Natural Circulation Flow Experiments Assessments for Passive Safety System Predictive Capability Analysis of MARS-KS

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1. Introduction

Passive safety systems such as PRHRS and PCCS are being introduced to many advanced nuclear power plants, and system analysis codes are used to validate the performance of passive safety systems. Since the passive safety system operates using the density difference, gravity, and phase change without an external power source, the driving force is quite small when it compared with active safety system and the uncertainty is expected to be large. On the contrary to this, since most of the models in the system analysis code were developed for the active system, it is necessary to verify whether the system analysis code can properly predict the thermal hydraulic phenomenon of the passive safety system. For this reason, the purpose of this study is to confirm the heat removal performance of the system in low driving force situations such as natural circulation flow. MARS-KS [1] is a regulatory verification code developed by the Korea Atomic Energy Research Institute. In this study, the passive safety system prediction performance of MARS-KS is assessed by simulating natural circulation flow experiments.

2. Description of Natural Circulation Flow Experiment Facilities

In this study, AKIAU-R-1P [2], Vijayan et al. [3], and Bettis [4] experiments that conducted natural circulation flow in the loop are analyzed with MARS-KS. The AKIAU-R-1P and Vijayan et al. experiments are single-phase flow experiments, and the Bettis experiment is a two-phase flow experiment.

2.1 AKIAU-R-1P Experiment [2]

The AKIAU-R-1P experiment is a single-phase natural circulation flow experiment conducted at Alibad Katoul Islamic Azad University, and the schematic diagram of the experimental facility is as shown in the Fig. 1. In this study, changes in natural circulation flow rate are observed at a heater power of 250W ~ 1,500W and the pressure of the loop is maintained at atmospheric pressure using an expansion tank.

2.2 Vijayan et al. Experiment [3]

The Vijayan et al. experiment is a single-phase natural circulation flow experiment which is conducted to study the effect of heater and cooler orientations in a rectangular loop. The schematic diagram of the experimental facility is as shown in the Fig. 2. In this experiment, natural circulation flow rate is tested for a total of four cases depending on the location of the heater and cooler, but in this study, VHVC (Vertical Heater Vertical Cooler) is selected and analyzed. The power of the heater is 100W ~ 1,000W and the pressure of the loop is maintained at atmospheric pressure using the expansion tank as in the AKIAU-R-1P experiment.

2.3 Bettis Experiment [4]

The Bettis experiment is performed the two-phase natural circulation flow tests with water at 800 to 2000 psia.

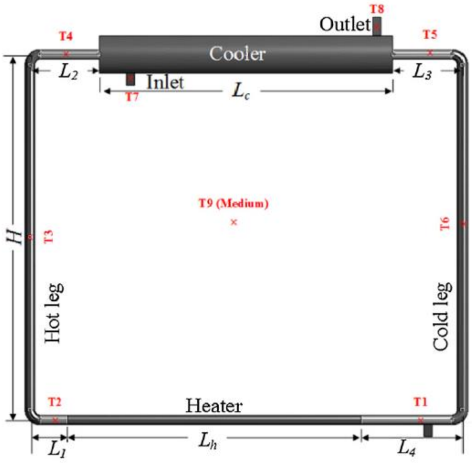

Fig. 1. Schematic of AKIAU-R-1P experiment [2]

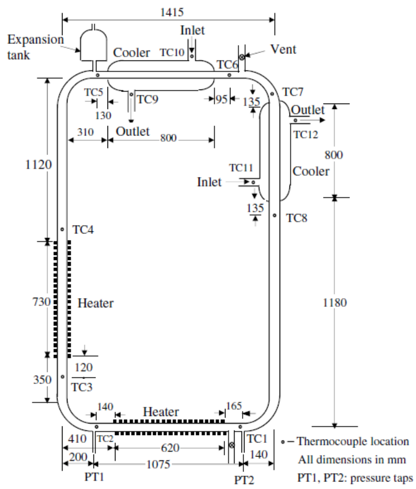

Fig. 2. Schematic of Vijayan et al. experiment [3]

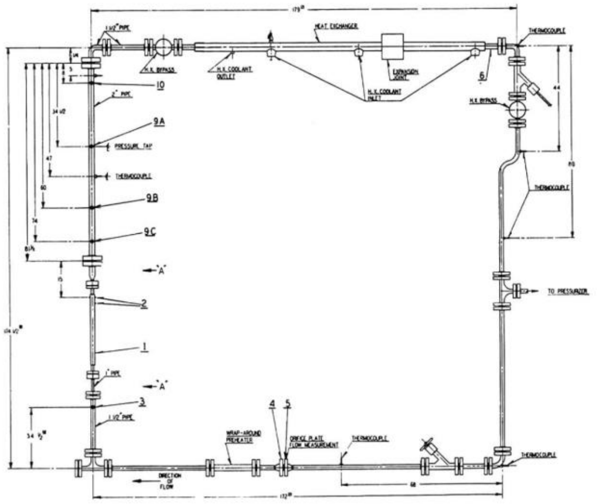

Fig. 3. Schematic of Bettis natural circulation loop [4]

The schematic diagram of the experimental facility is as shown in the Fig. 3. The main loop is in the shape of a vertical rectangle 14.5ft high and 15ft long and the heater is in the bottom of left vertical pipe. The exit flow quality is range of 0.0 ~ 0.7 and the heater power is range of 700W ~ 1,800W.

