Condensation Performance Evaluation of Evacuate containment with Xenon, Air and CO_2 for Small Modular Reactor

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1. Introduction

Evacuated containment concept is attracting widespread interest in fields such as small modular reactors (SMR). Vacuum condition of the evacuated containment has benefits including a low hydrogen flammability and an eliminated potential degradation. Especially, it increases steam condensation rates for containment heat removal during loss of coolant accident (LOCA) events. Although this approach takes some advantages, it requires a consideration of a higher maintenance cost than other containment designs. Thus, there is a challenging area to fill up the inside of containment with a gas as substitute for vacuum. However, even small amounts of the presence of non-condensable gas causes a large reduction of condensation rates. It could be threatened safety of the reactor because long-term cooling is established via recirculation of condensate to the reactor vessel. Therefore, it is necessary to determine the condensation performance when gases fill up the containment.

The purpose of this study is to evaluate the condensation performance of evacuate containment when non-condensable gases (xenon, air, and CO_2) fill up the containment using mathematical method. To quantify the condensation performance, condensation rate was calculated by a recent correlation [1]. Finally, the condensate level of the containment was determined and compared with the core height for recirculation.

2. Methodology

The current study involved collecting thermal hydraulic data and calculating the condensation rate with the mathematical method. The mathematical method in this study needs pressure, temperature, and mass flow rate of steam to calculate the condensation rate. Thus, these parameters were collected by the reference.

2.1. Input data with RELAP5 of reference

Input data for condensation rate calculation was collected from RELAP5 simulation results [2]. Susyadi et al. examined the thermal hydraulics of NuScale's evacuated containment during stuck open of reactor vent valve accident using RELAP5 code. Their results which are containment pressure, temperature, and steam mass flow rate through the vent valve were used to the condensation rate calculation in this study. These parameters were calculated until 3,600 second in RELAP5 simulation. A detailed information regarding the RELAP5 simulation is given in table I [2].

Table. I Simulation conditions of RELAP5

Parameter	**Value**
Pressure of RPV [MPa]	12.755
Average temperature in RPV [K]	557.0
Containment pressure [MPa]	0.0051
Containment temperature [K]	305.37

2.2. Mathematical method

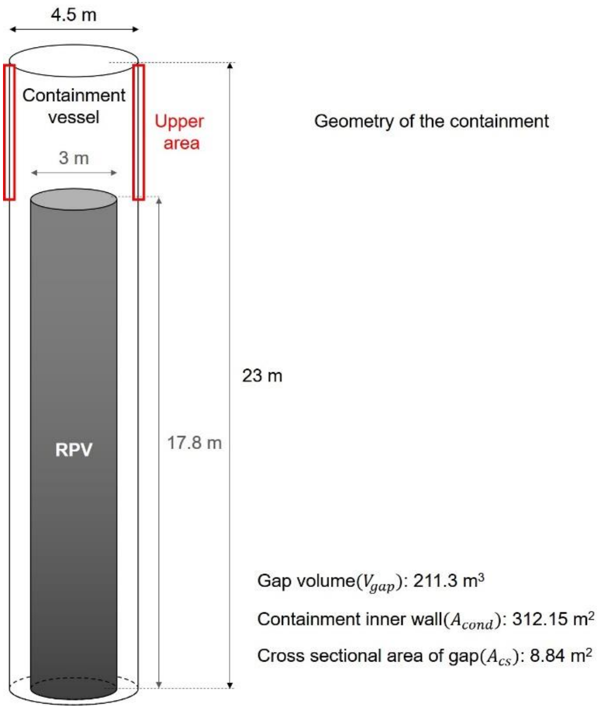

Fig. 2. Geometry of containment vessel for condensation rate calculation

Geometry information of the containment was referred to NuScale. To simplify the calculation, RPV and the containment vessel were assumed a cylinder as shown in Fig. 1. A gap which is a space between the containment inner wall and the outer wall of RPV was filled with the gas before the accident. When the steam goes out of the RPV during accident, the condensation occurs on the containment inner wall. However, it is not practical to assume that the condensation occurs on the whole area of the containment inner wall. Therefore, it is assumed that the condensation occurs only upper area which is located upper of the RPV as shown in Fig. 1.

