Analytical Investigation on Natural Circulation and Flow Instability in the FINCLS Facility for SMART

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1. Introduction

Natural Circulation (NC) is an important mechanism to impose the driving force on a fluid loop system, and being actively investigated for several field applications. In nuclear industry, the NC flow characteristic is widely treated as a key design parameter for advanced boiling water reactors and integral pressurized water reactors without pumps and/or with passive safety systems [1].

The SMART [2] is a small modular nuclear reactor that has been developed at the Korea Atomic Energy Research Institute (KAERI) and is in the process of the second standard design approval of SMART100 using intensive technology validation data for future construction abroad. The system design was validated against accidents that include station black out (SBO), in which the SMART can assure integrity of nuclear fuels by removing decay heat through natural circulation. Thus, in SMART, NC performance, flow instability characteristics and its thermal-hydraulic behaviors are of interest in the enhancement of passive safety system with long-term cooling capability.

Facility to Investigate Natural Circulation in SMART (FINCLS) [3] was constructed to understand single- and two-phase natural circulation phenomena in SMART using a simplified loop. A set of single-phase natural circulation tests were performed under different pressure conditions from 0.5 MPa up to 15.0 MPa and also analytical works were done to simulate natural circulation phenomenon observed in the FINCLS facility for SMART application [3, 4].

In this paper, the NC test data were analyzed to evaluate the thermal-hydraulic characteristics of natural circulation and flow instability in the FINCLS facility for SMART.

2. Natural Circulation Tests using FINCLS

2.1 Description of the FINCLS Facility

The FINCLS facility was established for a comprehensive understanding of the NC phenomena expected to occur at SMART [2]. The configurations and features of this facility are derived from those of SMART with a simplification, as shown in Fig. 1.

The flow area, inventory volume and core power of FINCLS were scaled down by a factor of 1/64 compared to SMART-ITL, which has the scaling ratio of 1/49 against SMART, while the height was conserved to preserve the NC behavior and to avoid the hydrostatic distortion. The reduced inventory of FINCLS enables us to perform various experiments within reasonable time. The flow resistance values can be regulated by means of orifices with the appropriate bore size. The loop configuration was derived from the SMART design with simplified geometrical features and commercial pipe components.

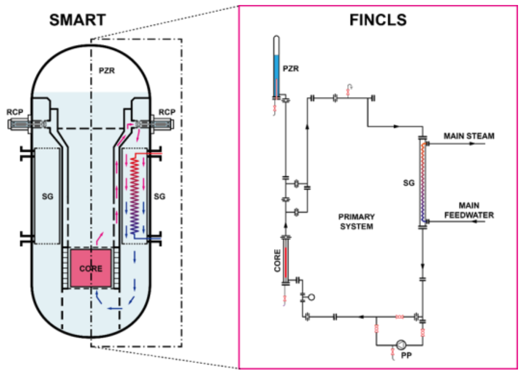


Figure 1 Design concept of the FINCLS facility.

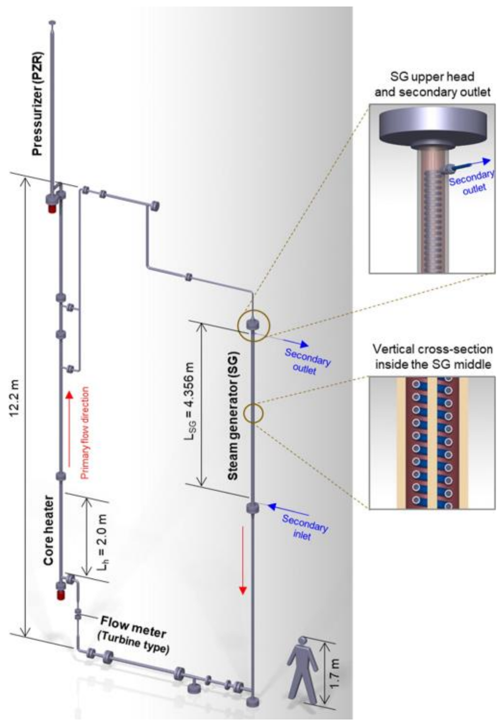


Figure 2 Schematic diagram of the FINCLS facility.