3. Natural Circulation Loop Form Loss Modelling for MARS-KS

3.1 Form loss coefficient modelling

In natural circulation flow, the difference in flow rate due to pressure drop is large because the driving force is relatively small. Therefore, to simulate the form loss of the natural circulation loop, each form loss coefficients are simulated using the equations of the CRANE book [5] as shown below. In this analysis, form loss due to Elbow, Branch, and Orifice and abrupt area change are existed.

$$K_{Elbow,90^\circ} = 30f, \qquad K_{Tee\ branch} = 20f$$

$$K_{Expansion} = \frac{2.6(\sin\theta)(1-\beta^2)^2}{\beta^4}, \theta \le 45^\circ$$

$$K_{Expansion} = \frac{(1-\beta^2)^2}{\beta^4}, 45^\circ < \theta \le 180^\circ$$

$$K_{Contraction} = \frac{0.8(\sin\frac{\theta}{2})(1-\beta^2)}{\beta^4}, \theta \le 45^\circ$$

$$K_{Contraction} = \frac{0.5(1-\beta^2)\sqrt{\sin\frac{\theta}{2}}}{\beta^4}, 45^\circ < \theta \le 180^\circ$$

$$K_{Orifice} = \frac{1-\beta^2}{C^2\beta^4}$$

3.2 Friction factor modelling

In general, the friction factor in the above equation is the value which is assumed fully turbulent flow. However, in the case of natural circulation flow, the flow rate is small, so that the flow could not be developed fully turbulent. For that reason, in here, the friction factor according to the flow regime is calculated using the formula of Swapnalee and Vijayan [6] as shown in below. Therefore, the friction factor used in this assessment is shown in Fig. 4 according to the Reynolds number.

$$f = \frac{a}{Re^b} \begin{cases} a = 64, b = 1 & for\ Laminar flow \\ a = 1.2063, b = 0.416 & for\ transient\ flow \\ a = 0.316, b = 0.25 & for\ turbulent\ flow \end{cases}$$

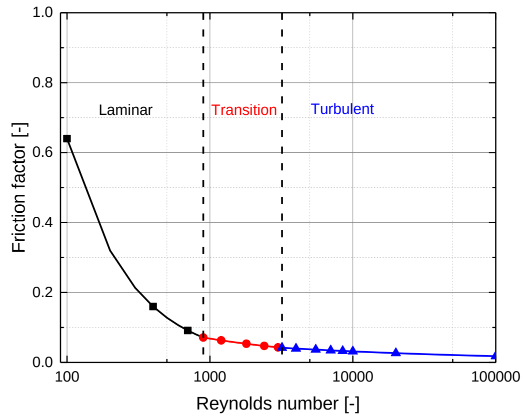

Fig. 4. Friction factor according to the Reynolds number

4. MARS-KS Calculation Results

The MARS-KS nodalization for the AKIAU-R-1P, Vijayan, Bettis experiment is shown in Figure 5.

4 cases of AKIAU-R-1P experiment and 18 cases of Vijayan experiment are analyzed for the evaluation of single-phase natural circulation flow in a closed loop. The geometries of the two experiments are similarly simulated as in the node figure. Assuming fully turbulent flow at the elbow and branch, the mass flow rate results are predicted to be high as shown in the red results in Fig. 6 and Fig. 7. It is determined that the cause of the error is that the flow rate of the experimental devices exist in the laminar and transition regions, not the turbulent flow, and the friction factor is predicted to be low. For this reason, the results of modifying the form loss of the corresponding part according to the method described in Chapter 3 are the green results. As shown in the figure, it is confirmed that the results are closer to the experimental results and the error is reduced. In addition, the effect of heat loss is analyzed for the AKIAU-R-1P experiment, and the results are shown in blue line. Due to heat loss, the temperature difference between the hot and cold parts in the loop decreased, and the flow rate of natural circulation decreased. Consequently, the results appeared to be closer to the experimental results.

