Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 8-10, 2024

Analytical Study on Stratification of Released Hydrogen in a Containment Building

Jongtae Kim [a*], Kukhee Lim [b]
[a] *KAERI, Daeduk-daero 989-111, Daejeon, Korea*
[b] *KINS, Gwahak-ro 62, Daejeon, Korea*
[*] *Corresponding author: ex-kjt@kaeri.re.kr*

1. Introduction

In the event of a severe accident in a nuclear power plant, hydrogen generated in the reactor is released into the containment building through the rupture of the primary reactor cooling system or the pressure relief valve. Hydrogen is released in the form of a high-speed jet flow due to the pressure difference between the reactor and the containment building and diffuses as it moves to the upper part of the containment building by a buoyancy force.

The process by which hydrogen generated in the reactor core is released into the containment building or the behavior of the hydrogen jet such as hydrogen diffusion, mixing with the atmosphere, and hydrogen stratification is a very important phenomenon from the perspective of hydrogen safety. Because the behavior of hydrogen in the containment building is greatly affected not only by the hydrogen generation process in the reactor but also by the geometric characteristics of the containment building, it is difficult to simply evaluate the hydrogen distribution using dimensionless numbers such as Froude number or Richardson number. Therefore, by using a 3D analysis code for the hydrogen behavior, it can be evaluated according to the characteristics of the nuclear reactor and containment building.

In this study, the adequacy of the analysis model through analysis of a hydrogen jet flow experiment using a 3D hydrogen behavior analysis code is evaluated and a simple-shaped geometric model of a large nuclear power plant is built to evaluate the jet flow and stratification characteristics of hydrogen. To verify the analytical model, a three-dimensional analysis of the LSGMF (large-scale gas mixing test facility) [1] helium jet flow experiment performed at AECL in Canada was conducted. The shape of the containment building of APR1400, a large nuclear power plant currently in operation in Korea, is simplified to evaluate the effect of the geometric characteristics of the containment building on the flow of hydrogen jets.

2. Methodology

To increase the efficiency of numerical calculations for multi-component mixed gases and to strengthen the conservation of mass of gas components, ideal gas-based equations of state and numerical algorithms are used. In other words, the multi-component ideal gas based Euler approach is applied to the gas phase. The mass, momentum, and energy transport equations for multi-component mixed gases and the mass conservation equations for each gas component are as follows [2].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}) = S_\rho \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{U}) + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) - \nabla \cdot \boldsymbol{R} = -\nabla \mathrm{p} + \rho \boldsymbol{g} + \boldsymbol{S}_m \quad (2)$$

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \boldsymbol{U}) - \nabla \cdot \boldsymbol{J}_i = S_{Y_i} \quad (3)$$

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla \cdot (\rho h_s \boldsymbol{U}) - \nabla \cdot \boldsymbol{q} = \frac{\partial p}{\partial t} - \left[\frac{\partial}{\partial t}(\rho K) + \nabla \cdot (\rho K \boldsymbol{U})\right] + S_h \quad (4)$$

, where the definitions of the variables in the equations are as follows.

ρ	density of gas mixture
$\boldsymbol{U}$	gas velocity
Y_i	mass fraction species i
h_s	sensible enthalpy
P	pressure

The governing equations from Eq. (1) to Eq. (4) together with a two-equation turbulence model are discretized using the finite volume library in the OpenFOAM [3] platform. A steam condensation model is implemented in the numerical model. Although the numerical solver includes a steam condensation model, this study did not consider the condensation phenomenon to evaluate the effect of the shape of the reactor containment, especially the shape of the steam generator compartment where hydrogen is released, on the stratification of the hydrogen jet.

3. Validation

At AECL in Canada, an experimental facility called LSGMF was built to verify the GOTHIC-3D [4] code for the jet flow and stratification of hydrogen in a containment building and experiments were performed under various conditions. In this study, we performed verification of the 3D analysis model for the LSGMF experiment.

The large-scale gas mixing test is an experiment conducted to evaluate diffusion by hydrogen buoyant jets and verify the analysis model in a large space with an internal space of approximately 1000 m^3. The experimental facility consists of double compartments, with the outer compartment being used as a control room and the inner compartment being sealed and used as an experiment space. The experimental space consists of two connected compartments, large and small. The outer wall is a concrete structure, with an I-beam at the top, a ventilation duct for pressure control on the side wall, and an air conditioning device in the middle installed on a shelf. Fig. 1 shows the shape and configuration of the LSGMF experimental facility.

