Analysis of Single- and Two-phase Natural Circulation using SPACE

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1. Introduction

Passive safety system (PSS) such as passive auxiliary feedwater system (PAFS) and passive residual heat removal system (PRHRS) has been widely adopted in several advanced light water reactors (ALWRs) and small modular reactors (SMRs) [1 ~ 3].

PSS is operated by natural circulation which has relatively less driving force such as gravity, density difference, and phase change, whereas active safety system (ASS) is operated by forced circulation based on external power source such as pump. Due to the less driving force of PSS, performance of PSS is sensitive to pressure drop of system.

System analysis codes such as RELAP5, MARS-KS, and SPACE were generally used for performance evaluation of PSS. System analysis codes adopted single- and two-phase pressure drop models which were developed and validated under forced convection experimental conditions. For the analysis of PSS, therefore, it is important to evaluate the applicability of pressure drop models for prediction of natural circulation flow rate.

Park et al.[4] evaluated prediction performance of pressure drop of SPACE 3.22 for straight tube under single- and two-phase flow condition. They reported that prediction errors of pressure drop were obtained within 5 % for single phase condition and 30 % for two-phase flow condition.

In this study, prediction performance for natural circulation flow rate of SPACE 3.22 was evaluated using experimental data from closed natural circulation loop tests. Through the evaluation results of single- and two-phase natural circulation flow rate, the applicability of pressure drop models was evaluated.

2. Natural circulation experiments

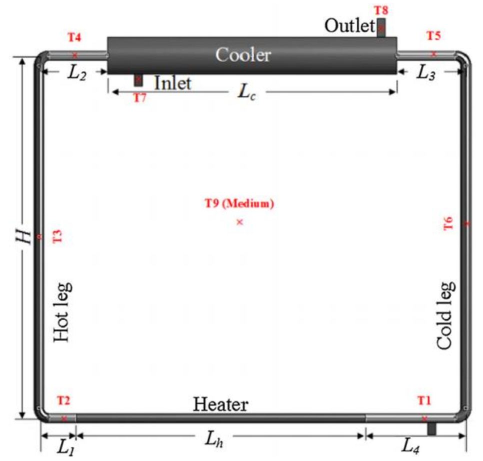
In this study, three closed natural circulation loop experiments were used for code evaluation. Description of experiments is follows.

2.1. AKIAU-R-1P experiments

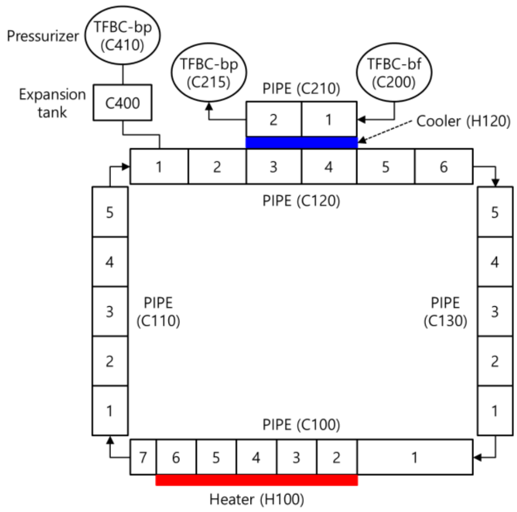
AKIAU-R-1P experiment was conducted by Seyyedi et al.[5] using closed loop. Flow rate during single-phase natural circulation were measured with various experimental condition. The test facility of AKIAU-R-1P experiment is shown in Figure 1(a). Followings are experimental condition for AKIAU-R-1P experiments.

- Pressure: 0.1 MPa
- Heater power: 250 ~ 1500 W
- Temperature: 16.6 ~ 47.5 ℃

Input model of AKIAU-R-1P experiment consisted of four PIPE components (C100, C110, C120, C130) for closed loop and one PIPE (C210) component for cooling channel, flow boundary (C200-TFBC-bf) for coolant inlet, and pressure boundary (C210-TFBC-bp) for coolant outlet. Two heat structures for heater (H100) and cooler (H120) were also modeled. Expansion tank (C400) and pressurizer (C410-TFBC-bp) were modeled to maintain system pressure. Node diagram of AKIAU-R-1P experiment for SPACE code analysis is shown in figure 1(b).



