STEAM CONDENSATION EFFECT IN HYDROGEN VENTING FROM A BWR REACTOR BUILDING

Kondo, M.[1]**, Erkan, N.**[1] **and Okamoto, K.**[1]
[1] **Nuclear Professional School, The Graduate School of Engineering, The University of Tokyo,**
2-22, Shirakata, Shirane, Tokai, Naka, Ibaraki, 319-1188, Japan
kondo@vis.t.u-tokyo.ac.jp, erkan@vis.t.u-tokyo.ac.jp, okamoto@n.t.u-tokyo.ac.jp

ABSTRACT

In the accident of Fukushima Daiichi nuclear power plants, hydrogen was accumulated in the reactor buildings and exploded. To prevent such explosions, hydrogen venting from reactor buildings is considered. When the gas mixture is released to a reactor building through a reactor containment, together with the hydrogen some amount of steam might also be released. The steam condenses if the building atmosphere is below the saturation temperature, and it affects the hydrogen behavior. In this study, the condensation effect to the hydrogen venting is evaluated using CFD analyses, by comparing the case where a hydrogen-nitrogen mixture is released and the case where a hydrogen-steam mixture is released.

1.0 INTRODUCTION

In Fukushima Daiichi nuclear power plants, hydrogen was accumulated in the reactor building and exploded. The explosion effected the following accident management procedures. It revealed that hydrogen could flow into the operating floor, which is the top floor of the reactor building, during the accident. To prevent hydrogen accumulation and explosion in BWR buildings, hydrogen venting was considered in Japan. The effectiveness of the venting was evaluated using a computational fluid dynamics (CFD) code [1,2]. However the CFD calculations needed high computational costs and took long time. On the other hand, a lumped parameter (LP) model was proposed [3] and used along with CFD calculations. In the LP model, it is assumed that the distribution of the temperature and gas concentration are uniform in the operating floor, but its prediction agreed well with the CFD calculations. Since the LP model needs much shorter time to evaluate one case, because of its lower computational costs, the basic property of the phenomena with respect to the hydrogen venting was studied through some sensitivity analysis [4].

However, both the CFD calculations and the LP evaluations did not take steam condensation into account. Since the water in reactor core may evaporate and flow out of the reactor pressure vessel to the reactor containment during the course of severe accident, the steam may come into the operating floor together with the hydrogen, and it may condense when it touches the relatively cold building walls. When the steam condenses on the walls, the concentration of non-condensable gases like hydrogen may increase because they are left in the air. Therefore the steam condensation has to be considered. To evaluate such steam condensation effect to the hydrogen venting, the situation where hydrogen and steam simultaneously flow into the operating floor is to be considered.

In a BWR building, steam can also be generated from the spent fuel pool (SFP) located in the operating floor. When the SFP cooling stops, effect of generated steam to the building atmosphere is not negligible. It may rise the temperature in the building. Therefore, the atmosphere in a BWR building without SFP cooling was evaluated using a CFD and LP model [5]. However the evaluation treated only the mixture of the steam and the air.

In this study, the steam condensation effect to the hydrogen venting is evaluated using CFD calculations. The case where a hydrogen-steam mixture flows into the building is compared with the case where a hydrogen-nitrogen mixture flows into the building. To shorten the time needed for the evaluations, a LP model is developed and its results are compared to those of the CFD calculations.

2.0 COMPUTATIONAL FLUID DYNAMICS CALCULATION

2.1 Calculation Conditions

In this study, STAR-CCM+ ver.8.02 was adopted as a CFD tool. Calculation geometry is shown in Figure 1. The operating floor of the BWR building and part of the outside space near the venting window was calculated. Pressure boundary was adopted for the surrounding faces of the outside space. The pressure for the boundary was given using barometric formula [6] as

$$P_{downwind}(z) = P_0 \exp\left(-\frac{Mg}{RT} z\right) , \qquad (1)$$

where z, P_0, M, g, R and T are elevation from the floor, atmospheric pressure at z=0, average molecular weight of the air, gravity, gas constant and temperature of the air outside the building, respectively.

