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Thermal-hydraulic Analysis of The Cold Neutron Source Using CUPID Code

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1. Introduction

A cold neutron source (CNS) is a device to moderate thermal neutrons to cold neutrons. A cold neutron has energy below 5 meV. It has various applications, such as real-time observation of temporal changes in atoms and molecules. To get cold neutrons from the HANARO, which is a Korean research reactor, the neutrons should pass through a moderator, such as liquid hydrogen.

However, in the HANARO reactor, there have been trip events due to the abnormal pressure of the CNS. Between 2009 and 2019, a total of 19 trips occurred, 10 of which were attributed to high or low pressure trip variables of the CNS[1]. To address this issue, thermal-hydraulic analysis is required.

In this study, thermo-siphon in the CNS of HANARO under steady-state was analyzed using CUPID code to develop a hydrogen thermal-hydraulic analysis tool. CUPID is a two-phase three-dimensional thermal-hydraulic code developed by KAERI[2].

2. The cold neutron source in the HANARO reactor

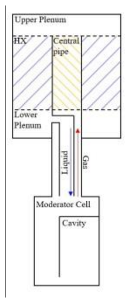

Fig. 1 Schematic diagram of the CNS.

The CNS in HANARO uses liquid hydrogen as a moderator. To remove heat load, CNS adopts a two-phase thermo-siphon[3]. The operating pressure is 152 kPa, and the operating temperature is 21.82 K under a cold condition[4]. Fig 1 illustrates Schematic diagram of the CNS.

The thermo-siphon in the CNS is shown in Fig. 2. First, ① the hydrogen gas is cooled and liquefied in the heat exchanger, then moves to the lower plenum. ② The hydrogen liquid accumulated in the lower plenum overflows when it reaches a certain level. Then, ③ the liquid hydrogen moves to the moderator cell through the inner tube of low temperature pipe. ④The liquid hydrogen in the moderator cell gets heat by nuclear heat from neutrons. ⑤, Hydrogen gas is vaporized and rises along the outer tube of low-temperature pipe. ⑥, ⑦ Hydrogen gas returns to the central pipe and the process goes back to ①. Through this process, the CNS maintains operation state.

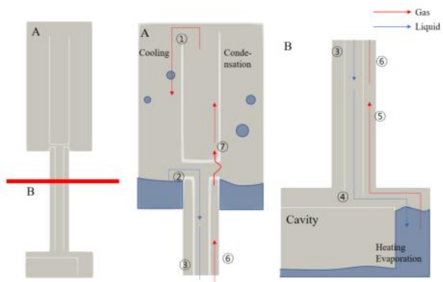

Fig. 2. Thermo-siphon in the CNS.

3. Implement and validation of hydrogen properties in CUPID

3.1. Implement of hydrogen properties

A hydrogen steam table is generated with NIST REFPROP to input thermo-physical properties of hydrogen to CUPID. The properties data in NIST REFPROP consists of formulas for calculating thermo-physical properties. Instead, hydrogen steam table is input into CUPID to enhance the efficiency of calculation and is validated using the NIST data and Selected Properties of Hydrogen (SPH)[5].

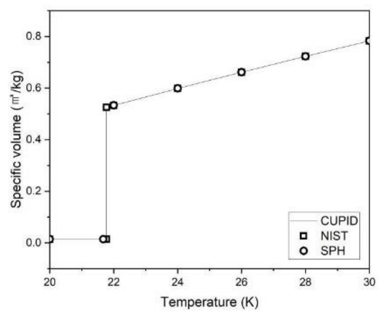

Fig. 3. Comparison of specific volume.

Fig. 3 shows the specific volumes of CUPID, NIST and SPH data. The maximum error is about 0.21%. The result shows the implement of hydrogen properties is in a good agreement.

3.2. Assessment of hydrogen analysis ability

Hydrogen in the CNS exists in two phases: gas and liquid. Hydrogen has different thermo-physical properties from water. Therefore, it is necessary to assess the CUPID code's ability to analyze hydrogen phase changes. To evaluate the ability of the CUPID code, a hydrogen condensation problem was analyzed. The initial pressure is atmospheric pressure, and the initial temperature is 20.4 K. Hydrogen is saturated under these conditions. The pressure at the pressure boundary face is atmospheric pressure, too. The void fraction inside the grid and at the interface is 100%. Geometric information of the mesh is shown in Fig. 4. A cooling rate of 1500 W was applied to gaseous hydrogen up to a height of 1.0 m.

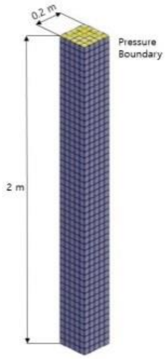

Fig. 4. Test mesh.

For the analytic solution, it was calculated in the following way. Assuming that the total amount of cooling at t seconds is Q(t) and the specific volume of liquid hydrogen is v_l, the volume of the hydrogen liquefied by Q(t), V_l is as follows:

$$V_l = \frac{Q(t)}{h_l - h_g} v_l$$

Enthalpy of each phase is represented as h.

