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Filling Ratio Effect on Thermal Performance of PRHRS for an Integral Reactor

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is an integral type reactor with a rated thermal power of 330MW developed by Korea Atomic Energy Research Institute (KAERI). Since the Fukushima accident, the passive cooling systems of nuclear reactors have received a great amount of attention. SMART is equipped with passive systems in order to ensure safety of the reactor and to achieve simple design. Passive Residual Heat Removal System (PRHRS) is one of the passive safety systems which is activated after an accident to remove the residual heat from the core and the sensible heat of the reactor coolant system (RCS) through the steam generator until the condition of the RCS reaches the safe shutdown cooling state.

In the present study, a numerical program is developed using MATLAB software in order to estimate the thermal performance of the PRHRS for SMART. The details of the program will be described and the results of calculations will be demonstrated. By using the program, the steady-state and transient (quasi-steady state) characteristics during the operation of the PRHRS are investigated. The spatial distribution of the thermal hydraulic variables such as temperature, pressure and quality can be obtained from the steady-state solution and the temporal behaviors of temperature and pressure in the RCS can be predicted from the transient analysis. Performance of the PRHRS in accordance with the filling ratio will also be analyzed. It is revealed that the filling ratio is a key value to determine the performance of the present PRHRS.

2. Methods and Results

The schematic of the PRHRS is shown Fig. 1. The PRHRS removes residual heat and sensible heat of the RCS by using natural circulation only, when an accident occurs. Main driving force for the natural circulation is the head difference between the condensation heat exchanger (CHX) and a steam generator (SG). The PRHRS is composed of an emergency cooldown tank (ECT), a condensation heat exchanger and a makeup tank (not shown in the figure). There are four trains of the PRHRS among which three trains are assumed to be available. Each train is connected to a set of two steam generators. When an accident occurs, the main steam isolation valve (MSIV) and feedwater isolation valve (FIV) are closed automatically. Then a closed loop of natural circulation is formed through the steam generators, the condensation heat exchanger and the connecting pipelines.

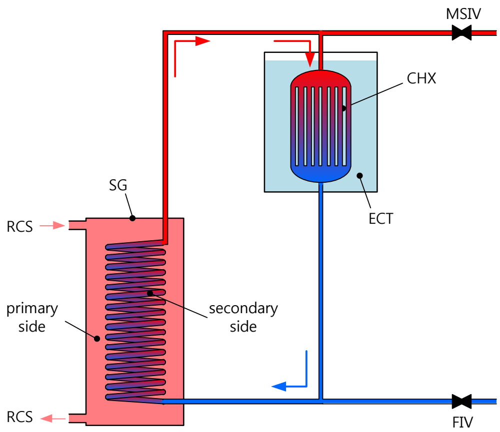

Fig. 1. The schematic of the PRHRS

2.1 Condensation Heat Exchanger

The superheated or saturated steam produced from the steam generators enters into the condensation heat exchanger, where it undergoes a phase transition to subcooled water. The condensation heat exchanger is immersed in water reservoir contained in the ECT. The condensation occurs at the inside of the tube wall. On the other hand, the pool boiling occurs at the outer wall of the tube. In the present study, the tube is divided into infinitesimal one-dimensional control volume along the axial direction. At each volume, the temperature of tube wall and heat transfer rates of condensation and pool boiling are calculated. Heat transfer coefficients inside and outside of the tube are predicted by using Shah[1]'s correlation and Rohsenow[2]'s correlation, respectively.

2.2 Steam Generator

The subcooled water provided through a feedwater line enters into the steam generators, where it undergoes a phase transition to a superheated or saturated steam. The flow boiling occurs at the inside of the tube wall. On the other hand, single-phase heat convection occurs at the outside of it. Same procedure is applied as described in section 2.1. The tube is divided into infinitesimal one-dimensional control volume along the axial direction. At each volume, the temperature of tube wall and heat transfer rates of flow boiling and convection are calculated. Heat transfer coefficients inside and outside of the tube are predicted by using Chen[3]'s correlation and SKBK[4] correlation, respectively.

