Hybrid Cooling Concept for the Passive Residual Heat Removal System in the SMART

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1. Introduction

Passive safety systems in nuclear power plant have been widely investigated [1, 2] due to its inherent characteristics of using natural forces such as natural convection and gravity to circulate the coolant, and less dependent on active components like pumps and diesel generators.

The Passive Residual Heat Removal System (PRHRS) is one of the innovative design features adopted in the SMART plant being developed at Korea Atomic Energy Research Institute (KAERI). Fig. 1 shows the schematic diagram of the PRHRS in the SMART plant. There are four PRHRS trains in SMART. Each train has a Heat eXchanger (HX), an Emergency Cooldown Tank (ECT), a makeup tank, and valves. The capacity of the heat exchanger in each PRHRS train is 1% of the plant nominal power.

One drawback of the current PRHRS design is that the passive system does not work permanently. The ECT contains a finite volume of water. A very large amount of water should be stored for 36-hour operation. After this water dries up, the PRHRS can not cool the reactor anymore, if additional water is not supplied from other source. Overcoming this drawback, a new hybrid cooling concept is proposed in this study. The concept combines water and air cooling modes. The new PRHRS can cool the reactor in the initial stage effectively and operate permanently without any assistance from active components or an operator's intervention.

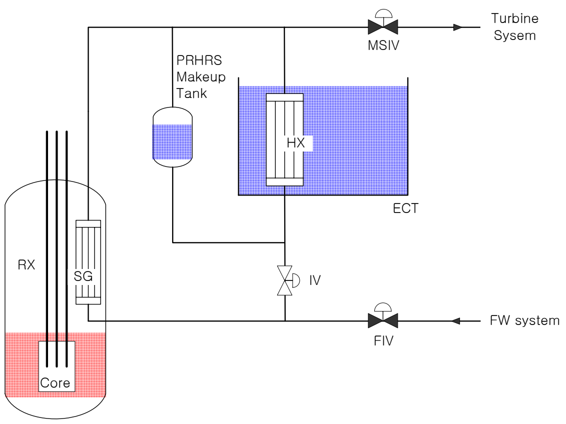

Fig. 1. Schematic diagram of the passive residual heat removal system in SMART plant

2. Hybrid Passive Residual Heat Removal System Development

The PRHRS with the water cooling mode has more cooling capability and a finite operational period, whereas the system with air cooling mode has less cooling capability and an infinite operational period.

A large decay heat is released from core just after it is tripped. The amount of the decay heat exponentially decreases as time passed. The decay heat is about 2% of the rated power during the initial one hour and decreased to 0.4% after 36 hour elapses.

Two cooling modes can be logically combined into one system based on the decay heat trend. Initially the heat exchanger is cooled through the water cooling mode. After the ECT dries up and the heat exchanger is exposed to an air, the heat exchanger is cooled by the air driven naturally from outer environment. Through this combination, we can effectively utilize each cooling mode.

Fig. 2 shows the schematic diagram of the hybrid PRHRS concept. The ducts for the air inflow/outflow are added into ECT. The inflowing air is heated by the heat exchanger and goes up. A chimney installed on the ECT increases the air flow rate. The external air is driven into the ECT through the inlet duct and guided into the heat exchanger. Generally the heat transfer coefficient of air flow is very lower than the water flow, so the heat transfer area should be significantly increased. High-finned tubes are introduced for the higher cooling capability, which is shown in Fig. 2. The upper portion of the heat exchanger is designed with the high-fin tubes and the lower portion with normal tubes. The lower portion plays a role to make water level low and secure the air flow path.