The design parameters in pressure and temperature for the primary and secondary systems are completely identical to the reference system, SMART-ITL. Since the natural circulation in SMART design is closely associated with the lower power condition than that in the nominal operation, the maximum core power of FINCLS is designed to be 50 kW corresponding to 47.5% of scaled full power. Due to the lowered maximum core power, the maximum flow rates for primary and secondary systems are also lowered to 60% of the scaled full capacity.

2.2 Single-phase natural circulation tests

A series of single-phase natural circulation (SPNC) tests comprising 30 steady-state conditions were performed. The imposed and obtained variables for the SPNC tests are presented in Table 1.

Table 1 Test matrix of the SPNC tests using FINCLS

Test group	No.	Core power	PZR temp.	Core inlet temp	Feedwater temp.
		kW	**°C**	**°C**	**°C**
SPNC-0.5MPa	5	5.21 - 25.2	151.8	23.9 ± 0.67	16.9 ± 0.17
SPNC-1MPa	5	5.14 - 25.7	179.9	26.4 ± 3.83	22.7 ± 0.88
SPNC-2MPa	7	5.85 - 35.4	212.4	80.7 ± 4.50	21.2 ± 0.35
SPNC-6MPa	7	18.7 - 48.2	275.6	151.5 ± 3.90	13.4 ± 0.52
SPNC-15MPa	6	24.9 - 49.6	342.2	234.2 ± 3.00	15.6 ± 0.52

The temperature conditions for the entire SPNC tests are clearly depicted in Fig.3. As shown in the figure, the core inlet temperatures are roughly separated in four different groups, at which the core outlet temperatures are varied depending on the core power input.

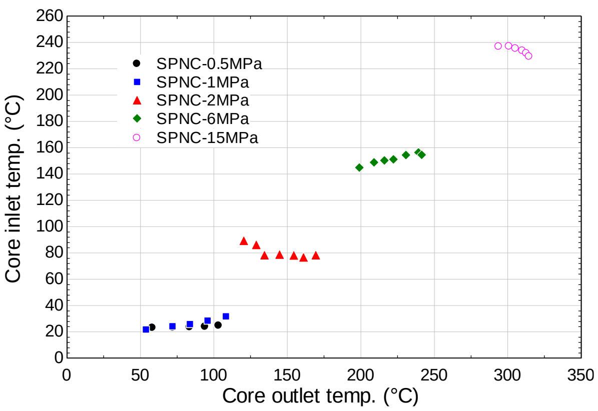


Figure 3 Core inlet and outlet temperatures obtained during steady-state tests

3. Analyses on the FINCLS NC Tests

3.1 Analysis using a force-balance equation

The adequacy of a simplified model using a force balance equation was validated using the experimentally measured NC flowrates. This validation is important because subtle difference in the calculation of the driving force or friction loss can lead to a quite different NC flow rate and decay heat removal rate. The single-phase NC flow rate can be predicted by solving a force-balance equation directly [5].

The single-phase NC flow rate is determined by equating the pressure gain from density difference to the pressure loss from the friction and form loss:

$$g(\rho_h - \rho_c)H = \sum_{i=1}^{N}\left(\frac{f_i L_i}{D_i} + K_i\right)\frac{W^2}{2\rho_i A_i^2} \qquad (1)$$

In Eq. (1), ρ, H, f, L, D, K, W, and A represent density, elevation difference between the core and steam generator (SG), friction coefficient, pipe length, pipe diameter, form loss coefficient, NC flow rate and pipe cross-sectional area, respectively. The subscripts, h and c, represent hot and cold conditions and the subscript i represents one of the segmented regions along the primary flow loop.