2.3 Filling Ratio

Filling Ratio (FR) is defined as the ratio of the fluid mass the system actually contains to the maximum amount of mass it could contain if it were completely filled[5]. The performance of the PRHRS substantially depends on the total mass of fluid within the system, as described in the following sections. Therefore, it is of great importance to control the PRHRS mass inventory and narrow the gap as low as possible between maximum and minimum filling ratio. The closing time of MSIV and FIV is one of the variables to determine the range of filling ratio. It is assumed that FR is in the range of between 0.23 and 0.32 for the present study.

2.4 Design Requirements

The PRHRS is designed to meet the following requirements.

(1) The temperature of the RCS should be lower than that of safe shutdown condition at 36 hours after an accident occurrence and maintain this state until 72 hours.
(2) The cooling rate of the RCS should not exceed the maximum allowable value.

The results will be demonstrated to see if these rules are met or not in the following section.

2.5 Calculation Procedure

The MATLAB code presented in this study, calculates temperature, pressure, enthalpy, quality, mass flow rate, etc., of the secondary closed loop at the steady state condition. Once temperature variation of the primary loop is defined, a transient analysis assuming quasi-steady state can be conducted. In the present study, ANS-71[6] decay curve is adopted for the temperature variation of the primary loop.

2.6 Results

Figs. 2 and 3 show the temporal behavior of the normalized RCS temperature and the normalized cooling rate, respectively. When FR is 0.32, the heat removal performance is lower and the rate of temperature drop is relatively slow. However, it still meets the first condition of section 2.4. The y-axis value of 1.0 stands for the safe shutdown temperature. As shown in the figure, after reaching the safe shutdown temperature, the RCS temperature continues to decrease.

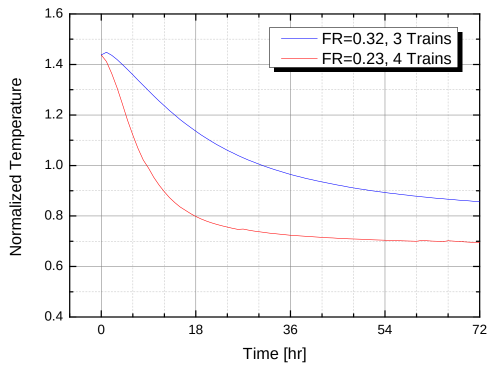

Fig. 2. Temporal behavior of temperature of the RCS

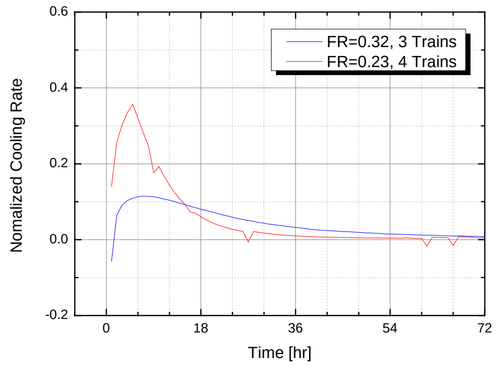

Fig. 3. Temporal behavior of cooling rate of the RCS

In case of lower FR, the rate of temperature drop is relatively fast. In order to check the second condition as described in section 2.4, the cooling rate of the RCS is evaluated in Fig. 3 assuming that every single train of the PRHRS is available. Even if all trains are operable to cooldown the RCS, the cooling rate did not exceed the maximum allowable value, which marks 1.0 at the y-axis in Fig. 3. Therefore the second condition of section 2.4 is also confirmed to be met.

3. Conclusions

In the present study, thermal performance of the PRHRS in accordance with the filling ratio was analyzed. It was revealed that the filling ratio is a key variable to determine the performance of the present PRHRS. The present PRHRS is confirmed that it is designed to meet the safe shutdown condition in the designated range of the filling ratio.

ACKNOWLEDGEMENT

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