Preliminary study on Single-Phase Natural Circulation for the FINCLS Facility

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1. Introduction

FINCLS (Facility to Investigate Natural Circulation in SMART) is a simplified test loop for overall understanding of thermal-hydraulic phenomena on both single- and two-phase flow natural circulations in the SMART design [1]. In the FINCLS design, a scaling method introduced by Ishii [2] was adopted for conserving the thermal-hydraulic characteristics of the reference system, and then for avoiding distortion by the scale reduction. The volume and core power in the FINCLS facility were scaled down to 1/64 against SMART-ITL [3]. The height of facility was conserved to that of SMART-ITL to remain the hydrostatic characteristics.

This paper focuses on preliminary analysis of FINCLS to predict mass flow rate of natural circulation, and to compare mass flow rate calculated by the MARS-KS code [4] to the target.

2. Description of FINCLS

Fig. 1 shows the schematic diagram of the FINCLS including primary system loop. In the primary system, the main components (steam generator (SG), reactor pressure vessel, pressurizer (PZR)) and measuring instrument are arranged. For conserving the flow features in the core flow path, the core design is conducted by the dimensional analysis for Reynolds number with the hydraulic diameter.

FINCLS is established with commercially available pipes for simplification, while the reference system, SMART-ITL, has complex flow paths with various types of geometry. It is therefore impossible to satisfy the similarity in terms of flow and friction characteristics along the entire flow. Instead of the similarity, the adjustment of total friction loss by utilizing an orifice is considered to satisfy the scaled mass flow rate for single-phase natural circulation.

In this design considering the basic structure of core heater, the maximum electric power of heater is determined to 50 kW which corresponds about 47.5% of scaled full power. The PZR is utilized as a pressure regulator of the primary system to ensure the sufficient degree of sub-cooling. Upper space in PZR is normally filled with the saturated vapor generated by PZR heater which is installed on the bottom.

The design of SG is focused on satisfying 100% of the scaled capability in heat transfer as well as to be capable of sufficient heat removal during various experimental tests. The secondary fluid path of SG is designed with applying the single helical tube arrangement with once-through path to ensure the effective heat transfer area.

The flow rate is driven by the coolant circulation pump at the bottom of loop during initial operation. When the operating mode is switched to the natural circulation, the bypass line for the coolant circulation pump is isolated. Then, the flow rate is driven by the difference in fluid density between hot leg and cold leg.

3. Analysis Methods

3.1 Theoretical approach

The single-phase momentum equation of closed system for steady state [5] can be expressed as

$$-g \oint \rho dz = \frac{1}{2} K_1 \frac{\dot{m}^2}{A^2 \rho_l} \tag{1}$$

where K_1 is the sum of frictional and form losses around the loop. Integrating around the closed system, expressing the density variation in terms of the volumetric thermal expansion coefficient, β, and noting the temperature rise is governed by the energy input, one finally obtains, for a set heat input rate $\dot{Q}_0$,

$$\dot{m}_{1\Phi} = \left| \frac{2A^2 \beta g \rho_l^2 \Delta L \dot{Q}_0}{C_p K_1} \right|^{1/3} \tag{2}$$

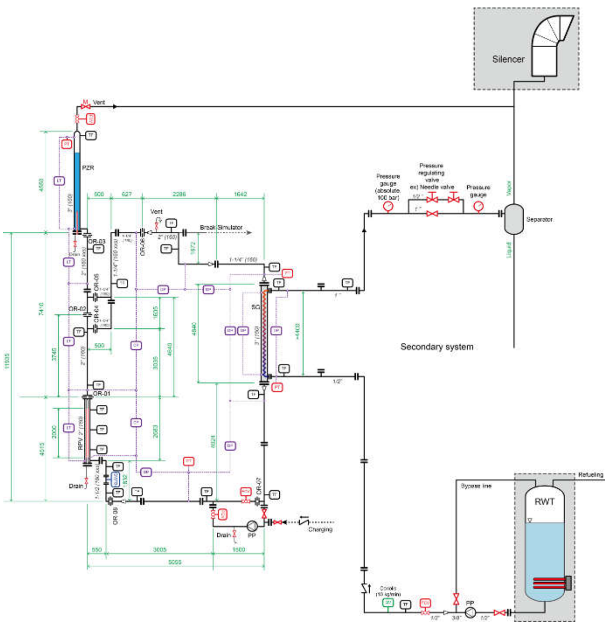

Fig. 1. Schematic of FINCLS.

where ΔL is the height differences between the thermal centers of the core and steam generator. If neither ΔL nor K_1 are accurately known, only the power and flow rate relationship could be evaluated (the one-third power law).