(a) Schematic diagram of test facility [5]



(b) Node diagram
Fig. 1. Test facility of AKIAU-R-1P experiment.

2.2. Vijayan et al. experiments

Vijayan et al.[6] conducted single-phase natural circulation experiments using closed loop, as shown in Fig. 2(a). Single-phase natural circulation flow rate were measured with two types of loop configuration: vertical heater horizontal cooler (VHHC) and vertical heater vertical cooler (VHVC). Experimental conditions are summarized below.

- Pressure: 0.1 MPa
- Heater power: 100 ~ 1015 W
- Temperature: 28 ~ 72.5 ℃

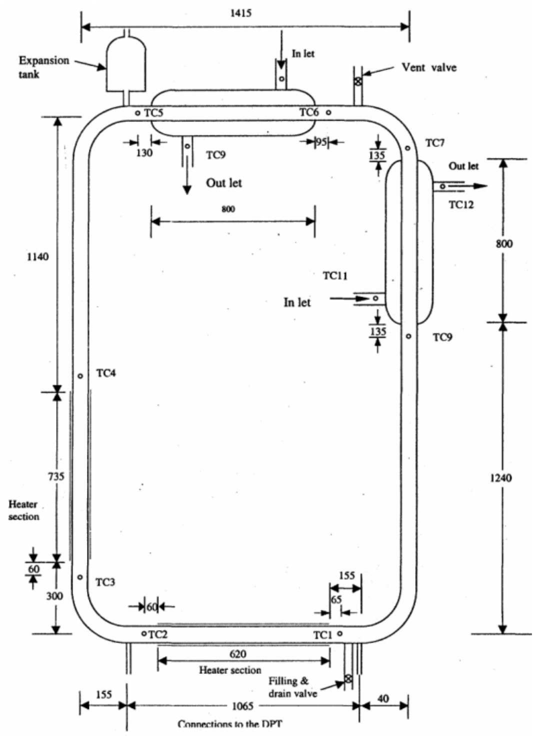
Input model of Vijayan experiment consisted of four PIPE components (C100, C110, C120, C130) for closed loop and one PIPE (C210) component for cooling channel, flow boundary (C200-TFBC-bf) for coolant inlet, and pressure boundary (C210-TFBC-bp) for coolant outlet. Two heat structures for heater (H110) and cooler (H120 for VHHC, H130 for VHVC) were also modeled. Expansion tank (C400) and pressurizer (C410-TFBC-bp) were modeled to maintain system pressure. Node diagram of Vijayan experiment for SPACE code analysis is shown in figure 2(b, c).

2.3. Bettis experiments

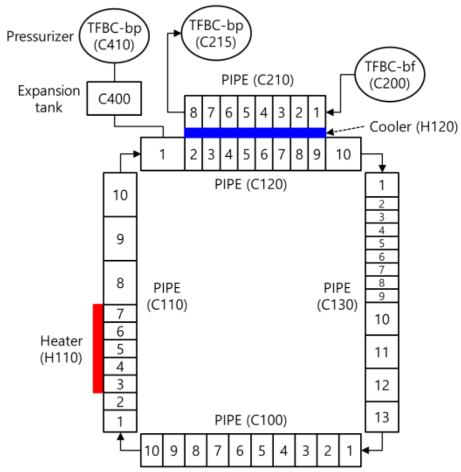
Bettis experiment was conducted by Mendler et al.[7]. Two-phase flow rate was measured by closed natural circulation experiments. The test facility of Bettis experiment is shown in Fig. 3(a). Bettis experiments were conducted using rectangular channel (0.2 inch spacing, 1 inch width, 27 inch long). Followings are test conditions of Bettis experiments.