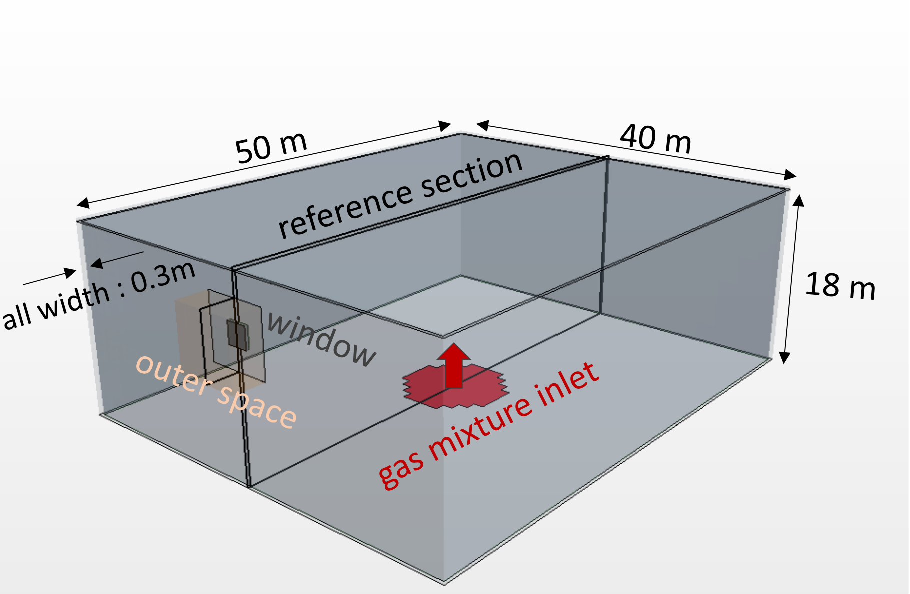


Figure 1 calculation geometry

Gas mixture including hydrogen flowed into the building through the velocity inlet boundary whose diameter was about 10 m. The size of the venting window was set 2 x 2 m, assuming a relatively small blow-out panel. The adopted calculation model and parameters are shown in Table 1. Transient calculation was conducted for the phenomenon of 24 hours after the hydrogen started to flow into the operating floor. To calculate the condensation on the wall, the fluid film model which enables the condensation calculation was adopted. The property of concrete was used to calculate heat conduction in the building wall.

Table 1 calculation models and parameters

Items		Settings
Time & Space	time integration	implicit unsteady
	time step width	1.0sec
	inner iteration	10 times
	dimension	3
	gravity	9.81 m/s2

Gas space	working fluid	multi-component gas
	gas species	H_2, O_2, H_2O, N_2
	equation of state	ideal gas equation
	turbulent model	realizable k-epsilon
	turbulent Prandtl number	0.9
	turbulent Schmidt number	0.9
	mass diffusivity	Schmidt number = 1.0
	molecular weight	volume weighted average
	specific heat	mass weighted average
	thermal conductivity	volume weighted average
Fluid film	working fluid	water
	equation of state	constant density
	latent heat	2.5×10^6 J/kg
	saturation pressure	Antoine equation
	density	997.561 kg/m3
	specific heat	4181.72 J/kgK
	thermal conductivity	0.620271 W/mK
Wall	material	concrete
	density	2240 kg/m3
	specific heat	750 J/kgK
	thermal conductivity	0.53 W/mK
	heat transfer coefficient outside	4.0 W/m2K

The mesh configuration for the calculation is shown in Figure 2. Hexahedron mesh was adopted. The mesh size in the gas space of the operating floor was basically 1 m, but for the space near the window, finer mesh was used. The layer mesh having a thickness of 0.05 m was adopted along the building wall, and the mesh thickness in the wall was also set to 0.05 m.