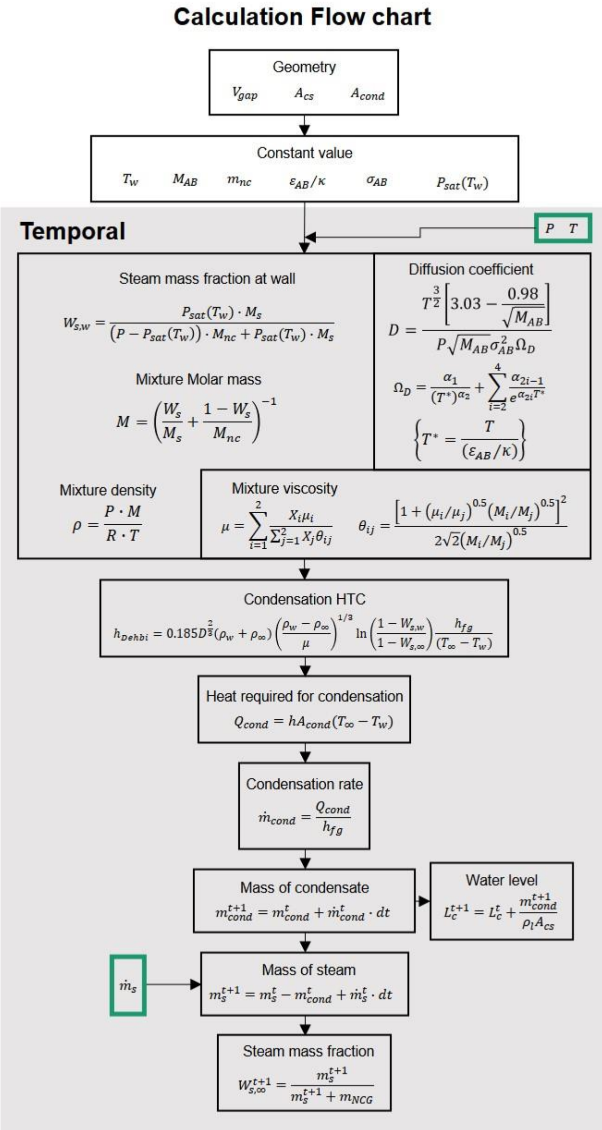

Fig. 2. Flow chart of the condensation rate calculation

To calculate the condensation rate, condensation heat transfer coefficient (HTC) was determined by using Dehbi correlation [1]. A diffusion coefficient, steam mass fraction, and mixture density and viscosity are used to the calculation of the condensation HTC (Eq. 1).

$$h = 0.185 D^{\frac{2}{3}} (\rho_w + \rho_\infty) \left(\frac{\rho_w - \rho_\infty}{\mu} \right)^{\frac{1}{3}} \frac{h_{fg}}{(T_\infty - T_w)} \ln \frac{1 - W_{s,w}}{1 - W_{s,\infty}} \quad (1)$$

The condensation rate can be calculated by heat transfer rate of condensation as shown in Eq. 2, but it could not excess the steam mass at that time step in the containment.

$$\dot{m}_{cond} = \frac{Q_{cond}}{h_{fg}} = \frac{hA_{cond}(T_\infty - T_w)}{h_{fg}} \quad (2)$$

The calculated condensation rate updated the mass of remaining steam, and it can determine the steam mass fraction of next time step. Transient calculation was proceeded until the 3,600 second of simulation time, and the results of condensate level in the containment were compared with that of each gases case. Fig. 2 shows flow chart of the condensation rate calculation.

