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Computational Evaluation of Natural Circulation Behavior Developed in a Small Modular Reactor using MARS Code

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1. Introduction

In general, natural circulation mechanism has been vigorously considered in development of various advanced reactors for decades, including Small Modular Reactors (SMRs). SMRs have received attention over the world for potential advantages, such as outstanding flexibility for siting, lower capital investment, or advanced safety [1]. Among the benefits, adopting natural circulation (NC) is believed to ensure improved reactor safety as a vital way for cooling a reactor core or removing decay heat. In particular, an introduction of passive systems using NC mechanism could allow to achieve simplification of the SMR design and enhance the system reliability. Moreover, it is expected not only to alleviate any consequences of human errors and equipment failures, but also to improve the grace time for operators, especially in a severe accident [2].

However, the passive systems with NC show several weaknesses as comparing with active systems. Most of all, it is well-known that NC has inherently lower driving forces. Also, in a system point of view, due to its operational complexity, limited flexibility is expected in an operation of NC systems. Furthermore, there might be a lack of proper experimental data in the design of passive systems [2]. Thus, more delicate and extensive studies are required for the development of passive system with NC including experimental and computational approaches.

In this study, to assess the system capability with NC mechanism, crucial design parameters of a SMR are considered as a preliminary stage using the MARS-KS code, a safety analysis system code developed in Korea. With simulation results and comparison work, relevant design conditions or ranges of a SMR are discussed.

2. Modeling for Natural Circulation System and Simulation Results

2.1 MARS Modeling for SMR

In order to simulate the NC behavior, a SMR with a core power of 330 MWth was deemed as the reference modeling. After modeling the reference case, an important design parameter was investigated based on the reference input model. Figure 1 shows the nodal structure of the reference SMR modeling for the MARS simulation.

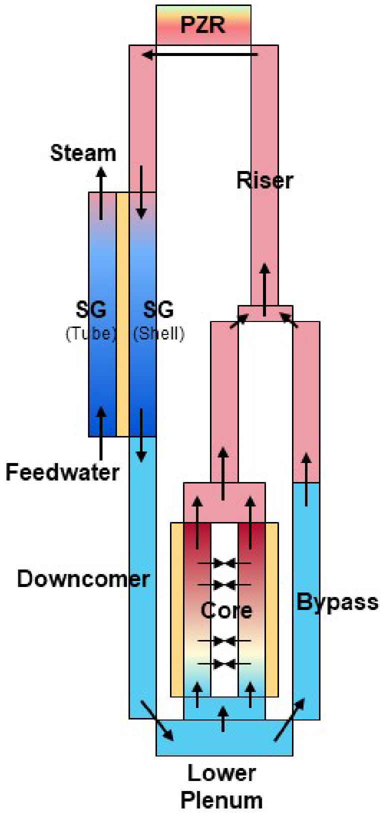

Fig. 1. Nodal structure of the reference SMR

The entire model has two main parts: the NC loop part for a primary side and the heat exchange part for a secondary side. The NC loop part or primary side including the reactor core is composed of seven major hydrodynamic sections: 1) core, 2) riser, 3) the shell side of the steam generator (SG), 4) downcomer, 5), lower plenum, 6) core bypass, and 7) pressurizer. At the core section, assigned heat is generated and the coolant entering the core flows upward to the rise section. The coolant turns around at the top of the riser and flows into the SG section. The generated heat at the core is transferred from the shell side to the tube side in the SG, and then the coolant cooled down passes through the downcomer section. The coolant is divided into the core and bypass flows from the lower plenum section, and finally it circulates in the primary side. Each hydrodynamic section described above was modeled as a pipe, a branch, or an annulus. The heat exchange part or a secondary side was modeled as a simple piping. To remove the heat transferred from the shell side of the SG, the feedwater flows through the tube side of the SG.

The pressurizer (PZR) section is utilized to maintain pressure of the primary side at 15 MPa. To generate or transfer the heat, three heat structures are modeled. First and second heat structures are assigned to the core section to generate the heat providing the driving force of NC: one for the average channel core and the other for the hot channel core. The third heat structure is allocated between the shell side and tube side of the SG to transfer the generated heat.

2.2 Theoretical Model for Natural Circulation System

In order to investigate the NC behavior, a theoretical model for the single-phase flow is considered. Jang *et al.* discussed the primary flow rate based on their experimental facility of REX-10 for the NC system [3]. When it is assumed that the coolant in the loop is incompressible, mass flow rate can be constant under the steady-state condition. Moreover, the coolant density is expected to change linearly as shown in the following relation with the Boussinesq approximation or the buoyancy consideration.

$$\rho = \rho_0\left[1-\beta\left(T-T_0\right)\right] \quad (1)$$

here, the subscript *0* means the reference value, and in this case the core is treated as the reference condition. The expansion coefficient β is given by

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_P \quad (2)$$

Since there is no active component in the NC loop, the frictional pressure drop ΔP_{fric} is evaluated to be the same as the buoyancy pressure drop ΔP_{buoy}, which is also the NC driving force. Furthermore, the frictional pressure drop can be expressed with the overall flow resistance R and the volumetric flow rate Q as shown below.

$$\Delta P_{fric} = \Delta P_{bouy} \quad (3)$$

$$\Delta P_{fric} = \frac{1}{2}\rho_0 R Q^2 \quad (4)$$

where, $$R = \sum\left(f_i\frac{L_i}{D_i A_i^2}+\frac{K_i}{A_i^2}\right) \quad (5)$$