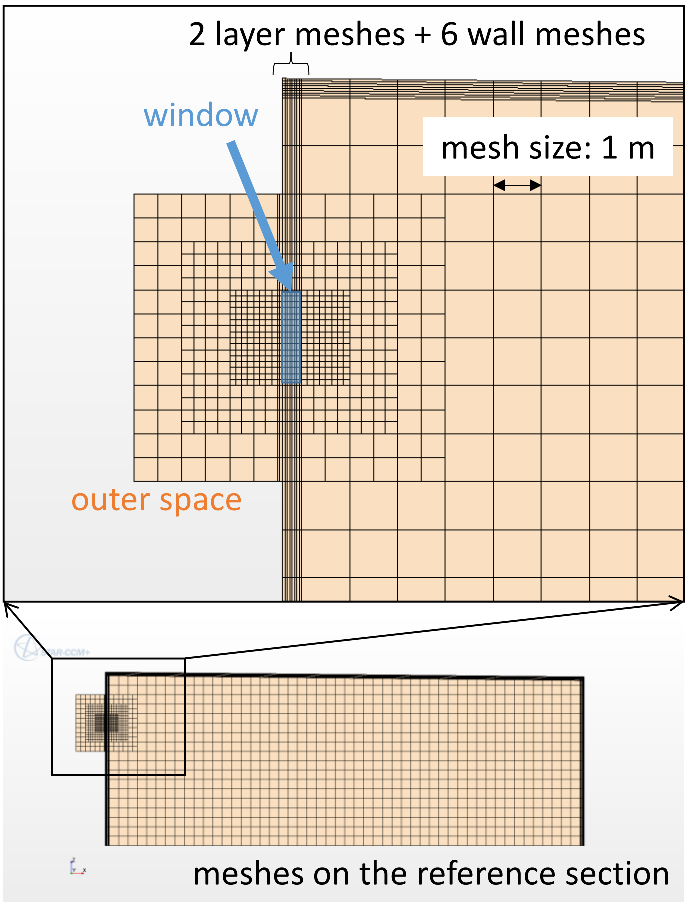


Figure 2 Mesh configuration for the calculation

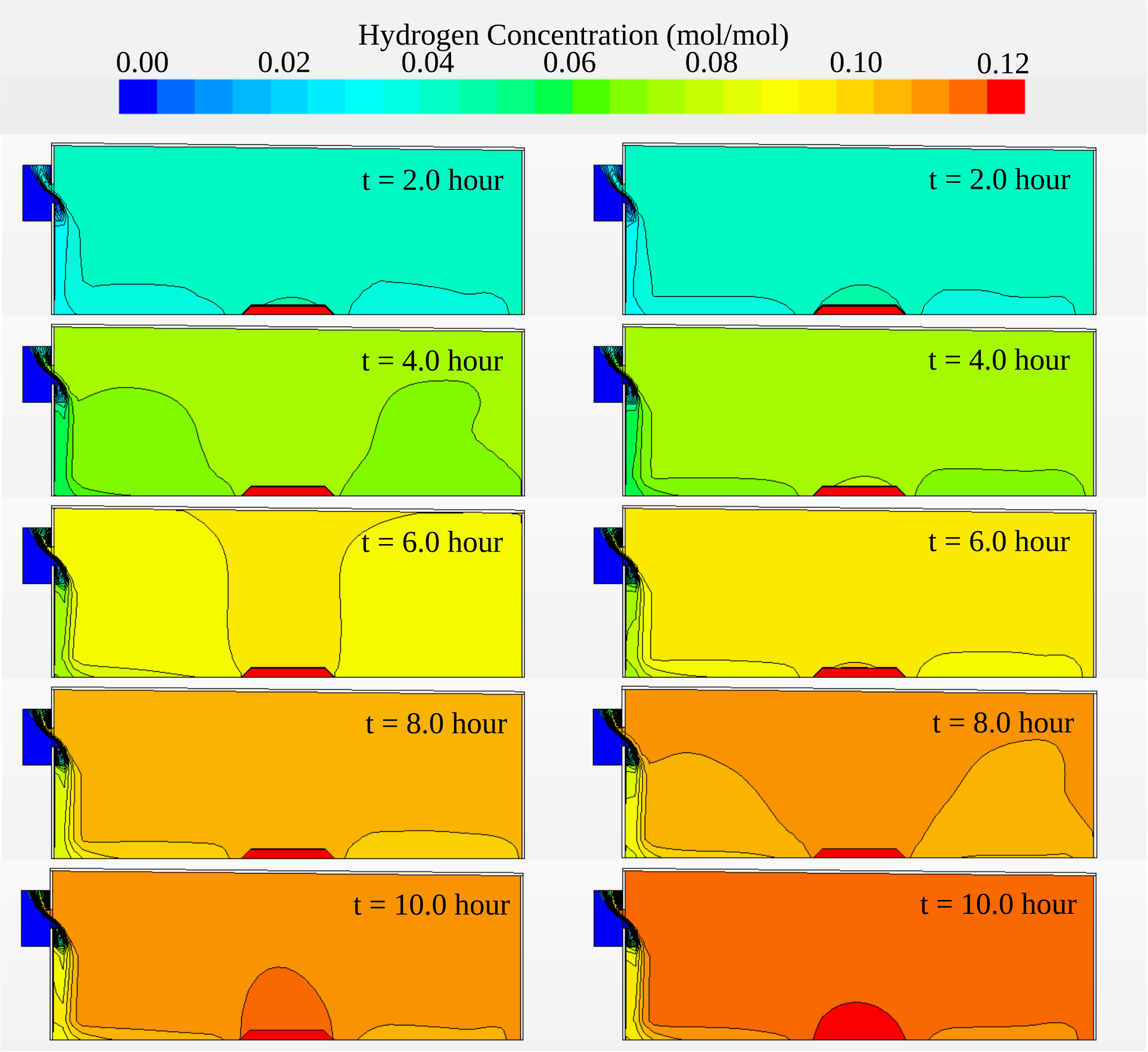
The case matrix is shown in Table 2. The temperature and the volume fractions of the air in the outside space were set 303K and O_2:N_2=0.21:0.79, respectively. The temperature of the inlet gas mixture was 573 K and the volume fractions were H_2:H_2O =0.5:0.5. The volumetric flow rate of the gas mixture was 0.72m^3/s, which was estimated with the assumption that 1600 kg hydrogen gas flowed into the building in 24 hours. For comparison, the case in which a hydrogen-nitrogen mixture was released instead of hydrogen-steam mixture was also calculated. The inlet conditions were set the same as the hydrogen-steam case, except for the inlet gas composition, which was H_2:N_2=0.5:0.5.

Table 2 case matrix for the calculations

items		**hydrogen-steam case**	**hydrogen-nitrogen case**
environmental condition	pressure	101325 Pa	101325 Pa
	temperature	30 C	30 C
	gas composition	N_2:O_2=0.79:0.21	N_2:O_2=0.79:0.21
Initial condition	pressure	101325 Pa	101325 Pa
	temperature	30 C	30 C
	gas composition	N_2:O_2=0.79:0.21	N_2:O_2=0.79:0.21
Inflow condition	temperature	200 C	200 C
	gas composition	**H_2:H_2O=0.5:0.5**	**H_2:N_2=0.5:0.5**
	volumetric flow rate	0.72 m3/s	0.72 m3/s
opening condition	width	2 m	2 m
	height	2 m	2 m