The Bettis experiment is analyzed for the evaluation of two-phase natural circulation flow in a closed loop. In this analysis, the pressure drop due to the elbow, branch and orifice is modeled by the method shown in

Chapter 3. Fig. 8 is a synthesis of the results of the separate analysis of the test section of the Bettis experiment for the evaluation of the performance of predicting two-phase flow in the straight pipe in a previous study [7]. As shown in Fig. 8, the pressure drop is predicted to be low in the two-phase flow, especially in the slug flow and annular-mist flow region. This is also found in the loop analysis result. As shown in the black result in Fig. 9, the pressure drop in the test section is predicted to be low, and the natural circulation flow rate is predicted to be high compared to the experiment. As a result of increasing the pressure drop in the test section for sensitivity analysis, it is confirmed that the analysis results are closer to the experiment results as shown in the red results.

5. Conclusions

Since the passive system has a small driving force, its performance may vary depending on the pressure loss in the pipe. Therefore, in this study, natural circulation flow experiments are analyzed to evaluate the natural circulation flow pressure drop prediction performance of MARS-KS. The two research results are summarized below.

Firstly, it was confirmed that the result of the single-phase natural circulation flow rate in the closed loop varies greatly depending on the modelling of the pressure drop in the pipe. In particular, it was confirmed that the accuracy greatly varies depending on the method of calculating the friction factor when input the form loss factor. Therefore, when evaluating natural circulation flow rate in the future, it is necessary to evaluate the flow regime (laminar, transition or turbulent flow), and it seems that it is necessary to input a form loss factor suitable for flow.

And then, the two-phase natural circulation flow rate in the closed loop was evaluated by simulating the Bettis experiment. In here, MARS-KS predicted a low pressure drop in the vertical upward two-phase flow section, and therefore predicted the natural circulation flow rate to be larger than the experiment results. Therefore, it seems that it is necessary to additionally evaluate the pressure drop prediction performance of the heated wall, especially the section where the phase change occurs, and it seems that attention should be paid to this when evaluating the natural circulation flow.

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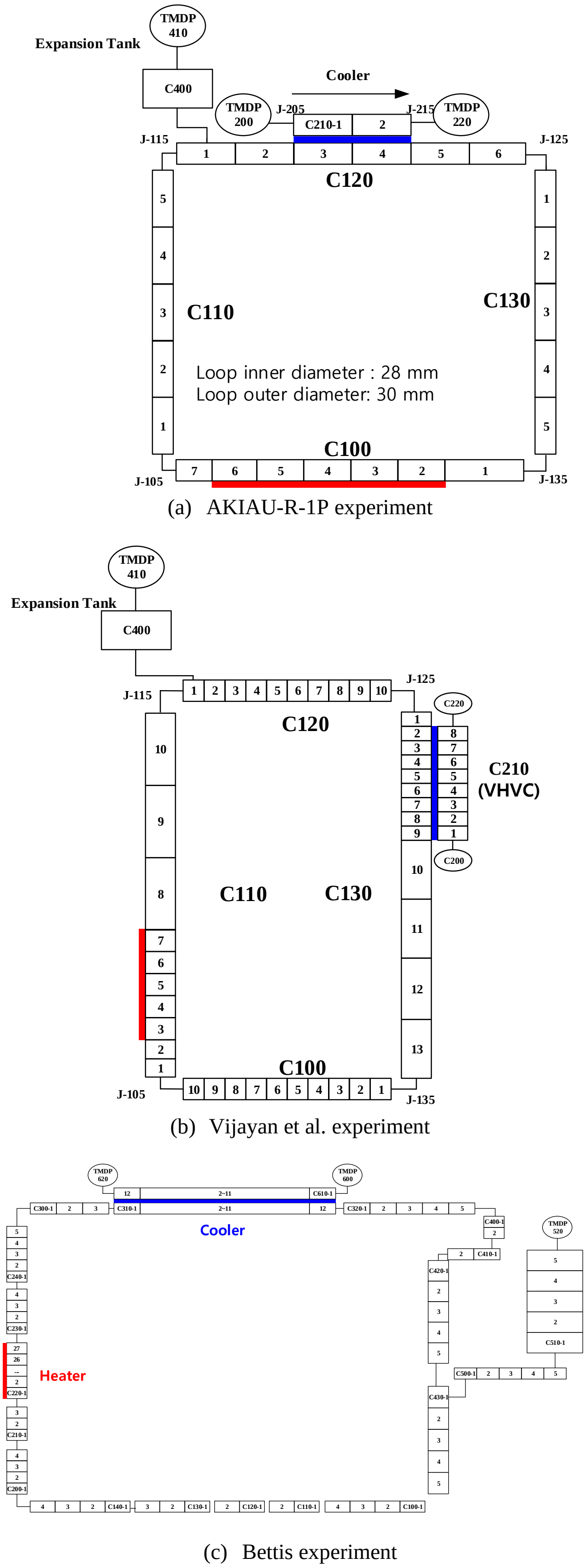