3. Result

Prior to the detailed comparison of the condensation rate, validation process is necessary to trust the results of the mathematical method. After that, the condensate level and the condensation HTC were compared between the vacuum case and the gases cases. In addition, the case that condensation area is the whole containment inner wall area, and the upper area case were also compared.

3.1. Validation of the calculation results

Susyadi et al. reported the condensate volume during the RELAP5 simulation [2]. It can be calculated using the mathematical method of this study, so it was compared with the reference data displayed in Fig. 3.

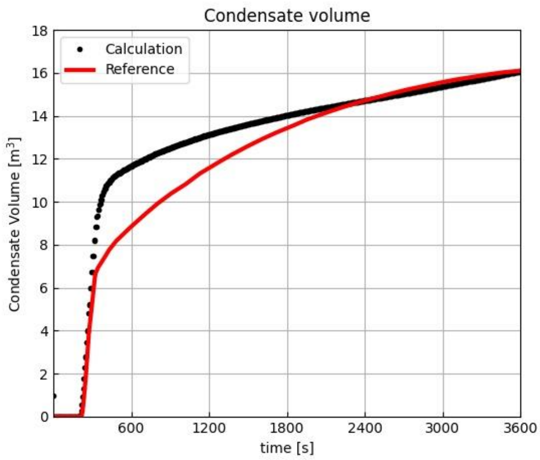

Fig. 3. Comparison of condensate volume

The reference shows that the volume was reached to 6.9 m^3 in 40 seconds after the transient started. However, the volume of the calculation was reached to 10.4 m^3 in same period. After that, the difference of the condensate volume between the reference and the calculation was reduced as time goes on. At the end of the calculation of 3,600 seconds, both cases had a similar condensate volume.

The discrepancy between the reference and calculation is come from some assumptions. First, the reference calculated heat transfer from the containment to a pool which is located to out of the containment. Furthermore, the Dehbi correlation is only valid for steam mass fractions up to 0.95, but the containment had steam mass fraction above 0.95 in all simulation. It could be reason that the calculation underestimated the condensate volume. Nevertheless, the trend of the calculation is similar with the reference data.

3.2. Effect of the non-condensable gases

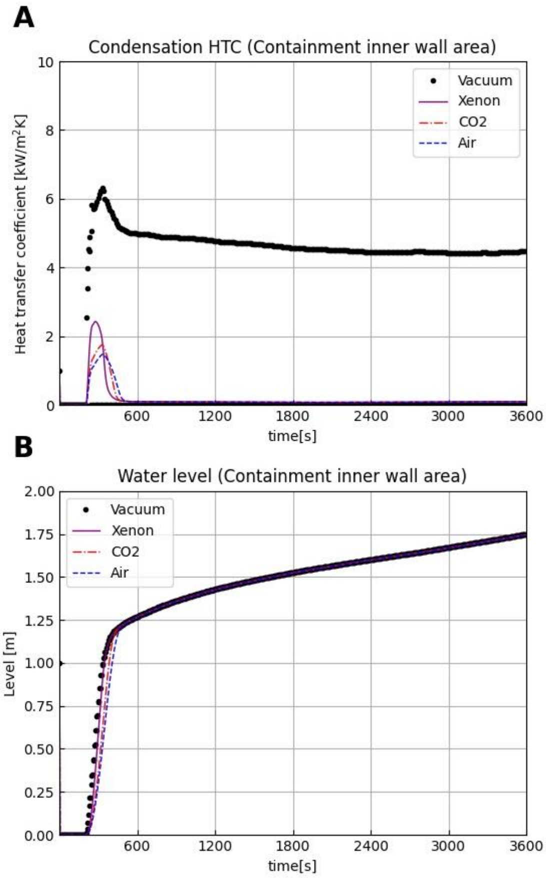

Fig. 4. The condensation HTC (A) and the condensate level (B) comparison between the vacuum and the three gases with the whole condensation area

