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Analysis of thermal-hydraulic operating condition considering design margin for the shutdown cooling water subsystem in HTGR

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1. Introduction

HTGR, High Temperature Gas-cooled Reactor, is one of the generation IV nuclear reactor concept. It can be applied to various industrial fields such as hydrogen production, process heat, sea water desalination in addition to electricity generation. Several HTGRs have been developed, constructed and operated in many countries since 1960s[1,2]. In KAERI(Korea Atomic Energy Research Institute) various researches [3,4] on HTGR have been performed and the R&D project on HTGR design for the non-electric application has been started recently.

HTGR has some unique features. It can be operated at higher temperature compared to traditional pressurized water reactor, which allows for more efficient electricity generation. Its coolant, Helium, is chemically inert and does no become radioactive. TRISO(TRIstructural ISOtropic) fuel particles, which is employed as fuel in HTGR, are highly resistant to high temperatures and radiation. HTGR employs multiple methods for core heat removal. Reactor cooling can be accomplished by the main loop cooling system, the SCS(Shutdown Cooling System) or by passive cooling from the core through the reactor vessel to the RCCS(Reactor Cavity Cooling System)[5]. Among those heat removal paths, SCS is designed to provide a secondary means of removing residual and decay heat from the shutdown reactor and transferring those heat to the ultimate heat sink during shutdown or refueling. It consists of a SCHE(Shutdown Cooling water-helium Heat Exchanger) which is located at the bottom of the reactor vessel and a helium circulator. The SCS is connected to a SCWS(Shutdown Cooling Water Subsystem) which consists of water pump, water-air heat exchanger and surge tank as shown in Fig. 1.

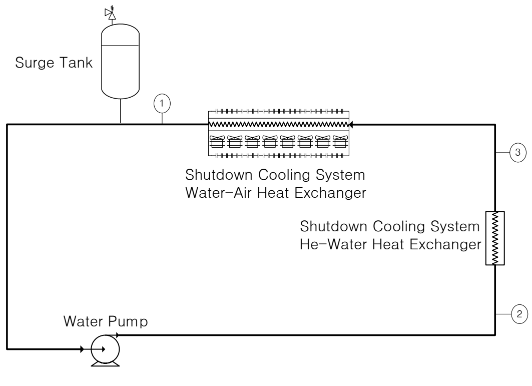

Fig. 1 Schematic diagram of SCWS

During SCS cooling operation the peak temperature will occur in the hottest tubes of SCHE[6]. Local boiling in SCHE will result in flow instabilities and possible tube failure due to dry out. Therefore, the SCWS operating condition such as temperature and pressure should be decided by considering appropriate margin to boiling.

In advance to take a first step of the HTGR design, the method and procedure to determine the thermal-hydraulic operating condition having user-defined design margin to prevent coolant boiling for the SCWS is described in this research.

2. Analysis Method

The simple heat balance calculation model on SCWS is developed based on Fig. 1. The nominal operating conditions for SCWS are assumed to be the same as those of HTR50S[2] as presented in Table 1. The heat loss and pressure loss within the system is neglected. The thermal duty and the inlet temperature of SCHE is assumed to be fixed. In the heat balance calculation, the mass flow rate($\dot{m}$) can be determined based on the enthalpy differences between the inlet($h_2(T_2, P_2)$) and outlet($h_3(T_3, P_3)$), as well as the thermal duty($\dot{Q}$) of SCHE as described in eq(1). NIST REFPROP[7] is used to calculate the coolant properties at various temperature and pressure conditions on each numbered point.

$$\dot{m} = \frac{\dot{Q}}{h_3(T_3,P_3) - h_2(T_2,P_2)} \quad (1)$$

In order to estimate the operating temperature margin to prevent coolant boiling in SCWS the boiling temperature is calculated with respect to various pressure and temperature condition at SCHE exit (#3 in Fig. 1) ranging from 1 to 5 MPa and from 100 to 300 ℃, respectively.

Table 1 Design specification of shutdown cooling system of HTR50S [2]

Parameters	Values
Thermal duty (MW)	4
SCHE Water Inlet temperature (℃)	47
SCHE Water Outlet temperature (℃)	100*
Flow rate (kg/s)	18*

* value is varied in this analysis

Then, the temperature margin to boiling is evaluated by the difference between operating temperature and boiling temperature. The operating pressure margin to prevent coolant boiling is calculated by comparing operating pressure to the saturation pressure within the considered pressure and temperature range.

3. Results

Fig. 2 shows the temperature margin to boiling at various SCWS operating conditions. X axis and Y axis represents the operating pressure and the operating temperature, respectively. Z axis represents the temperature margin to boiling. Negative value in temperature margin represents the superheated gas condition. To illustrate the available operational range without boiling, the horizontal plane where Z-value is zero is also plotted. As shown in the figure temperature margin is increased with the increase of pressure and the decrease of temperature. The temperature margin amounts to 164 ℃ at P=5 MPa and T=100 ℃. By elevating horizontal plane in Z direction, operating condition(pressure, temperature) having an appropriate temperature margin to boiling can be decided in Fig. 2.