- Pressure: 5.5 ~ 8.3 MPa
- Heater power: 772 ~ 1780 W
- Temperature: 230 ~ 259 ℃

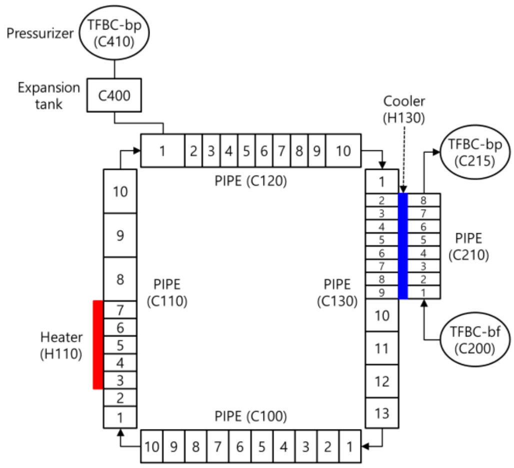
Closed loop of Bettis facility was model by PIPE components (C100 ~ C420) for pipes and FACE for pipe connections. Coolant channel was also modeled by PIPE component (C610), flow boundary (C600-TFBC-bf) for coolant inlet, and pressure boundary (C620-TFBC-bp) for coolant outlet. Two heat structures for heater (H220) and cooler (H310) were also modeled. Expansion tank (C510) and pressurizer (C520-TFBC-bp) were modeled to maintain system pressure. Node diagram of Bettis experiment for SPACE code analysis is shown in figure 3(b).



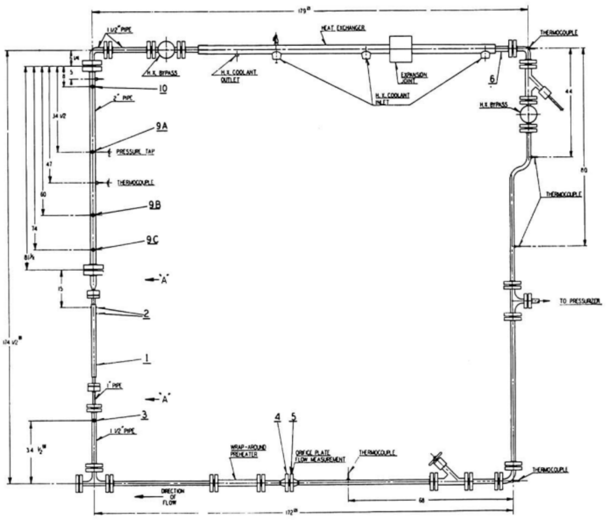
(a) Schematic diagram of test facility [6]



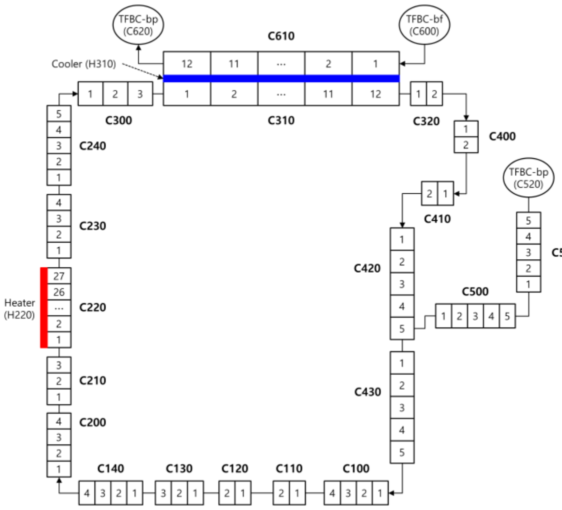
(b) Node diagram for VHHC



(c) Node diagram for VHVC
Fig. 2. Test facility of Vijayan et al. experiment.



(a) Schematic diagram of test facility [7]



(b) Node diagram of test section

Fig. 3. Test section of Bettis experiment.

3. Natural circulation analysis

3.1. Reynolds number dependent form loss modeling

Generally, form loss coefficient of elbow is modeled using Eq. (1).

$$k = 30f \quad (1)$$

k is form loss coefficient, f is friction factor. In general, constant value of friction factor for turbulent flow regime was used to calculate form loss coefficient in Eq. (1). In this study, calculated form loss coefficient based on constant friction factor (0.023) was used for *reference* case, which value was 0.69.