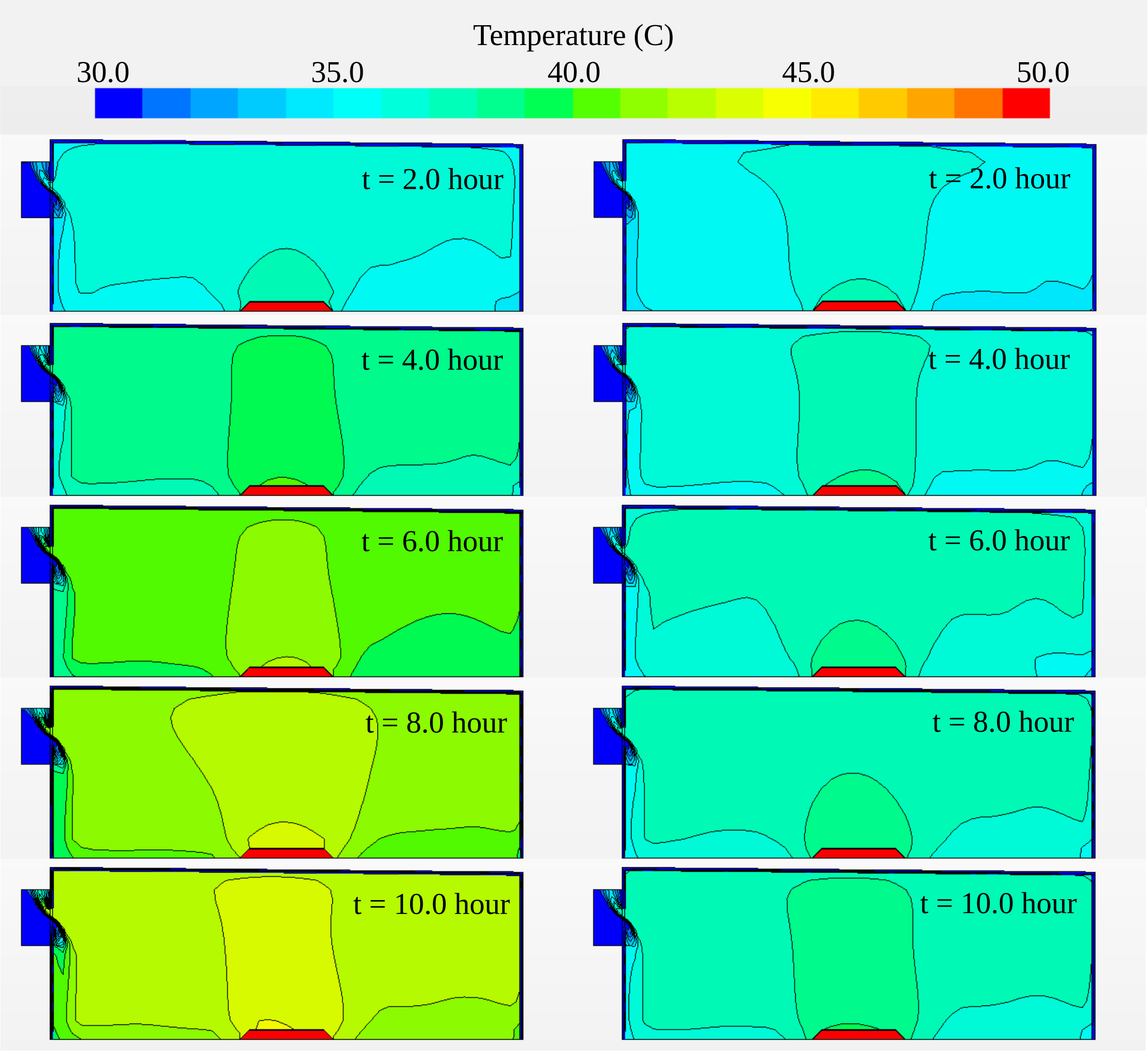
2.2 Calculation Results

The distributions of the hydrogen concentration in the hydrogen-steam case and the hydrogen-nitrogen case are shown in Figure 3. The hydrogen concentration distributions showed almost no difference. It indicates that the existence of the steam did not affect the hydrogen behaviour in the case of this study. However, the temperature distributions in both cases differed, which are shown in Figure 4. The temperature in the case with steam was higher. It is because the wall was heated by the condensation heat, and temperature rise of the wall resulted in the higher temperature of the gas mixture in the building. The history of volume averaged hydrogen concentration is shown in Figure 5. In both cases, the hydrogen concentration monotonically increased and approached the steady-state values. The hydrogen concentration in hydrogen-steam case was slightly lower although it is considered that hydrogen was left in the air when vapour condenses. It is because the temperature rise due to condensation heat got dominant in this case. The volume averaged temperature is compared in Figure 6. It shows more temperature rise in hydrogen-steam case and it enhanced the venting and intake through the window as shown in Figure 7. This is why the hydrogen concentration was lower in hydrogen steam case.