Though the equation looks simple, there are several things to be considered. First, heat loss along the piping leads to temperature drop along the primary loop. Heat loss makes it difficult to determine a single value for ρ. In our calculation, we neglected the density change along the pipes and simply used the core outlet and inlet temperatures to get ρ_h and ρ_c. Second, the elevation difference between the SG and core needs to be carefully calculated. Rather than the geometrical center-to-center elevation difference, the thermal center-to-center elevation difference was used. To get this value, the elevation of the average density inside the core or SG was obtained. Specifically, the measured weight of density-varying water was equalized with the weight of hot (ρ_h) and cold (ρ_c) water. The detailed calculation process can be referred in the previous paper [4]. The calculated elevation differences are given in Figure 4. Depending on heat transfer characteristics inside the SG, the elevation difference varied significantly. Third, variation of flow area in the primary loop was considered. In the right hand side of Eq. (1), pressure drop along different-diameter pipes were individually calculated and summed up. Fourth, form loss coefficients were determined. From the experiment, it was found that most of pressure drop occurred in the flow meter. In accordance with this observation, an appropriate calculated form loss coefficient was imposed in the flow meter. The form loss coefficient was determined as a function of Reynolds numbers from the pressure loss test at room temperature.

Eq. (1) was solved as follows. First of all, the NC flow rate (W) was guessed, for example, as a small value. Using this flow rate, friction coefficients were calculated using the following equations.

$$f = 64/Re \qquad \text{for } Re < 2000 \tag{2}$$

$$f = 1.211/Re^{0.416} \qquad \text{for } 2000 < Re < 4000 \tag{3}$$

$$f = 0.316/Re^{\,0.25} \qquad \text{for } Re > 4000 \tag{4}$$

The left and right hand sides of Eq. (1) were compared. If two were different, the guessed flowrate was increased slightly. This process was repeated until Eq. (1) was fulfilled.

The resultant flow rates were given in Figure 5. The mass flow rates of NC were displayed with the variation of core power in Fig. 5(a) and the mass flow rates of NC were compared between experiment and prediction in Fig. 5(b). The overall flowrate trend was predicted well with an accuracy of 1.8%.

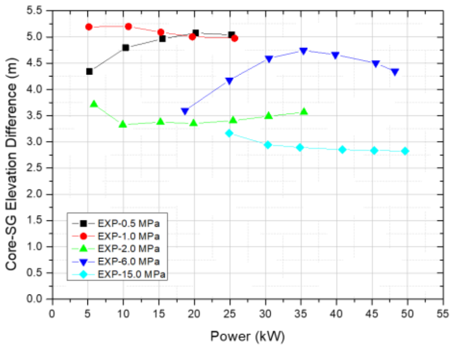
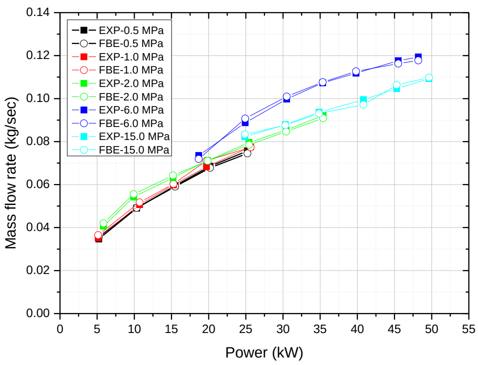
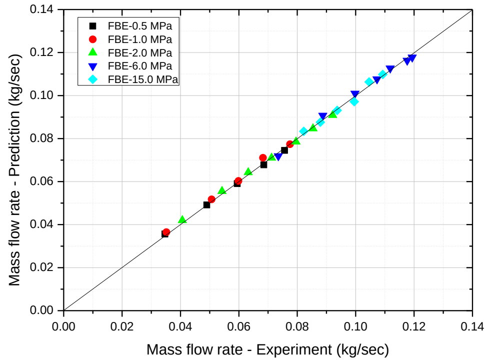


Figure 4 Core-SG elevation difference (H in Eq. (1)).