The LSGMF experiment was a helium injection experiment using small and large pipe nozzles, and detailed test conditions are shown in Table 1. A helium injection pipe is installed vertically in the middle of the floor, and in the experiment, a small pipe with a diameter of 5 cm and a large pipe with a diameter of 30 cm were used to evaluate the effect of hydrogen distribution depending on the diameter and speed of the jet.

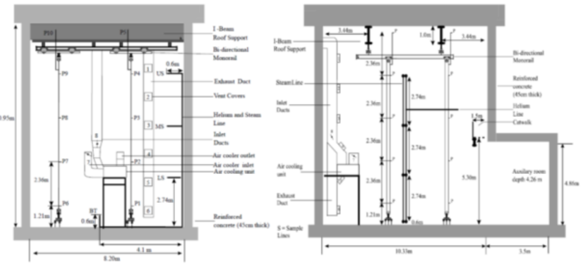

Fig.1. LSGMF test facility

Table 1. LSGMF test conditions

Parameter	Value
Venting system	Exhauste duct with 0.048 m^2 opening area
Obstacles	2 I-beams on the ceiling
Thermodynamic conditions	Pressure: 1 bar, Temperature: 18 °C
Helium injection	2.97 g/s, 0.0175 m^3/s at 16 °C
Nozzle	small pipe D = 0.0508 m, large pipe D = 0.305 m

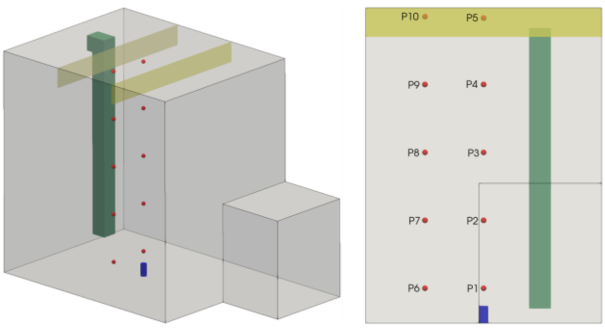

Fig. 2. Measurement locations for He concentration in the LSGMF test facility.

In the experiment, the helium concentration was measured at 10 measurement points (Fig. 2). P1 to P5 are located above the helium 2 nozzle, and P6 to P10 are measured 2 m from the nozzle.

Fig. 3 compares the change in helium concentration over time at point P10 with the experimental results using the large pipe. Point P10 is a point off the central axis of the nozzle, where the helium raised by the vertical jet reaches the ceiling and then spreads in the horizontal direction. Fig. 4 is the comparison of helium concentration changing over time at point P10 with the experimental results using the small pipe. It depicts that the helium concentration at the dome region is continuously increasing during the helium injection.

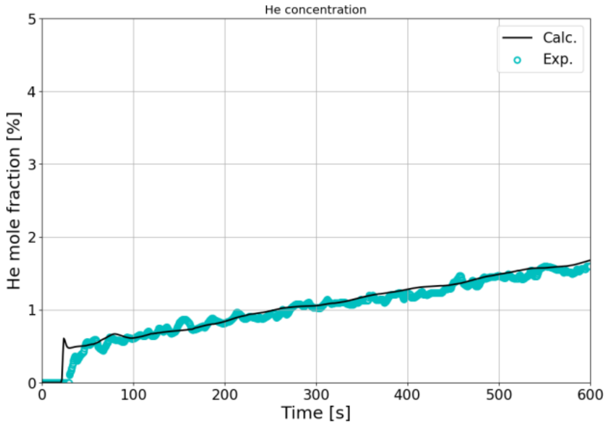

Fig. 3. Change in helium concentration at point P10 for large pipe nozzle).

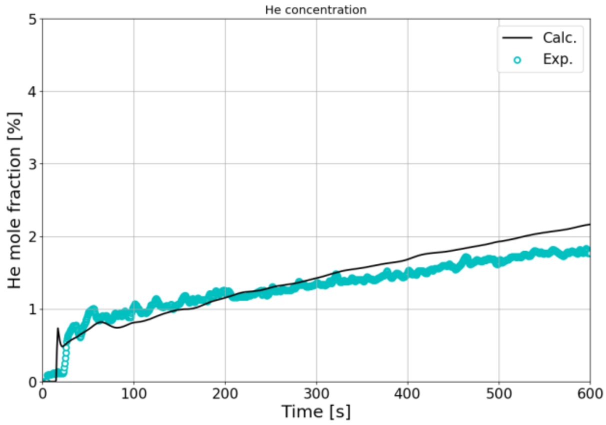

Fig. 4. Change in helium concentration at point P10 for small pipe nozzle).

