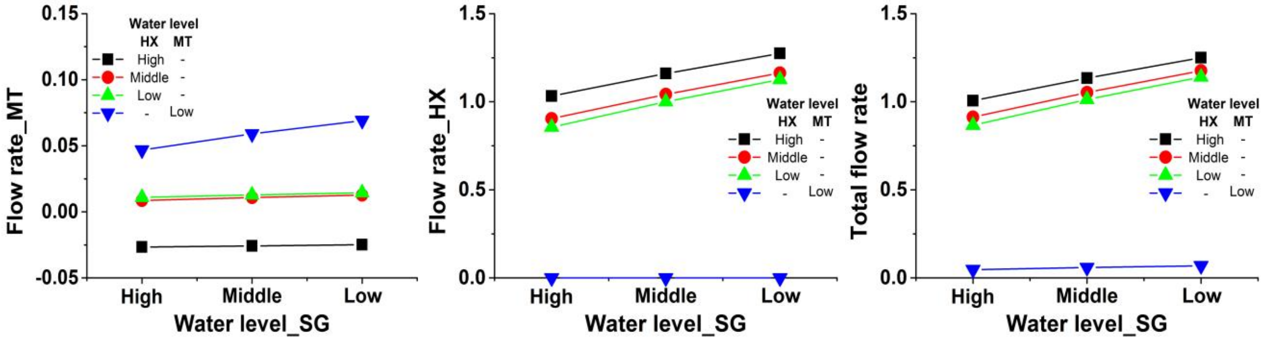
3. Results and Discussion

Table 1 shows various water level differences taken into account in the present study. Here, the assumed water level differences are presented in properly non-dimensionalized form of $H_{\mathrm{HX}} = h_{\mathrm{HX}} / h_{\mathrm{Ref}}$ and $H_{\mathrm{MT}} = h_{\mathrm{MT}} / h_{\mathrm{Ref}}$. For all groups, the water level difference between the secondary side of the SG and the HX (or MT) increases with a decrease of the SG water level. In group 4, however, H_{HX} shows a constant value of 0 regardless of the SG water level because the empty HX means that the SG water level is identical to that of the HX. Also, H_{HX} (or H_{MT}) in group 1 has the highest value among all groups due to the highest water level in the HX (or MT).

The flow rate variation according to the water level in

Table I: Water level differences in the PRHRS

SG water level	High	Middle	Low
Group 1 (HX water level: high)			
H_{HX} & H_{MT}	0.989 & 0.800	1.256 & 1.067	1.522 & 1.334
Group 2 (HX water level: middle)			
H_{HX} & H_{MT}	0.813 & 0.800	1.080 & 1.067	1.346 & 1.334
Group 3 (HX water level: low)			
H_{HX} & H_{MT}	0.733 & 0.733	1.000 & 1.000	1.267 & 1.267
Group 4 (MT water level: low)			
H_{HX} & H_{MT}	0.000 & 0.461	0.000 & 0.727	0.000 & 0.994



(a) (b) (c)

Fig. 3. Flow rate variation according to the water level in the PRHRS: (a) MT, (b) HX, and (c) PRHRS.

the PRHRS is plotted in Fig. 3. Here, the flow rate is a dimensionless quantity of $\dot{m}/\dot{m}_{\mathrm{design}}$. It is discernible from Fig. 3a that only group 1 has a negative MT flow rate. This means that the upward MT flow occurs in group 1, whereas the MT flow direction is downward in all other groups. This comes from the fact that the driving force of the upward MT flow by the water level difference between the HX and the MT is relatively high compared to that of the downward MT flow by the water level difference between the MT and the SG. Among all groups, group 1 shows the highest water level difference between the HX and the MT, and thus it results in a high driving force of the upward MT flow. Also, for all groups, it is noted that the downward flow rate is augmented as the water level in the SG decreases due to the higher H_{MT}.

The HX flow is shown to be qualitatively consistent with the MT flow, see Fig. 3b. However, it provides a much higher flow rate owing to the lower hydraulic resistance of the flow paths. It is noticeable from Fig. 2 that components such as the valve and the orifice installed in the MT flow path disturb the coolant flow. The check valve placed at the outlet of the HX blocks the reverse flow, and thus the HX flow rate is zero even though the MT has a higher water level compared to the HX, as shown in group 4 of Fig. 3b.

Fig. 3c discloses the total flow rate in the PRHRS, which is sum of the HX flow rate and the MT flow rate. In group 1, the total flow rate is slightly lower than the HX flow rate because the coolant discharged from the HX flows into both the SG and the MT. Group 1 of the highest HX water level gives rise to 0.6%, 13.4% and 25.0% higher total flow rates compared to the design flow rate for the high, middle and low water levels of the SG, respectively. However, the total flow rate obviously decreases when the MT is almost empty such as in group 4.

4. Conclusions

The effect of the water level of the SG, HX and MT on the natural circulation in the PRHRS has been investigated. The circulating flow rate is obtained by applying the fundamental hydraulic theory to the PRHRS. The results obtained at various water levels reveal that an upward MT flow occurs when the water level difference between the HX and the MT is high. However, this upward MT flow dwindles as the water level of the SG decreases because it enhances the driving force of the downward MT flow. The HX flow rate also increases with the decrease in the SG water level.

It is noted that a natural circulation in PRHRS mainly occurs through the flow path of the HX because the flow path configuration through the MT gives an inherently high hydraulic resistance. Thus, the total flow rate has a similar value as the HX flow rate. The highest HX water level yields 0.6%, 13.4% and 25.0% augmented total flow rates compared to the design flow rate when the SG water level is high, middle, and low, respectively. However, the low water level in the MT provides an extremely low total flow rate owing to the decline in the water level difference.

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REFERENCES

[1] K. K. Kim, W, Lee, S. C. Choi, H. R. Kim, and J. Ha, SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering, Vol.8, p.94, 2014.
[2] F. M. White, Fluid Mechanics, sixth ed., McGraw-Hill, New York, 2008.
[3] Flow of Fluids – Metric Edition, Crane Co., England, 1988.