$$\dot{m}_{1\Phi} = C\dot{Q}_0^{1/3} \tag{3}$$

where the constant C can be empirically determined. Following the scaling ratio of mass flow rate for single-phase natural circulation, the relation between SMART-ITL and FINCLS can be expressed as

$$\frac{\dot{m}_{FIN}}{\dot{m}_{ITL}} = \frac{C_{FIN}}{C_{ITL}} \cdot \left(\frac{\dot{Q}_{FIN}}{\dot{Q}_{ITL}}\right)^{1/3} \tag{4}$$

Then, the constant C for FINCLS can be calculated by

$$C_{FIN} = C_{ITL} \cdot \left(\frac{1}{64}\right)^{2/3} \tag{5}$$

In Eq. (5), C_{ITL} was previously determined from the results of experimental tests with SMART-ITL as 0.548, and C_{FIN} is thus 0.03425.

3.2 MARS-KS simulation

Table I shows initial and boundary conditions for MARS-KS simulation. The flow rate and temperature of feed water injected to SG is set as the boundary condition. The initial condition of primary system is set to have sufficient subcooled margin for avoiding boiling caused by a sudden temperature increase on the core surface. MARS-KS simulations for totally three cases are carried out depending on the core power being 10 kW, 20 kW and 30 kW. To maintain the pressure of primary system, PZR heater power is automatically controlled with ON/OFF control method for all cases.

Fig. 2 shows the nodalization of FINCLS facility for MARS-KS simulation. The orifice for adjusting total friction loss to target value is applied to the lower plenum. The orifice diameter is determined from several preliminary tests as 9.0 mm, which should be validated with experimental result in further study.

In SG component, the heat transfer correlations for helical shell and tube geometries are employed to primary and secondary side, respectively.

Table I: Initial and boundary conditions for MARS-KS simulation.

	Parameter	Value
Initial condition	1st Hot Leg temperature(K)	573
	1st Cold Leg temperature(K)	573
	1st PZR pressure(MPa)	15.0
Boundary condition	2nd feedwater flow (kg/s)	0.02
	2nd SG outlet pressure(MPa)	2.00
	2nd SG inlet temperature(K)	474

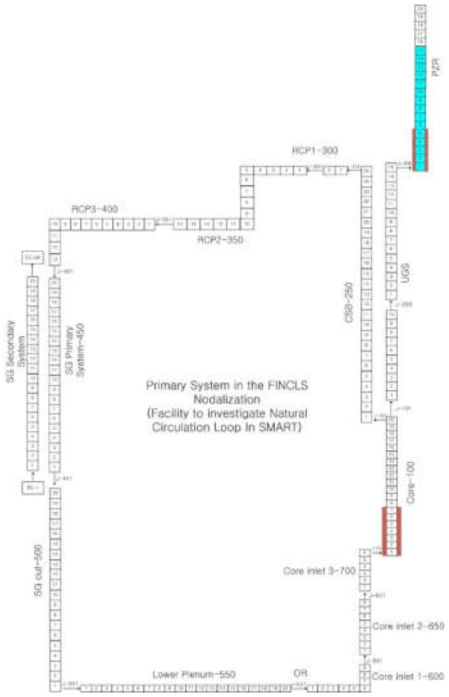

Fig. 2. Nodalization of FINCLS for MARS-KS simulation

4. Results and discussion

Figs. 3 to 6 indicates the results of MARS-KS simulation in terms of pressure, temperature, PZR level, and mass flow rate. Fig. 3 shows the transients in pressure of primary system for all cases. The pressures in cases with PZR heater control are converged to 15 MPa, while that in case without PZR heater is reached to lower pressure. The effect on pressure by PZR heater control is clearly identified.

Fig. 4 depicts that the larger temperature difference between the core inlet and outlet is observed in case of the higher core power. The fluid temperatures of hot leg for all cases are maintained as subcooled condition during transient due to PZR heater control.

Fig. 5 shows PZR levels depending on various core power. PZR water level in case with PZR heater control is proportional to the core power, since the fluid volume is proportional to temperature under constant pressure condition. On the other hand, PZR water level in case without PZR heater keeps similar to the initial condition due to the absence of vapor generation.

Fig. 6. Shows that mass flow rates driven by natural circulation are well converged to each specific value. As shown in the results, the mass flow rate is proportional to the core power which affects to the buoyancy effect.

As shown in Fig. 7, the results from MARS-KS simulation are superimposed to the characteristic curve obtained from the theoretical approach, which corresponds to Eq. (3) with C_{FIN}. The figure clearly illustrates that the results from MARS-KS are in good agreement within 5 % with the characteristic curve by applying the orifice of 9.0 mm diameter. Table II summarizes the results and errors between both approaches.