As shown in Figs. 3 and 4, it can be thought that the analytical model predicts reasonably well the mixing of the released helium and ambient air.

4. Evaluation of Hydrogen Stratification

Representative factors that affect the behavior of hydrogen include the release rate, the amount of hydrogen and water vapor, and the structure of the containment building and internal safety devices. The internal shape and volume of the containment directly affect the diffusion and mixing of hydrogen and water vapor. The containment building of the large pressurized water reactor-type nuclear power plants (APR1400 and OPR1000) currently in operation in Korea consists of two steam generator compartments, an annular operating deck, an annular space consisting of a large free volume and multiple compartments, and a large hemispherical dome.

The distributions of hydrogen in the OPR1000 and APR1400 containment buildings may be different from the hydrogen distributions in other types of reactor containment buildings. In EPR, which consists of a compartment-type containment building, the mixing of hydrogen is very important, and some devices are installed to improve it. In containment buildings such as

APR1400, which have a large dome-shaped free space at the top of the containment building, the stratification of hydrogen is one of the representative hydrogen issues.

Because the interior of the containment building is complex and consists of many compartments, the behavior of hydrogen is directly or indirectly affected by various factors. Therefore, there are limitations in understanding and evaluating individual phenomena such as hydrogen release, jet flow, and diffusion. In this study, we aim to evaluate the hydrogen jet flow and hydrogen distribution characteristics using a simplified geometry that considers only the representative features of the APR1400 containment building.

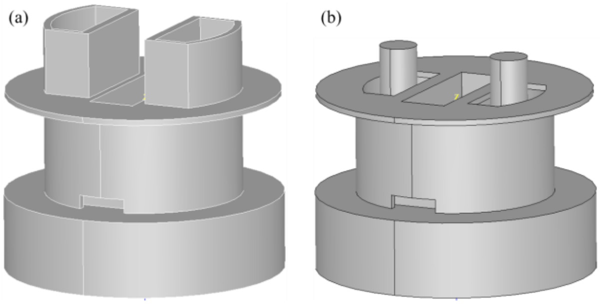

Fig. 5. Simplified APR1400 containment, (a) Model-1 with vertical walls of steam generator compartment, (b) Model-2 without vertical walls.

Fig. 5 shows simplified geometric models with the representative features of the APR1400 containment building. As shown in the figure, there is an IRWST outer wall at the bottom, and above it is a secondary shielding wall that separates the steam generator compartment and the annular compartment. The operating deck visible above the secondary shielding wall is in the form of a slab that separates the lower annular space from the upper space and allows air recirculation by a ventilation gap of 1 foot from the outer wall of the containment building. Above the operating deck is the upper outer wall of the steam generator compartment.

In the event of a high-pressure accident of the APR1400, hydrogen is released through the pressure relief valve installed at the top of the steam generator compartment, and in the event of a loss of coolant accident (LOCA), hydrogen is released through a fractured part. To simulate a typical loss of coolant accident, it can be assumed that a cold-leg pipe located at the bottom of the west (left in the figure) steam generator compartment is ruptured. Hydrogen is released as a jet through the steam generator compartment and into the upper dome. APR1400 has a vertical outer compartment wall on the upper part of the operating deck to protect the steam generator, and it is believed that this vertical bulkhead can affect the diffusion of hydrogen jets released through the steam generator compartment.

In this study, we aim to gain an understanding of hydrogen behavior in the APR1400 containment building by evaluating and comparing the hydrogen release rate and hydrogen distribution depending on the presence or absence of the upper outer wall of the steam generator.

To evaluate the jet flow and diffusion characteristics of hydrogen released from the bottom of the steam generator compartment for the simplified containment building, analysis was performed for four conditions as shown in Table 2. In all four cases, the total amount of hydrogen released was the same at 200 kg, and the release period was adjusted according to the mass flow rate of hydrogen to keep the total amount constant.

Table 2. Hydrogen release conditions

Case	H2 release time	H2 mass flow
Case-1	0 ~2000 s	0.1 kg/s
Case-2	0 ~1000 s	0.2 kg/s
Case-3	0 ~500 s	0.4 kg/s
Case-4	0 ~333 s	0.6 kg/s

First, an analysis was performed on the two simple containment models described above to evaluate the influence of the upper bulkhead of the steam generator compartment.