However, turbulent is not only flow regime in closed natural circulation loop but also laminar and transition flow could be possible due to low driving force of natural circulation. Therefore, Swapnalee and Vijayan [8] suggested Reynolds number dependent friction factor for laminar, transition, and turbulent flow regime, as shown in Eq. (2),

$$f = \frac{a}{Re^b} \begin{cases} a = 64, b = 1 & \text{for laminar} \\ a = 1.2063, b = 0.416 & \text{for transition} \\ a = 0.316, b = 0.25 & \text{for turbulent} \end{cases} \quad (2)$$

In this study, Eq.(2) was used for calculation of form loss coefficient of *K-loss modification* case based on experimentally measured Reynolds number. Through the Eq.(2), ranges of form loss coefficient were varied with 1.52 to 2.95 for AKIAU-R-1P experiments, 1.09 to 2.61 for Vijayan et al. experiments, respectively.

3.2. Analysis results of single-phase natural circulation

Analysis of single-phase natural circulation was conducted with AKIAU-R-1P and Vijayan et al. experiments. Analysis result of AKIAU-R-1P is shown in Fig. 4. In this figure, *reference*, *K-loss modification* and *K-loss + heat loss* cases represent the calculated natural circulation flow rate with turbulent based constant form loss coefficient, Reynolds number dependent form loss coefficient and Reynolds number dependent from loss coefficient with heat loss, respectively. Based on turbulent based constant form loss coefficient, calculated flow rate for *reference* case was higher than measured flow rate with 28.3 % of error. This result represents that turbulent based form loss coefficient was not appropriate to apply in laminar and transition flow regime. For the *K-loss modification* case, calculated flow rate was well matched with experimental results within 16.5 % of error. Additionally, heat loss for experimental loop was assumed to realize experimental environment. Heat transfer coefficient and ambient temperature were assumed by 5 W/m^2K and 15 ℃, respectively. For the *K-loss + heat-loss* case, prediction error of single phase natural circulation flow rate was reduced to 7.1 %.

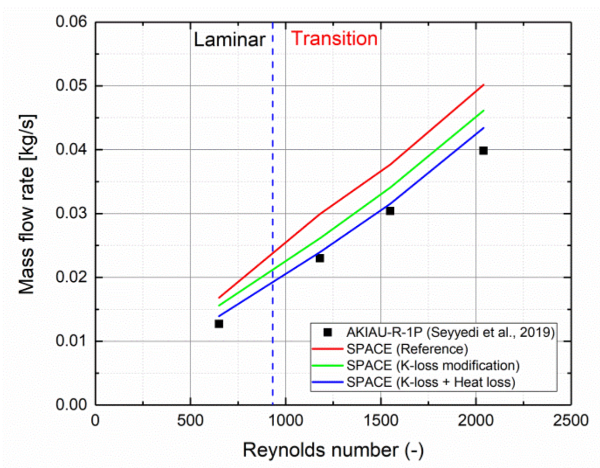
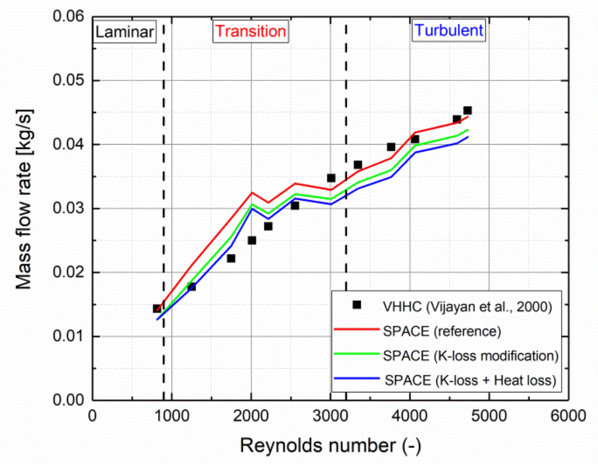


Fig. 4. Analysis results of single-phase natural convection using AKIAU-R-1P experiments.

