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Preliminary Performance Evaluation of Safety Grade Power Generation System for Integral Reactor

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1. Introduction

An integral reactor refers to a reactor in which main components such as reactor core, steam generator, pressurizer, and reactor coolant pump are placed in a single reactor vessel. Unlike large conventional reactors, there are no large pipes connecting main components. Therefore, LB-LOCA (Large Brake Loss Of Coolant Accident) can be excluded. In addition, the fully passive safety systems using natural force mitigate accident and maintain the reactor safe condition. Especially, PRHRS (Passive Residual Heat Removal System) discharges core residual heat to the ultimate heat sink of the power plant using natural circulation. The schematic diagram of PRHRS is shown in Figure 1. The residual heat is abandoned through the ECT (Emergency Cooling Tank, this is ultimate heat sink).

To utilize this residual heat, SGPGS (Safety Grade Power Generation System) was proposed. This system can either remove the residual heat or produce electricity. The concept of SGPGS was evaluated at previous research[1].

In this study, the performance of SGPGS was preliminarily evaluated to check appropriateness and availability.

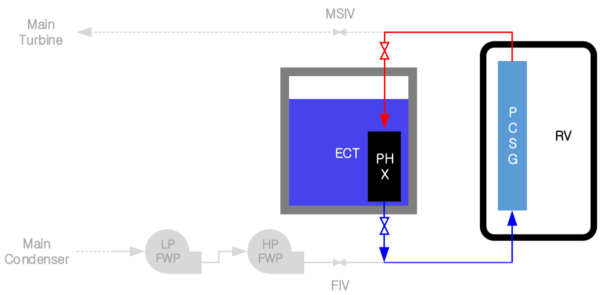

Fig. 1. Schematic diagram of PRHRS

2. Purpose and Configuration of SGPGS

2.1 Purpose

SGPGS performs a similar role of main turbine at power operation. The amount of generating power of SGPGS is much smaller than main turbine & generator, because the efficiency of main turbine system is higher than SGPGS.

When accident occurs, SGPGS removes the residual heat from the core and generates electricity, simultaneously.

2.2 Configuration

The schematic diagram of SGPGS is shown in Figure 2. SGPGS is composed of printed circuit steam generator, main steam line, flow control valve, bypass valve, turbine/generator system, condenser, feedwater pump, and feedwater line. This is a closed loop using forced convection. To operate at accident condition, all the components are designed with safety-grade.

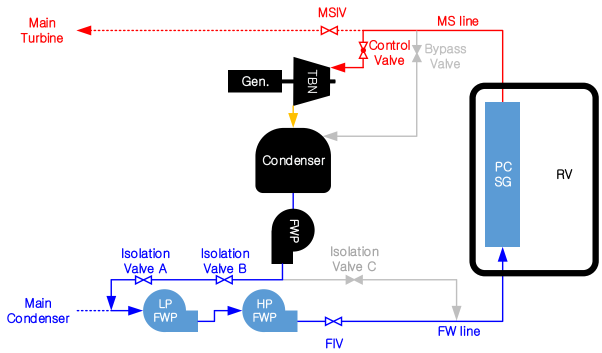

Fig. 2. Schematic diagram of SGPGS

3. Modeling of Each Components

3.1 Assumptions

The residual heat of the reactor core is assumed to add 20% margin to the ANS-72 decay heat curve.

The SG of this reactor is the type of printed circuit heat exchanger. The flow paths of the SG are very complicated. Therefore, it takes a lot of time and effort to calculate the heat transfer rate between RCS and SG in detail. To simplify the calculation, the heat transfer rate equations with RCS average temperature and secondary side flow rate as variables were provided from the designer of this SG.

Two sections of PRHRS and two sections of SGPGS are planned to be operated at the accident. However, the ratio of decay heat removal between PRHRS and SGPGS is unknown, because this is at initial design stage. Therefore, it is assumed that each system removes 50% of residual heat.

For simple calculation, continuity and energy equations are considered. (1-dimension)

3.2 Governing Equations

[at RCS]

$$m_{RCS} c_{p,RCS} \frac{\Delta T_{RCS}}{\Delta t} = \dot{q}_{RX} - \dot{q}_{PCSG}$$

where m, c_p, T, $\dot{q}$ stand for the mass, specific heat, temperature, heat transfer rate, respectively. The subscript RCS, RX, PCSG mean reactor coolant system, residual heat, printed circuit steam generator, respectively.

[at PCSG]

$$\dot{q}_{PCSG} = 0.01089 T_{RCS,avg} - 0.55577 \text{ [MW]}$$

(for W=2.5kg/s, $51.0 \le T_{RCS,avg} \le 149.9$)

$$\dot{q}_{PCSG} = 0.53777 T_{RCS,avg} - 79.5267 \text{ [MW]}$$

(for W=2.5kg/s, $149.9 \le T_{RCS,avg} \le 159.9$)

$$\dot{q}_{PCSG} = 0.00522 T_{RCS,avg} - 5.63503 \text{ [MW]}$$

(for W=2.5kg/s, $159.9 \le T_{RCS,avg}$)

where W means mass flow rate of feedwater.