The presence of the non-condensable gas remarkably decreases the condensation HTC. This is because the steam suffers diffusion boundary layer of the non-condensable gas on the condensing surface. This is consistent with the calculation results of the containment inner wall case as shown in Fig. 4. The condensation HTC of the non-condensable gases was significantly lower than that of vacuum. The condensation HTC of the vacuum reached around 6.3 kW/m^{2}K, but the air had only 1.47 kW/m^{2}K of the condensation HTC at the highest point. In addition, the density difference between the non-condensable gas and the steam induces the diffusion of the steam to contact with the condensing wall [1]. It caused the condensation HTC difference between the xenon, CO_2, and air as indicated in Fig. 4 A. The xenon has the highest density difference with the steam, so the xenon had the highest condensation HTC between them.

Although the condensation HTC of the non-condensable gases were considerably low than the that of the vacuum, the condensate level were not. This is because the condensation area was so large in this case, so the most steam was condensed. Eventually, the condensate level was almost all the same in the whole condensation area case.

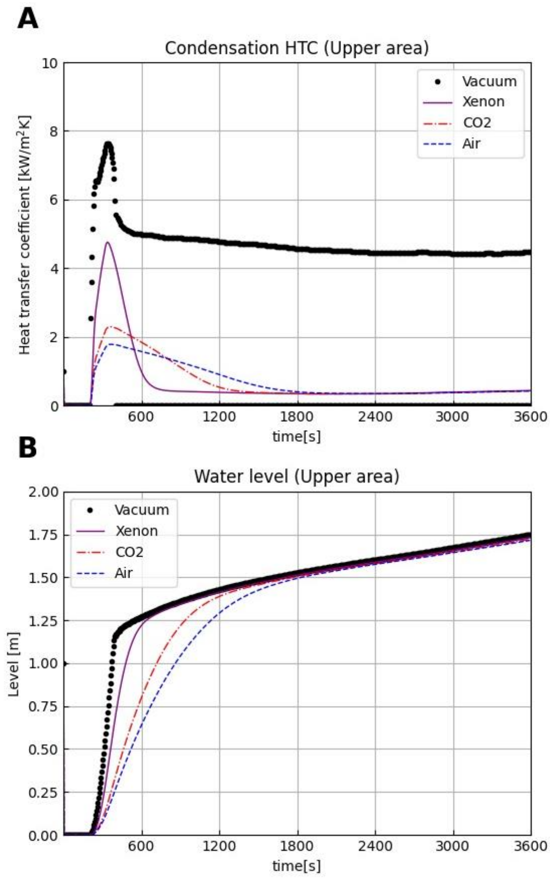

Fig. 5. The condensation HTC (A) and the condensate level (B) comparison between the vacuum and the three gases with the upper condensation area

However, it is impractical that the condensation occurs on the whole containment inner wall. Therefore, the same parameters were compared in the upper area condensation case as shown in Fig. 5. The condensation HTC of the vacuum and the non-condensable gas cases was higher than the case of the whole condensation area. When the condensation area decreases, the condensate volume is reduced. Thus, the remained steam mass in the containment was increased, and the condensation HTC eventually increased. Although the condensation HTC of the non-condensable gases were increased, the condensation rate was decreased because of the reduced condensation area. Therefore, the condensate level of the non-condensable gases was decreased than that of the vacuum as illustrated in Fig. 5 B. However, the condensate level of all cases was similar after 2,400 seconds. This is because the remained steam was almost all condensed at this point. These results suggest that the gas filled containment has not much disadvantage of the condensation performance.

4. Conclusion

This study evaluated the condensation performance of evacuate containment when non-condensable gases fill up the containment using mathematical method. The condensation HTC of the non-condensable gases were lower than that of the vacuum, but it had not significant effect on the condensation rate. Between the gases, the xenon had the highest condensation performance because of their density. The results show the feasibility of the gas filled containment, and it could be a cost-effective on SMR design.

REFERENCES

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