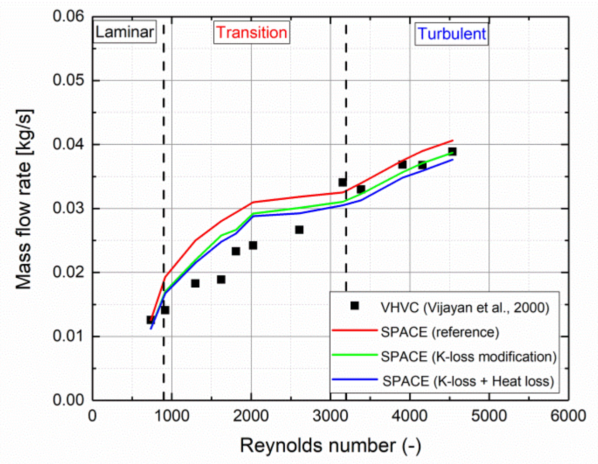
Fig. 5 shows calculation results of single-phase natural circulation flow rate using Vijayan et al. experiments. In this calculation, *reference*, *K-loss modification* and *K-loss + heat loss* cases were analyzed with both VHHC and VHVC configuration.

For the turbulent flow regime, calculated flow rates of *reference* case was well matched with experimental data within 3.5 % of error, because of flow regime was same as flow regime of friction factor for form loss coefficient in *reference* case.

For the transition flow regime, calculated flow rate of *reference* case was over-predicted with 26.7 % of error. To reduce prediction error, Reynolds number dependent form loss coefficient and heat loss were applied to *K-loss modification* and *K-loss + heat loss* cases. Through the modification, prediction error of single phase natural circulation flow rate in transition flow regime was reduced to 17.5 % and 15.1 % for *K-loss modification* and *K-loss + heat loss* cases, respectively.



(a) VHHC



(b) VHVC

Fig. 5. Analysis results of single-phase natural convection using Vijayan et al. experiments.

Despite of modification by Reynolds number dependent form loss coefficient and heat loss, prediction error in transition regime was higher than turbulent flow regime. The reason for that difference was originated by friction factor model in SPACE 3.22.

SPACE 3.22 adopted Churchill model [9] as friction factor model, as shown in Eq (3).

$$f = 8\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A+B)^{\frac{3}{2}}}\right]^{\frac{1}{12}} \tag{3}$$
$$A = \left[2.457\ln\frac{1}{\left(\frac{7}{Re}\right)^{0.9} + \frac{0.27\varepsilon}{D}}\right]^{16}$$
$$B = \left(\frac{37530}{Re}\right)^{16}$$

In this Eq.(3), ε is surface roughness and D is hydraulic diameter of pipe.

In comparison with Churchill [9] and Swapnalee and Vijayan [8] friction factor model, there was difference in transition flow regime, as shown in Fig. 6. Churchill model predicted friction factor lower than Swapnalee and Vijayan model. Therefore, SPACE 3.22 could over-predict single phase natural circulation flow rate in transition flow regime due to under-prediction of friction factor and pressure drop in pipe.

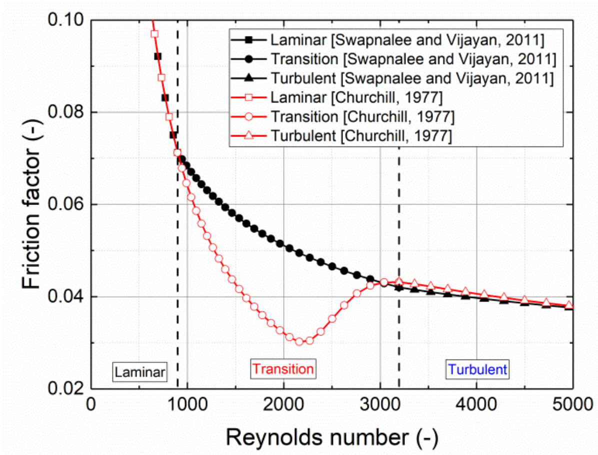


Fig. 6. Comparison of friction factor of Swapnalee and Vijayan [8] and Churchill [9]