[at Condenser [2]]

$$\overline{Nu_D} = \frac{\bar{h}_D D}{k_l} = C\left[\frac{\rho_l g(\rho_l - \rho_v) h'_{fg} D^3}{\mu_l k_l (T_{sat} - T_s)}\right]^{1/4}$$

where $\overline{Nu}$, h, k, D, C, ρ, g, h'_{fg}, μ stand for averaged Nusselt number, averaged heat transfer coefficient, thermal conductivity, geometry coefficient, density, gravitational acceleration, modified latent heat of vaporization, viscosity, respectively. The subscript D, l, v, and sat mean diameter, liquid phase, vapor phase, and saturated, respectively.

$$h'_{fg} = h_{fg}(1 + 0.68 Ja)$$

where Ja stands for Jacob number.

$$Ja = \frac{c_{p,l}(T_{sat} - T_s)}{h_{fg}}$$

$$\bar{h}_{D,N} = \bar{h}_D N^n$$

where N means the number of vertical tier of horizontal un-finned tubes. The superscript n means geometry coefficient

3.3 Detailed Information of Each Components

This system is included in nondisclosure project. Therefore, Partial results can be described and most of the design values are nondisclosure.

4. Results

When accident occurs, this integral reactor targets cooling the reactor below 215℃ within 36 hours and maintaining safe condition until 72 hours without operator action. Figure 3 shows the RCS average temperature variation with respect to feewater mass flow rate. In the case of 2.5kg/s of feedwater, RCS temperature was increased after accident occurred and decreased, because decay heat is larger than SGPGS cooling capability. As the feedwater flow rate increases, RCS temperature decreases rapidly.

The RCS cooling rate is shown in Figure 4. For the safe operation of integral reactor, RCS cooling rate is limited under 40℃/hr and is usually operated under 20℃/hr. In the case of 5.0 and 10.0kg/s, the RCS cooling rate exceeds the value of 20℃/hr. Even though feedwater flow rate is 2.5kg/s, RCS temperature increased at initial stage of accident. Therefore, for stable operation, the feedwater flow rate of 2.5~5.0kg/s should be supplied for preventing RCS temperature peak, and the feedwater flow rate of 2.5kg/s is needed to be flowed for maintaining proper RCS cooling rate.

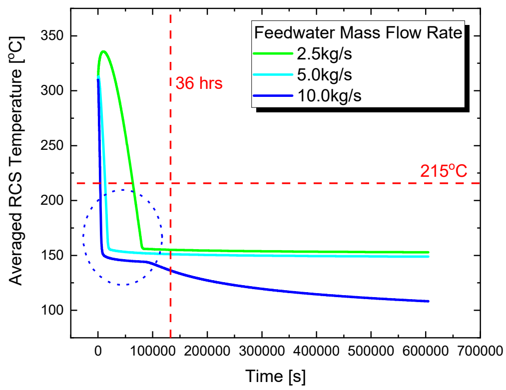

Fig. 3. Average RCS temperature with respect to feedwater mass flow rate

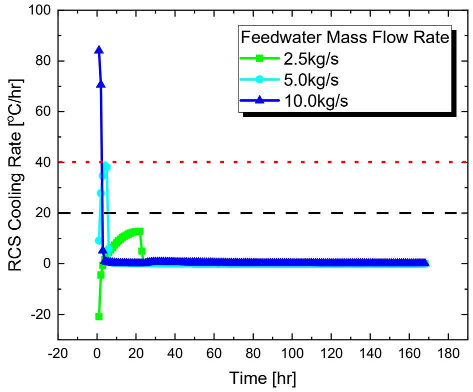

Fig. 4. RCS cooling rate with respect to feedwater mass flow rate

Figure 5 describes the mass quality at PCSG outlet. The faster the RCS cools, the faster the mass quality decreases. If the mass quality is under 1.0, the main steam starts to contain moisture. This causes the fast drop of turbine system efficiency. Therefore, for longer producing electricity, the supply of feedwater is needed to be small.

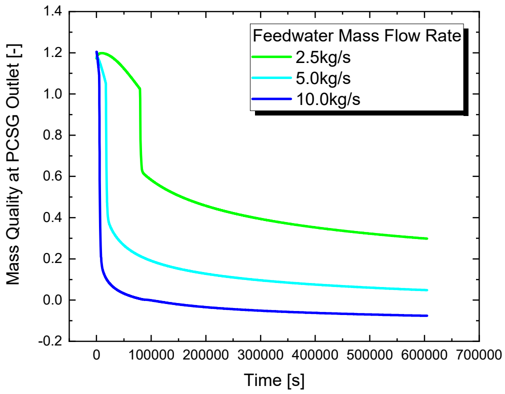

Fig. 5. Mass quality at PCSG outlet with respect to feedwater mass flow rate

The normalized generated electricity from turbine & generator system is shown in Table 1. The concept of SGPGS is applied for providing electricity to the safety grade components at accident for helping mitigation of abnormal condition of integral reactor. Therefore, the suitable and enough electricity should be generated by SGPGS. It is confirmed that this system can produce the 18% of electricity of normal operation at 7 days after accident.

Table 1: Normalized turbine data

	Normal Op.	7 days after Accident
Normalized Electricity [-]	1.00	0.18

5. Conclusions

In this study, the performance evaluation of SGPGS was conducted preliminarily. It was checked that this system can provide electricity until at least 7 days after accident. For validation of this study, the calculation using MARS code will be conducted in the future.

REFERENCES

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