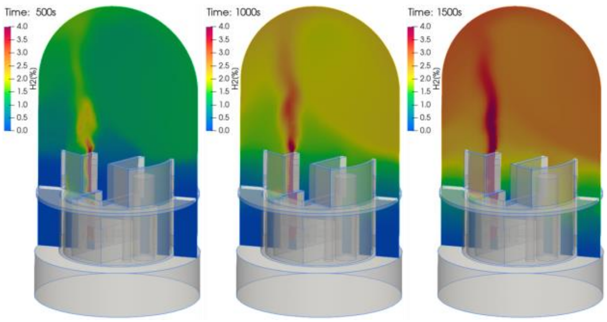

Fig. 6. Time-dependent hydrogen distributions of the case-1 for Model-1 containment with the vertical walls.

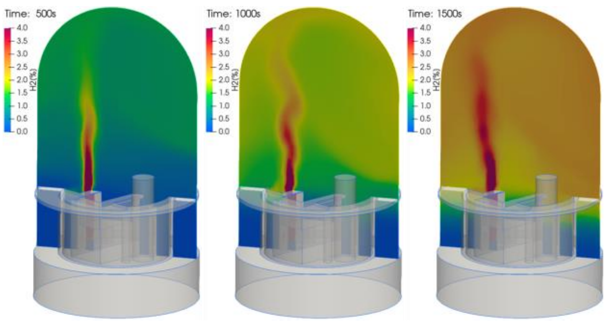

Fig. 7. Time-dependent hydrogen distributions of the case-1 for Model-2 containment without the vertical walls.

Figs. 6 and 7 are analysis results using hydrogen injection condition case-1 for containment building model-1 and model-2. Because the hydrogen concentration in the containment building was low except inside the steam generator compartment where hydrogen is released, the concentration distribution limit was limited to a maximum of 4 vol% to visualize the concentration distribution. In both cases, Model-1 and Model-2, the macroscopic flow structure of hydrogen released from the steam generator compartment is similar, but there is a difference in the space where hydrogen accumulates over time.

In the case of Model-1, which has a vertical bulkhead for the steam generator above the operating deck, the hydrogen cloud appears to have expanded to the end of the vertical bulkhead, but in Model-2, which does not have a bulkhead, the hydrogen cloud can be seen descending to the horizontal operating deck.

Hydrogen released from the bottom of the steam generator compartment moves upward along the vertical steam generator compartment in the form of a jet. As the vertical bulkhead ends, it moves upward in the form of free shear flow. The shear flow generates shear force due to the velocity gradient with the surrounding atmosphere, and an entrainment flow occurs as the shear force pulls upward the surrounding atmosphere. This shear flow of the hydrogen jet induces mixing or diffusion of momentum, temperature, and gas concentration with the surrounding atmosphere. In particular, because hydrogen has a low density, diffusion of momentum due to shear force and acceleration (increase in momentum) due to buoyancy occur simultaneously, and it moves to the upper dome in the form of a buoyant jet or plume.

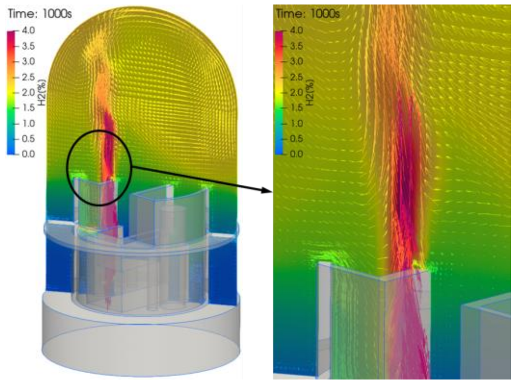

Fig. 8. Hydrogen stratification and gas velocity field at 1000s for Model-1 containment with the vertical walls.

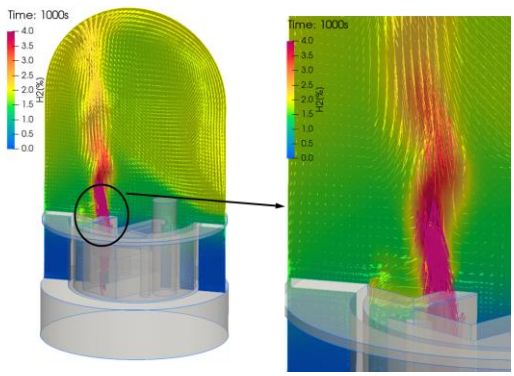

Fig. 9. Hydrogen stratification and gas velocity field at 1000s for Model-2 containment without the vertical walls.