Meanwhile, there was different tendency of prediction error of calculated flow rate in transition flow regime between AKIAU-R-1P and Vijayan et al. experiments. In the AKIAU-R-1P experiment, prediction error of flow rate in transition flow regime was significantly reduced by modification of form loss coefficient and heat loss. However, prediction error in Vijayan et al. experiment was higher than AKIAU-R-1P experiment. Those results were originated by scale of test facility. Total flow length and ratio of length to hydraulic diameter were 7.18 m and 266.9 for Vijayan et al. facility and 4.63 m and 165.2 for AKIAU-R-1P facility, respectively. To compare contribution of minor loss in elbow component, ratio of frictional pressure drop in elbow component to entire facility was quantified. In the AKIAU-R-1P, contribution of pressure drop in elbow component (0.543) was more significant than Vijayan et al. facility (0.271). Therefore, effects of form loss coefficient modification and heat loss were not significantly appeared in Vijayan et al. experiment.

3.3. Analysis results of two-phase natural circulation

Before two-phase natural circulation analysis, pressure drop models in SPACE 3.22 were evaluated by measured flow rate and pressure drop in test section of Bettis experiments. Test section was modeled by heat structure (H220) and single PIPE-component (C220-PIPE) with inlet flow (C210-TFBC-bf) and outlet pressure (C230-TFBC-bp) boundary condition, as shown in Fig. 7. Experimentally measured flow rate and thermodynamic condition in test section was applied to boundary condition.

Fig. 8 represents calculation results of two-phase pressure drop in test section of Bettis experiments. Calculated exit qualities of test section (see Fig. 8(a)) were well matched with measured values within 1 % of error. However, two-phase pressure drop in *reference* cases were under-estimated and prediction error was varied with flow regime of test section exit, as summarized in Table 1. For the best-estimate calculation, pressure drop correction factor was applied to two-phase pressure drop calculation as *modified* cases. Through the application of correction factor, prediction error of two-phase pressure drop was reduced from -36.24 % to -5.9 %.

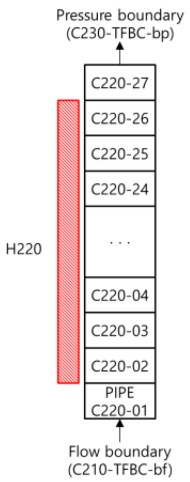
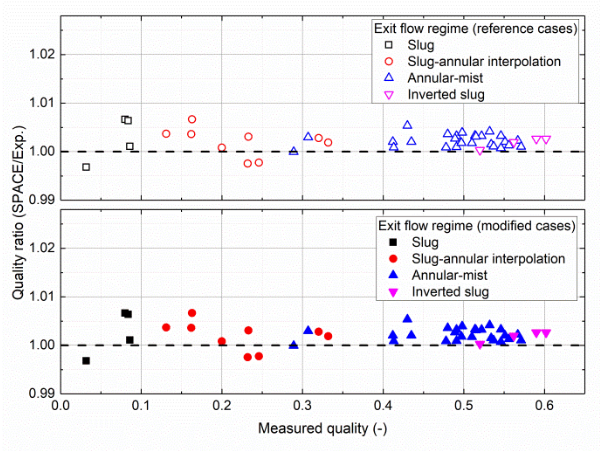
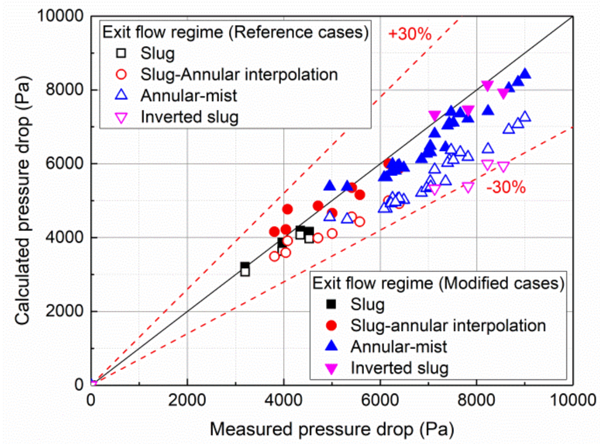


Fig. 7. Analysis results of two-phase natural convection experiments

Based on the results of two-phase pressure drop calculation, natural circulation analyses were conducted with *reference* and *modified* cases. In *reference* cases, constant value of turbulent friction factor (0.023) was used for form loss coefficient in minor loss components. For the *modified* cases, Reynolds number dependent form loss coefficient and correction factor for two-phase pressure drop were applied.