When the temperature is assumed to change linearly, the buoyancy pressure drop is given by

$$\Delta P_{bouy} = \rho_c \beta g \Delta T \Delta H \quad (6)$$

where, ΔT is the temperature difference between the core inlet and outlet, and ΔH is the elevation difference between the core and the SG. Since the heat generated at the core is transferred to the coolant, the buoyancy pressure drop is also expressed as follows in consideration of the energy balance equation.

$$\Delta P_{bouy} = \frac{\beta g \Delta H P}{Q\overline{c_p}} \quad (7)$$

Taking into account the frictional pressure drop discussed above, the mass flow rate for the NC loop is eventually given by

$$\dot{m} = \rho_0 Q = \left(\frac{\rho_0^2 \beta g \Delta H P}{\overline{c_p} R}\right)^{1/3} \quad (8)$$

In actual, however, there is inaccuracy concerning the assumptions for the obtained equation. In this regard, theoretical equation can be modified empirically with the exponential form of the power. Thus, the coolant flow rate for the NC system can be suggested as the simple form below:

$$\dot{m} = R_1 P^n \quad (9)$$

This equation indicates that the mass flow rate is proportional to the exponential form of the power P applied to the core, and the introduced coefficient R1 is independent on the mass flow rate. The values of R1 and n are normally determined in accordance with the characteristics of the system. For example, Jang et al. showed that the relationship was evaluated as

$$\dot{m} = 0.0013 P^{0.47768} \quad (10)$$

In their experiments, the parameters of R_1 and n were determined as 0.0013 and 0.47768, respectively. It is noted that their NC system was carried out with a power range of 60 kW – 180 kW. It implies that different R_1 and n can be obtained for other power ranges [3].

2.3 MARS Simulation Results

In the MARS simulation, the NC characteristics are discussed based on the reference SMR model with a core power of 330 MWth. The primary side is maintained at a pressure of 15 MPa, and the heat generated at the core is transferred to the secondary side through the SG. The secondary side modeled as the simple piping provides the secondary coolant flow to remove the transferred heat at a mass flow rate of 10 kg/sec. Among various SMR types, five reactors were selected based on their design power to investigate the effect of applied powers or decay heat on the primary flow rate. Table 1 shows the selected SMRs and corresponding design powers and current status obtained from open literature data [4].

Table I: Safety systems of SMRs [4]

SMR	Design power (MWth)	Status
CAREM (Argentina)	100	Under construction
SMART (South Korea)	330	Certified design (2012)
mPower (USA)	575	Under development
Westinghouse SMR (USA)	800	Conceptual design
IRIS (Int'l)	1000	Conceptual design

In the calculation, it is assumed that the reactor core generates decay heat constantly at 1% of the design power. Since the coolant at the secondary side continuously removes the heat, the primary coolant forms stable natural circulation flow. Figure 2 shows the NC mass flow rates developed with respect to the applied core power or decay heat. As discussed in the previous section, the NC flow is proportional to the exponential form of the powers. Using the aforementioned theoretical relation for the NC system, the mass flow rate is determined as

$$\dot{m} = 0.17678P^{0.41697} \quad (11)$$

In this study, R_1 and n were evaluated as 0.0013 and 0.47768, respectively.

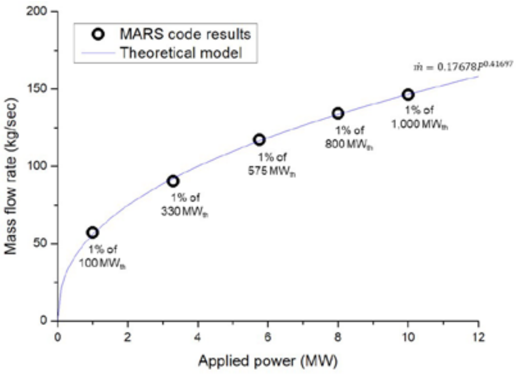

Fig. 2. Mass flowrates with the powers applied to the core

Consequently, this result implies that a proper range of mass flow rate can be derived from the obtained curve as a certain decay heat is presented. Although the relation is limited to the form of the reference SMR system, it may provide a range of other design parameters concerning the NC system.

Furthermore, it should be noted that, at the current stage the modeling of the secondary side is simplified as a preliminary step, a further detailed modeling of the SMR is planned, especially to simulate and investigate significant passive safety systems of a SMR such as PRHRS and PCCS, to mention a few.

3. Concluding Remarks

In this study, the NC behavior of the SMR was investigated. After selecting the SMR currently developed over the world, the MARS modeling was carried out to simulate the primary NC flow, and the effect of the applied powers on the mass flow rate was discussed. The major findings and future works in this study can be summarized as follows:

- The SMR with a core power of 330 MWth was modeled as a reference case. The powers applied to each core were set as the decay heat at 1% of the design powers. As a result, the stable NC flow in the primary side was established when the generated heat was removed continuously by the secondary flow.
- The NC flow by the MARS calculations show a good agreement in terms of the theoretical model of the NC system, which is proportional to the exponential form of the power. This indicates that mass flow rates can be inferred from the obtained curve as an applied power is presented.
- For the future study, the simplified modeling is needed to be improved to investigate significant more detailed behaviors of the passive safety systems currently suggested.

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