Figs. 8 and 9 show the velocity fields of Model-1 and Model-2. As shown in the figures, the buoyant jet of hydrogen reaches the dome and moves radially along the dome ceiling and downward along the outer wall of the containment building. Ambient gas mixed with the hydrogen that comes down the outer wall of the containment building can be entrained by the shear force of the hydrogen jet. In Fig. 8, there are vertical walls of the steam generator compartment above the operating deck, and these walls appear to block gas from entering the hydrogen jet. Conversely, in Fig. 9, since there is no vertical partition wall of the steam generator compartment at the top of the operating deck, the process of air mixing at the elevation of the operating deck can be seen. In other words, the entrained flow induced by the hydrogen jet appears to play a major role in hydrogen mixing at the top of the containment building.

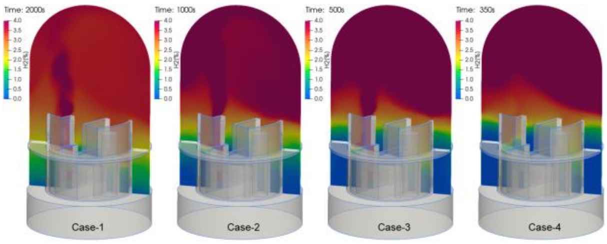

Fig. 10. Hydrogen distribution according to the hydrogen release rate of Model-1 containment with the vertical walls.

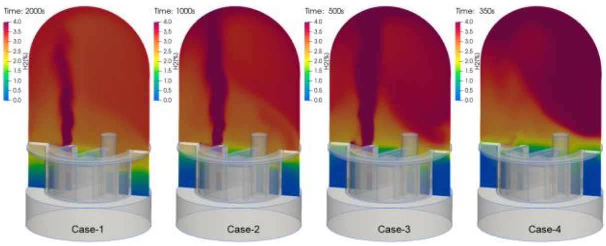

Fig. 11. Hydrogen distribution according to the hydrogen release rate of Model-2 containment without the vertical walls.

Figs. 10 and 11 compare the hydrogen distribution at the end of hydrogen release for the containment buildings Model-1 and Model-2 according to the hydrogen release rate. In both Model-1 and Model-2 cases, it appears that as the hydrogen injection rate increases, hydrogen clouds are formed more intensively in the dome area. In the case of Model-1, the entrainment flow generated by the hydrogen jet is limited by the vertical partition walls of the steam generator compartment, and the hydrogen cloud is stratified at the end of the partition walls, and this phenomenon becomes stronger as the hydrogen injection rate increases. Meanwhile, in the case of Model-2 (Fig. 11) which excludes the vertical walls of the steam generator compartment above the operating deck, it can be seen that the boundary of hydrogen stratification has expanded downward to the elevation of the operating deck. As described above, it is believed that the entrained flow induced by the shear force of the hydrogen jet enhanced the expansion of the hydrogen cloud as it descended to the operating deck elevation.

4. Conclusions

Hydrogen jet flow within a containment building is affected by the geometric characteristics of the containment building. Among the representative features of the APR1400 containment building are the operating deck and vertical bulkhead for the steam generator compartment. To evaluate the effect of containment building characteristics on hydrogen jet behavior, two types of simplified containment geometry models were created depending on the presence or absence of a vertical bulkhead for the steam generator above the operating deck, and the behavior of hydrogen jets was compared. The jet flow generates a shear force due to the velocity difference with the surrounding atmosphere, and this shear force generates an entrainment flow that pulls the atmosphere from the surroundings toward the jet.

In an open space, a jet flow can entrain a gas far away from the center of the jet, but in a closed space such as a containment building, the entrainment of the gas surrounding the jet is restricted. The jet flow that reaches the upper part of the compartment and recirculates has an increased correlation with entrainment flow.

This recirculating flow can affect the diffusion of hydrogen within the containment building and, in particular, can have a significant impact on hydrogen stratification. In the analysis results depending on the presence or absence of the steam generator vertical partition walls, it was confirmed that such a recirculating flow occurs and that this affects hydrogen stratification.

ACKNOWLEDGMENTS

This work was supported by the Korea Foundation of Nuclear Safety (KOFONS) (No. 2106007).

REFERENCES

[1] C.K. Chan, S.C. Jones, “Gas Mixing Experiments in a Large Enclosure”, 18th Annual Conference of the Canadian Nuclear Society, 1997.

[2] J. Kim, et al., Validation of Condensation Modeling for Containment Thermal Hydraulic Analysis, KAERI/TR-9997/2023, 2023.

[3] Open-source CFD platform OpenFOAM, http://www.openfoam.org, 2024

[4] M. Andreani, B. Smith, “On the Use of the Standard k-ε Turbulence Model in GOTHIC to Simulate Buoyant Flows with Light Gases”, The 10th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-10), Seoul, Korea, October 5-9, 2003.