(a) Prediction error of calculated quality at exit of test section

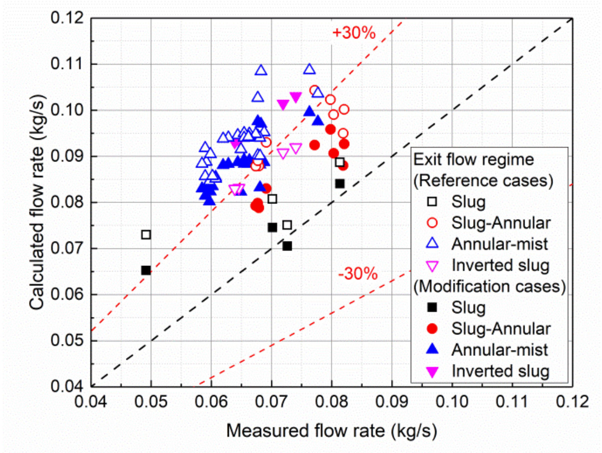


(b) Prediction error of calculated pressure drop of test section
Fig. 8. Analysis results of two-phase natural convection experiments

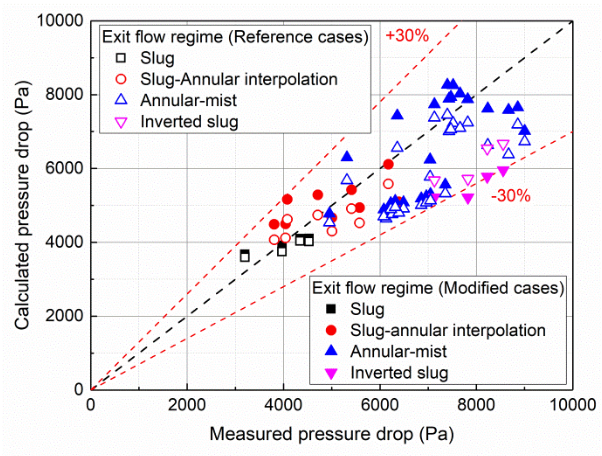
Table 1. Averaged prediction error of frictional pressure drop in test section of Bettis experiments

Exit flow regime	Averaged prediction error (%)		Correction factor
	Reference	*Modified*	
Slug	-24.11%	2.22%	1.32
Slug-annular interpolation	-38.25%	1.52%	1.62
Annular-mist	-34.36%	-9.08%	1.52
Inverted slug	-56.01%	-9.98%	2.27

Analysis results of two-phase natural circulation were shown in Fig. 9. Natural circulation flow rate (see Fig. 9(a)) calculated by *reference* cases were over-predicted due to the under-prediction of two-phase pressure drop, as shown in Fig. 9(b). However, in *modified* cases, prediction error of natural circulation flow rate was reduced from 38.4 % to 28.4 %. For the slug and slug-annular interpolation flow regime at flow exit, averaged prediction error was significantly reduced from 25.1 % to 14.2%. Prediction error of two-phase natural circulation flow rate was summarized in Table 2.



(a) Natural circulation flow rate



(b) Pressure drop of test section

Fig. 8. Analysis results of two-phase natural convection experiments

Table 2. Averaged prediction error of two-phase natural circulation flow rate in Bettis experiments

Exit flow regime	Averaged prediction error (%)	
	Reference	*Modified*
Slug	18.98%	9.84%
Slug-annular interpolation	27.86%	16.10%
Annular-mist	44.31%	35.69%
Inverted slug	42.67%	27.31%

4. Conclusions

In this study, single- and two-phase flow of natural circulation experiments were analyzed using SPACE 3.22. Reynolds number dependent form loss coefficient was helpful to reduce prediction error of single-phase natural circulation flow rate under laminar and transition flow condition. In two-phase flow condition, accurate prediction of pressure drop was important to reduce prediction error of natural circulation flow rate. The results of this study can be helpfully used for modeling of passive safety system using SPACE 3.22.

ACKNOWLEDGEMENT

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