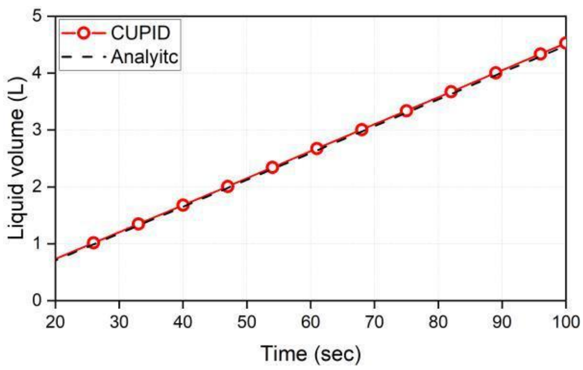

Fig. 5. Comparison of the liquid hydrogen volume.

The results between CUPID code and analytic solution are well matched as seen in Fig. 5. The error rate of CUPID code is confirmed approximately from 0.05 % to 0.79 % compared to the analytic solution.

4. Steady-state analysis

4.1. Modeling of the CNS

The hydrogen system of cold neutral resources becomes saturated under cold condition. Because major hydrogen flow occurs between the upper plenum and the moderator vessel, the mesh was made with the volume between the upper plenum and the moderator cell. Fig. 6 shows the computational mesh. The number of cells in the mesh is 9,009.

Fig. 6. Computational mesh.

As shown in Fig. 7, the hydraulic diameter was applied to the yellow region, and the hydraulic diameter and foam loss coefficient were also applied to the green region. In case of low-temperature pipe, hydraulic diameter 36 mm is applied to the outer tube, and 14 mm is applied to the inner tube, and the foam loss coefficient is 1.0. In cold conditions, hydrogen flow between the hydrogen buffer tank and the upper plenum rarely occurs. So the grid has no inlet or outlet. The red and blue regions are heating and cooling regions, respectively.

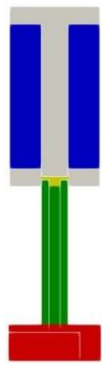

Fig. 7. Cooling region(blue), hydraulic diameter applied region(green), hydraulic diameter and foam loss coefficient applied region(yellow), heating region(red).

4.2. Steady-state analysis

For the steady-state analysis, a liquid level of 0.6 m is set as an initial condition. Fig. 8 shows initial height of liquid hydrogen in the mesh. Table 1 shows heat loads by reactor power[6]. Cooling rates are same with the heat loads.

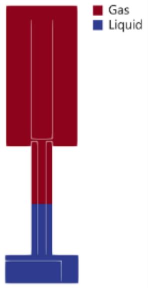

Fig. 8. Initial liquid hydrogen level.

Table 1: Heat load by reactor power

Reactor power (MW)	Heat load (W)
5	600
10	840
15	1,400
18	1,550
30	1,700

Fig. 9 and 10 summarize the calculation results in steady-state. As presented in Fig. 10, it can be seen that the liquid volume in the moderator cell decreases as the heat load and cooling rate increase. In the case of the mass flow rate of the low-temperature pipe, the heating value increased significantly when the heating value was less than 1,400 W

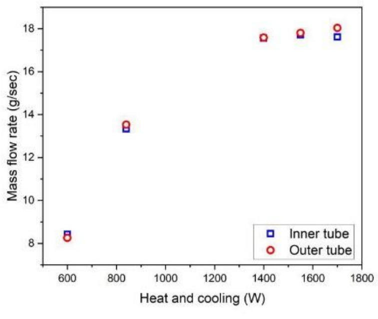

Fig. 9. Mass flow rate of inner and outer tube.

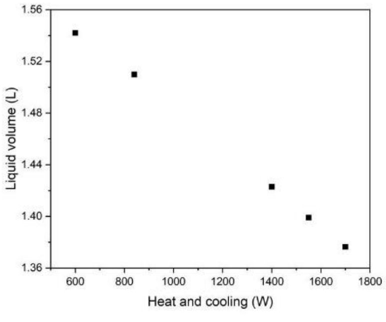

Fig. 10. Liquid volume in the moderator cell.

5. Conclusion

This study was conducted to develop a hydrogen thermal hydraulic analysis tool. For this purpose, the thermal hydraulic phenomenon in a CNS of the HANARO reactor was analyzed using the CUPID code. Hydrogen properties were implemented into the CUPID code and validated. And hydrogen two-phase flow was analyzed using the CUPID code and the error rates was less than 0.8 %.

In modeling of the CNS, hydraulic diameter and shape loss coefficient were applied to the low-temperature pipe to imitate the hydraulic characteristics of the CNS. And then steady-state was analyzed to check whether each phase was maintained well and thermo-siphon was performed well under various heating and cooling amounts.

As a result of the analysis, it was confirmed that thermo-siphon was performed well regardless of the heating amount and cooling amount. The mass flow rate in the low-temperature pipe was converged above 1,400 W of heat load, and it was confirmed that the volume of liquid hydrogen in the moderator cell decreased as the reactor power increased.

ACKNOWLEGDEMENT

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