(a) hydrogen-steam case (b) hydrogen-nitrogen case

Figure 3 Distribution of hydrogen concentration



(a) hydrogen-steam case (b) hydrogen-nitrogen case

Figure 4 temperature distribution

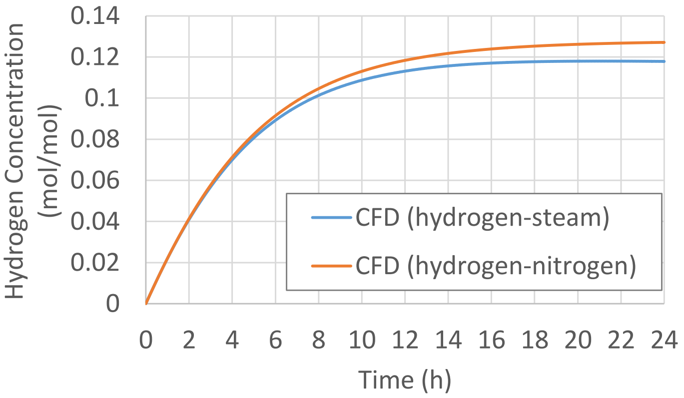


Figure 5 history of volume averaged hydrogen concentration

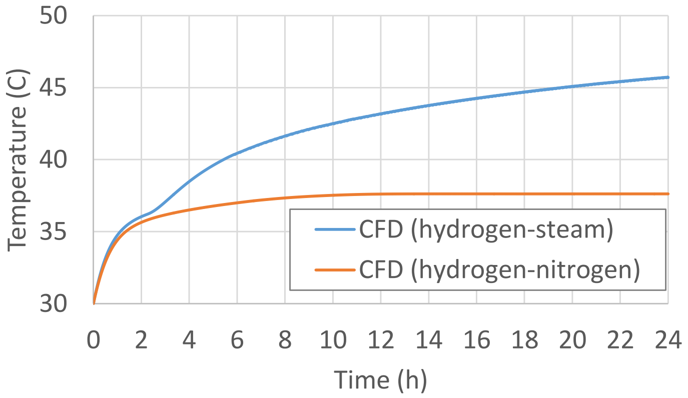


Figure 6 history of volume averaged temperature

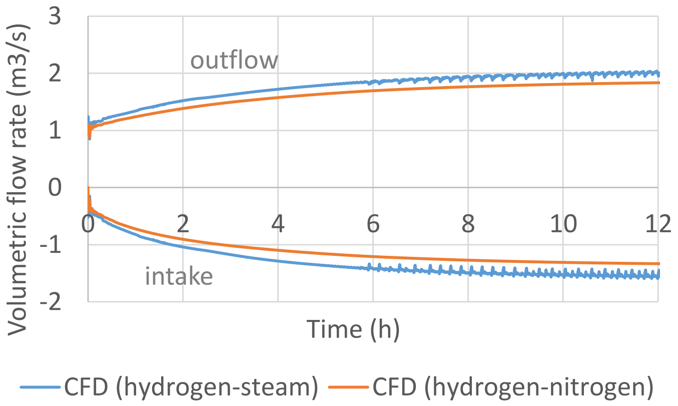


Figure 7 history of volumetric flow rate of intake and outflow

3.0 LUMPED PARAMETER EVALUATION

3.1 Evaluation Conditions

The schematics of the newly developed lumped parameter model is shown in Figure 8. In the lumped parameter model, the distribution of the gas composition and temperature were assumed to be uniform. The trend of the hydrogen concentration and temperature were evaluated using the model, where inflow and outflow were predicted based on the pressure difference inside and outside the building. In the model, steam condensation on the building wall was considered using Stephan's law [7]. Heat conduction in the wall and convection heat transfer to the outside were also considered. To estimate the inflow and outflow through the window, the equation similar to the correlation proposed by Epstein [8] was used. The velocity distribution at the window shown in Figure 9 was predicted based on Bernoulli's equation as