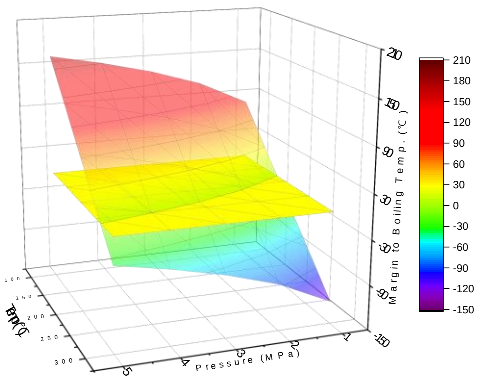

Fig. 2 Temperature margin to boiling at various SCWS operating conditions

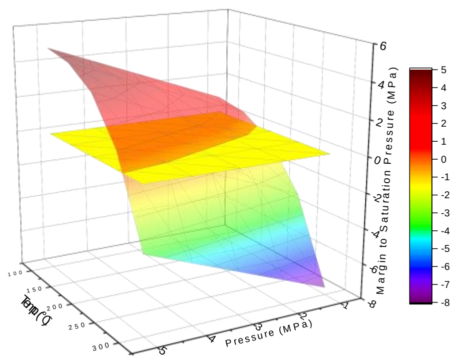

Fig. 3 Pressure margin to saturation pressure at various SCWS operating conditions

Fig. 3 shows the pressure margin to saturation pressure at various SCWS operating conditions. X axis and Y axis represents the operating pressure and the operating temperature, respectively. Z axis represents the pressure margin to saturation. Negative value in pressure margin represents the superheated gas condition. To illustrate the available operational range without boiling, the horizontal plane where Z-value is zero is also plotted.

As shown in the figure temperature margin is increased with the increase of pressure and the decrease of temperature. The pressure margin amounts to 4.9 MPa at P=5 MPa and T=100 ℃. The pressure margin to boiling at the specific thermal-hydraulic condition can be confirmed in this plot.

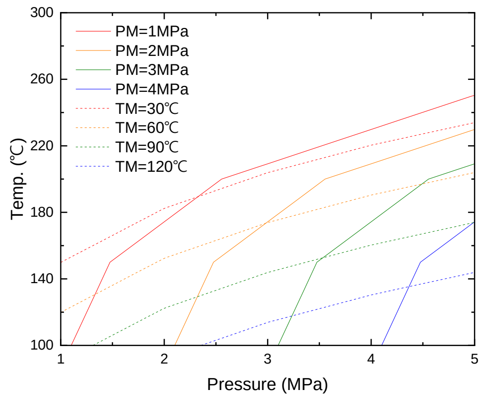

Fig. 4 Available operating range considering the temperature margin and pressure margins to boiling

Fig. 4 illustrates the available operating range of SCWS based on variations in temperature margin and pressure margin. The dash line and the solid line represent the temperature margin(TM) and pressure margin(PM), respectively. Each curve is derived using cross-sectional lines formed by increasing the horizontal plane of Fig. 2 and Fig. 3 axially by 30 ℃ and by 1 MPa, respectively. Once the user specifies the design margins for temperature and pressure, the SCWS operating condition at SCHE exit should be decided within the overlapping area formed by the two curves.

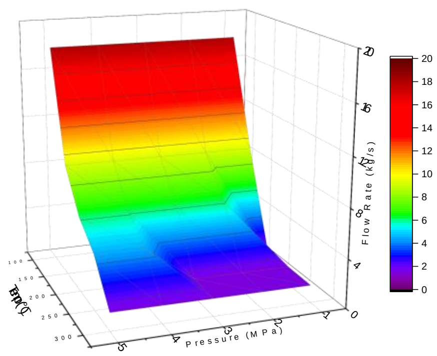

Fig. 5 Flow rate at various SCWS operating conditions

Fig. 5 shows the flow rate at respective operating temperature and pressure conditions. Z axis represents the flow rate in SCWS. As shown in the figure required flow rate is increased with the decrease of temperature and it amounts to 18 kg/s at T=100℃. Final operating flowrate can be derived at the pressure and temperature condition specified at Fig. 4.

Following the aforementioned procedure and data, the operating condition(pressure, temperature and flowrate) to coolant boiling, having user-specified design margin in SCWS can be determined.

4. Conclusions

The simple calculation model to evaluate operational margin to coolant boiling on SCWS in HTGR is developed based on NIST property database. A curve illustrating the available operating range based on the design margin to coolant boiling has been presented, based on the reference reactor condition. The described method can be applied to determine the operating condition of SCWS under development.

5. Acknowledgement

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