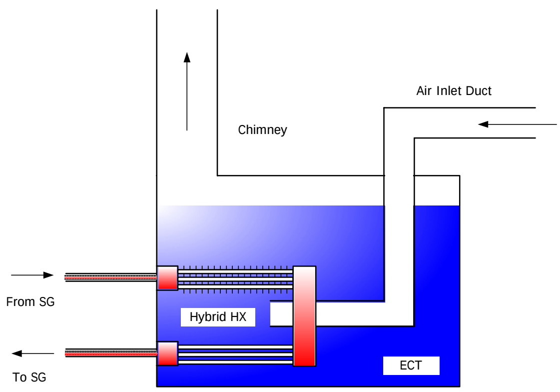

Fig.2. Schematic diagram of the hybrid PRHRS concept

3. Heat Exchanger and ECT Design

The high-finned tubes are introduced to increase the heat transfer rate for the air cooling mode. A preliminary sizing calculation for the high-finned tubes was carried out based on the design data from the reference [3]. For this calculation, the inlet/outlet air ducts are assumed as shown in the Table.1. Briggs and Young's heat transfer correlation is used for the outside heat transfer of the high-finned tubes [4].

$$\frac{h_0 d_r}{k_{air}} = 0.134\left(\frac{d_r \rho_{air} V_{max}}{\mu_{air}}\right)^{0.68} \mathrm{Pr}_{air}^{1/3}\left(\frac{H}{s}\right)^{-0.2}\left(\frac{Y}{s}\right)^{-0.12} \quad (1)$$

V_{max} is the maximum air-side velocity going through the finned tube bank and the other quantities have their usual meaning. Fin spacing, s, is related to the number of fins pre inch, N_f by the equation:

$$s = \left(\frac{1}{N_f}\right) - Y \quad (2)$$

Robinson and Briggs's correlation is utilized for the pressure drop across banks of the finned tube banks [5].

$$f_r = 9.47\left(\frac{d_r \rho_{air} V_{max}}{\mu_{air}}\right)^{-0.32}\left(\frac{P_t}{d_r}\right)^{-0.93} \quad (3)$$

Where f_r is the friction factor and P_t is the transverse pitch between adjacent tubes in the same row. The friction factor is defined as:

$$f_r = \frac{\Delta p_{air}}{2n\rho_{air} V_{max}^2} \quad (4)$$

Table 2 shows the high-finned heat exchanger design value when the ECT water volume is selected for 36 hr mission time. The HX heat transfer area and ECT water volume mainly depend on the switchover time. As the switchover time increase, more ECT water volume and less HX heat transfer area are required, as shown in the Fig.3.

Table.1 Inlet/outlet duct design value

Outlet duct length	20 m
Outlet duct height	15 m
Outlet duct diameter	1.5 m
Inlet duct length	20 m
Inlet duct diameter	1.5 m
Outlet duct bending #	3
Inlet duct bending #	5

Table 2. High-finned heat exchanger design value

Tube length	2 m
Tube OD	25.4 mm
Fin height	12.7 mm
Fin thickness	1 mm
Fin clearance	13.2 mm
Lateral number of tubes	24
Longitudinal number of tubes	6
FPI	7
Fin efficiency	0.9

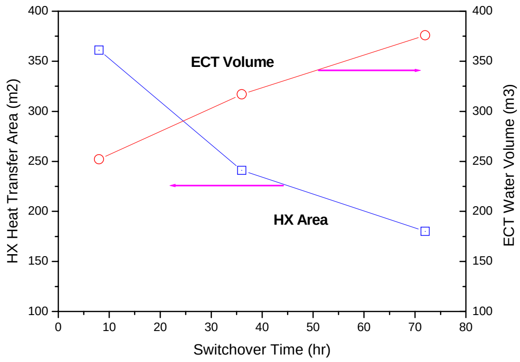

Fig.3. Heat transfer area and ECT water volume as a function of switchover time

4. Conclusions

New hybrid cooling concept for the PRHRS is proposed in this study. The concept combines water and air cooling modes. Initially the heat exchanger is cooled through the water cooling mode. After the ECT dries up, the heat exchanger is cooled by the air driven naturally from outer environment. Preliminary sizing calculations for the high-finned tubes are carried out as a function of the switchover time.

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