$$u_{in}(z) = -\sqrt{\frac{|2\Delta P(z)|}{\xi \rho_{air}}} \quad (\Delta P(z) < 0) \qquad (2)$$

and

$$u_{out}(z) = \sqrt{\frac{|2\Delta P(z)|}{\xi\rho}} \quad (\Delta P(z) > 0)\,, \tag{3}$$

where z, $u(z)$, $\Delta P(z)$, ρ, ρ_{air} and ξ are elevation, vertical velocity distribution, pressure difference between outside and inside the building, density of the gas mixture inside the building, density of the air outside, and pressure loss coefficient, respectively. In this study, ξ=2.7 was adopted for the pressure loss coefficient. It was a coefficient for a small hole in a large pipe [9]. The volumetric flow rate of inflow and outflow was estimated by integrating the distribution as

$$Q_{in} = -\int_{z_{in\_l}}^{z_{in\_h}} w u_{in}(z) dz \tag{4}$$

and

$$Q_{out} = \int_{z_{out\_l}}^{z_{out\_h}} w u_{out}(z) dz\,, \tag{5}$$

where w is the width of the window. The evaluation conditions were set the same as the hydrogen-steam case shown in Table 2, and the results were compared to those of CFD.

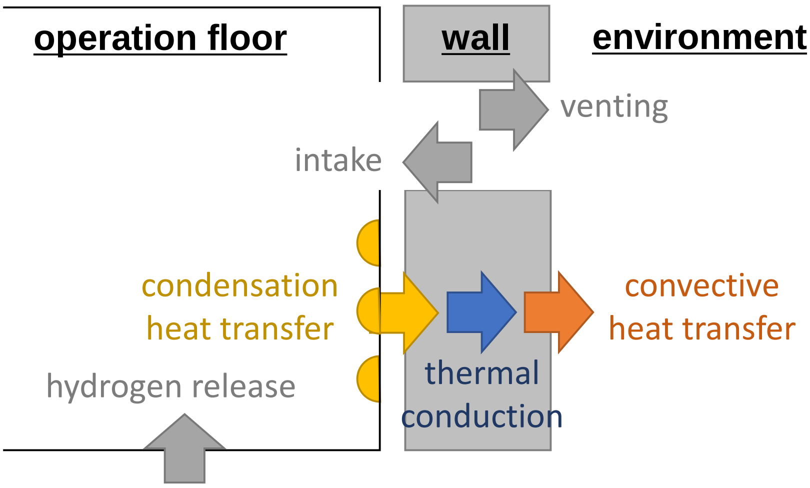


Figure 8 nodalization in lumped parameter model

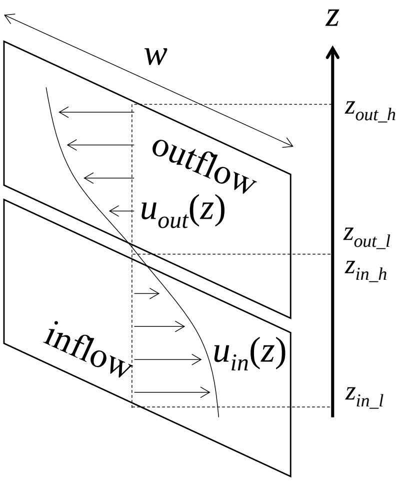


Figure 9 vertical velocity distribution at the window

3.2 Comparison between CFD and LP

More hydrogen was accumulated in the LP calculation than in CFD calculation, but their difference was small (Figure 10). This deviation may be improved by adjusting the pressure loss coefficient used in LP evaluation. However in this study, the coefficient was conservatively set using the value for a small hole in a large pipe [9], so the hydrogen concentration in