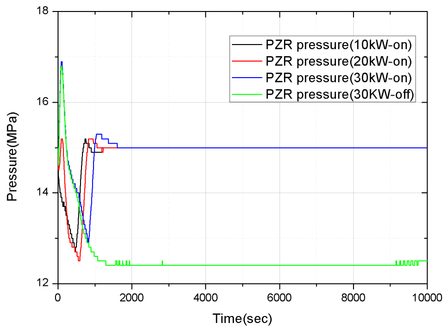

Fig 3. Effect on pressure depending on PZR heater control

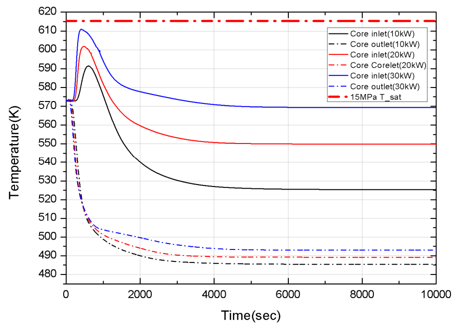

Fig. 4. Fluid temperatures at core inlet and outlet for various core powers.

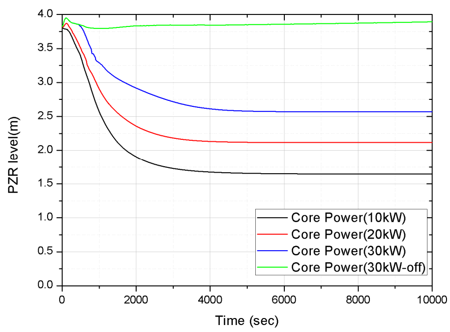

Fig. 5. PZR level for various core powers.

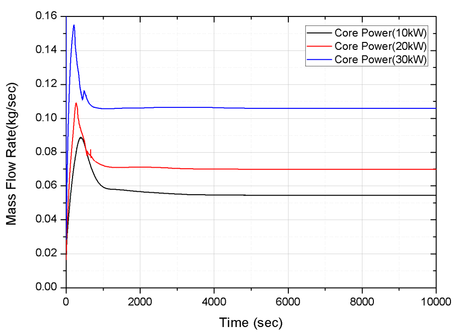

Fig. 6. Mass flow rate for various core powers.

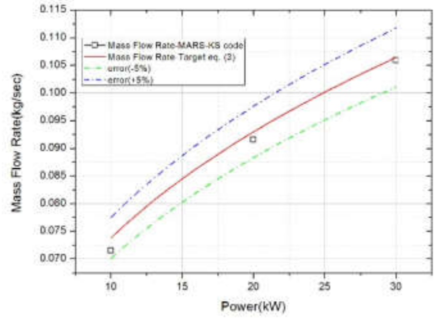

Fig. 7. Comparison of mass flow rate between the MARS-KS code and the target.

Table II: Error of mass flow rate for various core powers.

Power (kW)	MARS-KS (kg/s)	Theoretical (kg/s)	Error (%)
10	0.07154	0.07379	3.05
20	0.09151	0.09297	1.57
30	0.10597	0.10642	0.42

5. Conclusions

FINCLS is a simplified test loop for comprehensive understanding of thermal-hydraulic phenomena in the primary loop of SMART-ITL.

For realizing the scaled mass flow rate of natural circulation, adjusting total friction loss by applying an orifice with appropriate diameter is considered. Orifice diameter is determined as 9.0 mm from preliminary tests using MARS-KS code. MARS-KS simulations for totally three cases are carried out depending on the core power. The results of MARS-KS simulation clearly shows transient behavior and convergence to each steady-state in terms of pressure, temperature, PZR level, and mass flow rate. The results clearly describe that the simulated results by MARS-KS are closely matched to the characteristic curve within 5 % error by applying the orifice of 9.0 mm diameter. Subsequently, the experimental results and the MARS-KS code will be compared about mass flow rate when the orifice is installed.

REFERENCES

[1] Kim, K. K. et al., SMART: The First Licensed Advanced Integral Reactor, *Journal of Energy and Power Engineering*, vol. 8, pp. 94-102, 2014.

[2] M.Ishii and I. Kataoka, Similarity analysis and scaling criteria for LWRs under single-phase and two-phase natural circulation, NUREG/CR-3267.

[3] Eunkoo Yun, Hwang Bae, Sung-Uk Ryu, Sung-Jae-Yi and Hyun-Sik Park, Design review and controllability assessment of the SMART-ITL secondary system for the SMART design with experimental investigation, Annals of Nuclear Energy, vol. 109, pp. 538-547, 2017.

[4] KAERI, MARS code manual Vol.1: Code structure, system models and solution methods, 2009.

[5] R.B. Duffey and J.P. Sursock, Natural Circulation Phenomena Relevant To Small Breaks and Transients, vol. 102, pp. 115-128, 1987.