Fig. 5. MARS-KS nodalization for natural circulation loop experiments

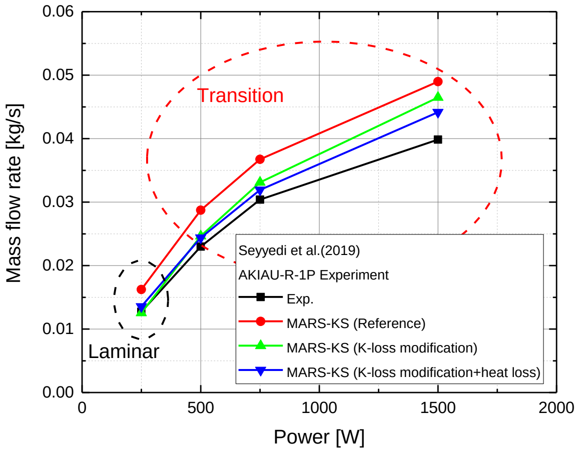


Fig. 6. Single-phase natural circulation flow assessment results - AKIAU-R-1P

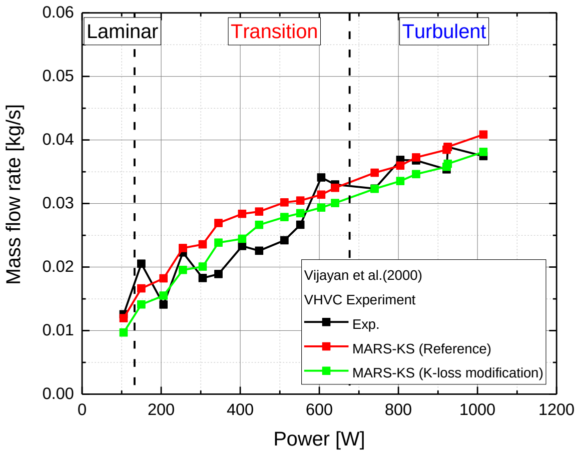


Fig. 7. Single-phase natural circulation flow assessment results - Vijayan experiment

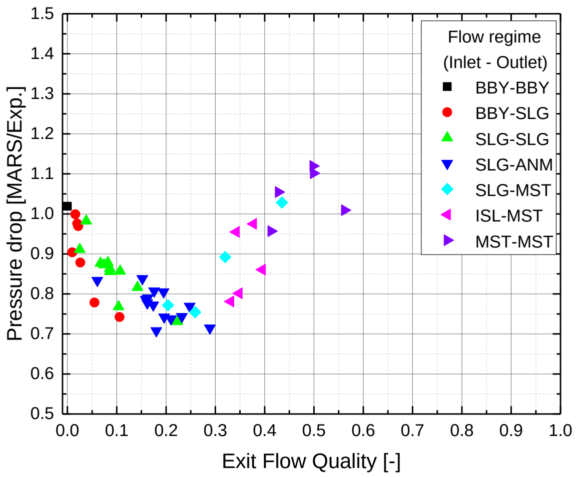
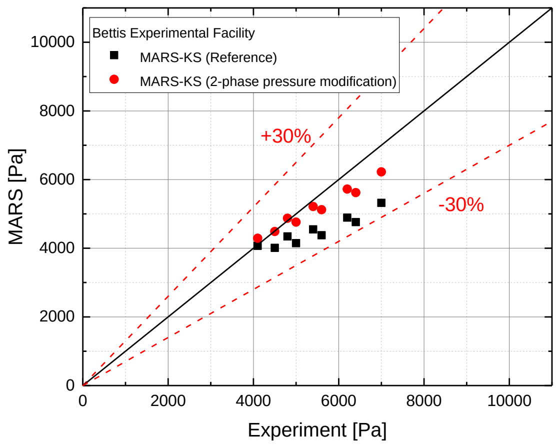
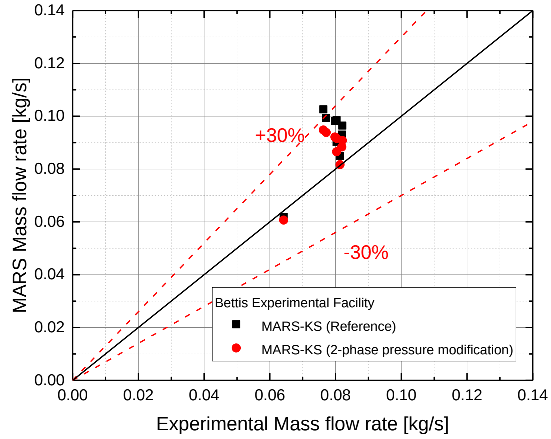


Fig. 8. Two-phase flow pressure drop calculation results - Test section of Bettis experiment



(a) Pressure drop



(b) Mass flow rate

Fig. 9. Two-phase natural circulation flow assessment results - Bettis experiment

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