the LP evaluation is higher. The steam concentration histories were almost the same in both evaluation (Figure 11). Temperature was higher in CFD results before the beginning of the condensation, which is around t = 2 hours, but agreed well after that time (Figure 12). The time needed for the evaluations were 754947 seconds for CFD calculation, and 11 seconds for LP evaluation, respectively. Therefore the LP model could predict the similar trends much faster than the CFD calculation.

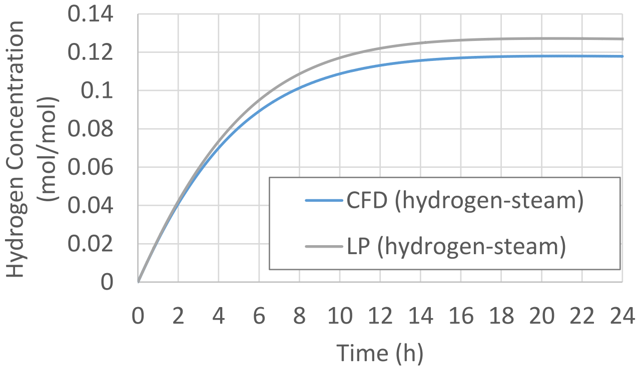


Figure 10 comparison of hydrogen concentration history between CFD and LP

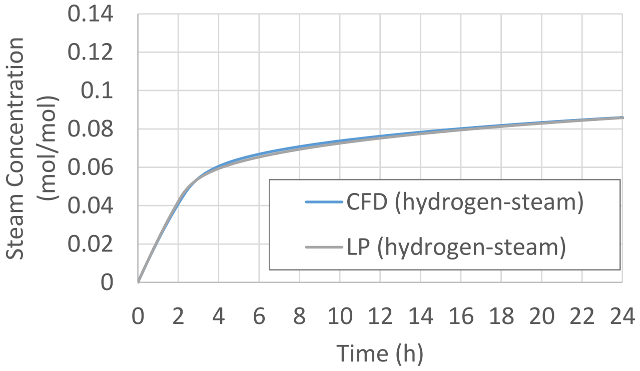


Figure 11 comparison of steam concentration history between CFD and LP

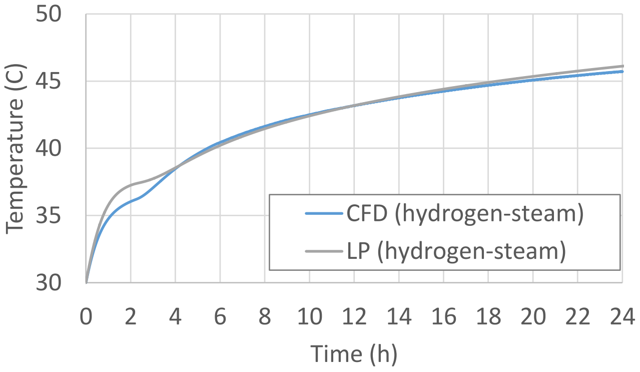


Figure 12 comparison of temperature history between CFD and LP

4.0 CONCLUSION

In this study, the steam condensation effect to the hydrogen venting is evaluated using CFD calculations. The case where hydrogen-steam mixture flows into the building are compared to the case where hydrogen-nitrogen mixture flows into the building. The hydrogen concentration was lower in the hydrogen-steam case than in the hydrogen-nitrogen case. It is because the hydrogen venting through the window was enhanced by the temperature rise due to condensation heat.

A LP model is also tested and its results are compared to those of the CFD calculation. The results of the LP model and the CFD calculation agreed for the most part, and the time needed for the evaluation was much shorter using the LP model.

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