(a) Mass flow rates of SPNC with the variation of core power (EXP: test data; FBE: prediction by force balance equation).



(b) Comparison of mass flow rates of SPNC between experiment and prediction.

Figure 5 Mass flow rates of SPNC.

3.2 Prediction of flow instability against FINCLS data

The two-phase flow instability is classified into static instability, dynamic instability and compound instability. The typical static instabilities are flow excursion instability (or Ledinegg instability) and flow distribution instability in parallel channels, and one of the typical dynamic instability is density wave oscillation (DWO) [6].

A dimensionless stability map was developed by Ishii and Zuber [7] with phase change number Npch and subcooling number Nsub. As can be seen in Figure 6, the higher the pressure in the Npch-Nsub plane is, the narrower the dimensionless variable is. The figure shows the high dependency of the range of Npch and Nsub on system pressure for the characterization of flow instability.

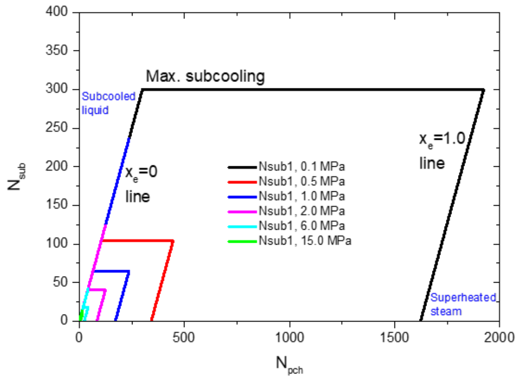


Figure 6 Range of Npch and Nsub according to system pressure.

Although the possibility of flow instability occurrence is very low, both DWO and Ledinegg instability, as defined by Guido, et al. [8], is checked against the FINCLS NC test data, as shown in Fig.7. Two cases of Re = 2,200 and 17,000 were considered to calculate the stability boundaries. When the test data is plotted in a

Nsub vs. Npch plane, the calculation results show that the FINCLS data is well under the stable condition against both DWO and Ledinegg instability.

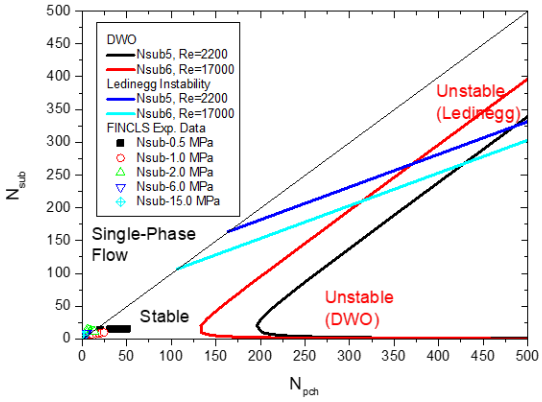


Figure 7 Density wave oscillation (DWO) and Ledinegg stability thresholds obtained with the present analysis for a single channel system of FINCLS, plotted in a Nsub vs. Npch plane.

However, in the case of multiple core channels of a specific type of small modular reactor, the flow distribution instability may occur in parallel channels in the NC condition of prototype reactor. Further experimental and analytical studies are necessary to resolve the issue of natural circulation and flow instability in that NC condition.

4. Conclusions

The thermal-hydraulic characteristics of natural circulation and flow instability are investigated analytically based on the FINCLS NC test data for SMART.

First of all, the FINCLS facility is described and a set of NC tests are introduced in brief. Second, the mass flow rates of NC were predicted using a force balance equation and the predicted value is in good agreement with the test data with an accuracy of 1.8%. Third, the NC data from FINCLS is plotted in a non-dimensional stability map and shows that the NC test data is under the stable condition against both DWO and Ledinegg instability.

However, in the case of multiple core channels, it is expected that further experimental and analytical studies are necessary to resolve the possible flow instability issue.

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