THE EFFECT OF NATURAL VENTILATION THROUGH ROOF VENTS FOLLOWING HYDROGEN LEAKS IN CONFINED SPACES

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ABSTRACT

Hydrogen energy is gaining global popularity as a green energy source, and its use is increasing. However, hydrogen has a rapid diffusion rate and a broad combustion range; thus, it is vital to take safety precautions during its storage. In this study, we examined the change of hydrogen concentration in a confined space exposed to a hydrogen leak according to the size of the leakage hole and the leakage flow rate, assuming an extreme situation. In addition, we investigated rectangular vents (that serve as explosion panels in the event of an explosion) to assess their ventilation performance according to the area of the vent when used for emergency natural ventilation. The vent areas tested represented 12%, 24%, and 36% of the floor area, and they were installed in the ceiling of the test enclosure. When exposed to a simulated hydrogen leak, the enclosure acquired a hydrogen concentration of 1%, which is 25% of the lower flammability limit (LFL), in less than 6 s across all test cases. The time to LFL varied from approximately 4–81 s. In an assessment of the emergency ventilation duration, the ventilation time required to reach safe hydrogen concentrations decreased and showed less deviation as the vent size was increased. For the largest vent size tested, the LFL was reached in <1 min; it took 145.6 s to acquire a 1 vol% of hydrogen, which is relatively fast. However, there were no significant differences between the performance of large and medium-sized vent areas. Therefore, through the results, we found that it is reasonable to apply the area Kv = 3.31 (24% of the floor area) or less when considering the design of a roof vent that can serve as both an emergency ventilation and an explosion vent. This suggests that it is difficult to expect an improvement in ventilation performance by simply increasing the area of the vent beyond a certain area. Through these results, this study proposes a practical and novel method for future design and parameters of safety functions that protect areas where hydrogen is present.

1.0 INTRODUCTION

As the world is moving toward carbon neutrality to reduce greenhouse gas emissions, the use of hydrogen energy is gaining attention as a new eco-friendly energy source to replace fossil fuels, and its global use is gradually increasing. As a result, hydrogen energy technology is rapidly developing and related industries are being revitalized. However, since hydrogen is highly flammable and pose an explosion hazard, it is necessary to consider any factors that hinder the safe use of hydrogen energy along with guidelines promoting the successful development of the hydrogen economy [1]. Hydrogen gas has a wide combustion range at concentrations of approximately 4% to 75% in the air. Its density at standard state conditions is about 14 times lower than that of air, and it is highly flammable with a flame propagation speed around 8 times that of conventional methane in an explosion. It is also the lightest substance with atomic number 1, so it disperses quickly in the event of an accidental leak and burns easily in the presence of an ignition source. Because of these dangerous properties, many scholars are interested in evaluating the risk of hydrogen fires and explosions. For example, Park et al. [2] examined the risks of compressed hydrogen release, jet fire, and heat flux using HyRAM software, assuming a hydrogen refueling station accident. They compared the modeled results with experimental data and compiled F–N curves and safety distances, to be used for risk assessments in planning hydrogen refueling station installations in urban areas. In another study, the authors combined LOPA and RISKCURVES software to identify the risk that hydrogen refueling stations pose in urban areas and to assess how to minimize damage in the event of a jet fire or explosion caused by gas leakage [3].

However, in order for hydrogen-related fires and explosions to occur, hydrogen leakage must precede and accumulate an appropriate concentration. In this process, fundamental safety designs must incorporate the prevention of hydrogen gas buildup leading to an explosive atmosphere if accidents are to be avoided [4]. Over the past few years, there has been plentiful research investigating the hazards posed by hydrogen and the role of ventilation in hydrogen leak accident. Since it is not feasible to conduct empirical experiments with hydrogen, due to safety and cost issues, many studies use computational fluid dynamic (CFD) simulations or helium gas. Yassine et al. [5] studied hydrogen behavior in relation to the shape and height of explosion vents in the event of a leak inside a residential garage through CFD simulation. The results highlighted the importance of vent geometry, with rectangular and square shapes being more effective than round and triangular shapes. They further reported that the closer the vent is located to the ceiling, the more effectively it prevents hydrogen buildup.

Lee et al. [6] conducted a CFD simulation of the hydrogen pressure regulation in Ulsan Hydrogen Town in South Korea to investigate small-scale leakage scenarios. They suggested an appropriate vent location configuration and compared the ventilation capacity by vent size relative to floor area. In addition, a hydrogen leakage management strategy was proposed using forced-nitrogen purging. Barley et al. [7] investigated the relationship between leakage rate, vent design, and hydrogen concentration through laboratory tests and CFD modeling. Their set-up consisted of two vents, a lower and an upper one, and the degree of ventilation was measured with the opening of vents. Experimental results were compared to computational data to validate the model. Matsuura [8] also used CFD simulations to study hydrogen dispersion and accumulation in a semi-confined space with natural and forced ventilation. Various combinations of roof vents and door vents were considered by changing their size and location, and their effectiveness was compared with that of natural and forced ventilation. Ji et al. [9] investigated hydrogen leakage and diffusion characteristics by installing a 1.8 m × 2.2 m × 2.9 m dedicated room with 0.12 m^3 of vents on three sides of the room and ventilation fans on the remaining side. hydrogen concentrations were measured as the vent, ventilation fans, and supply shut-off valves operated. In addition, Xie et al. [10] compared the effectiveness of different ventilation fan geometries on hydrogen leakage in a garage with vehicles through CFD simulations.

The aforementioned studies confirmed that hydrogen behavior and ventilation performance vary, depending on the location and shape of the vent when a hydrogen leak occurs. In addition, these studies analyzed the ventilation effect in scenarios where natural ventilation is always present, with variables comprising only vent shape and location and the presence or absence of forced ventilation. However, it is equally important to consider the possibility of mechanical defects in the safety measures that have been set in advance. From a safety perspective, the installation of appropriate protective devices and buffers in any system is essential to reduce the likelihood of an accident occurring or to reduce the damage caused by one [11]. James Reason's Swiss cheese model describes deficiencies in safeguards as the cause of accidents by analogizing them to a randomly punctured cheese, as shown in Fig. 1. In these terms, accidents occur when the deficiencies in safeguards happen to fall in a straight line. This analogy applies equally well to the process of mitigating damage after an accident has occurred and is compounded to produce results [12,13]. In the end, no single safeguard can completely prevent an accident, so safeguards should be layered extensively to reduce accident risk. Indeed, it is common for natural and forced ventilation systems to develop defects and fail to provide adequate ventilation. Due to the low minimum ignition energy of hydrogen (mixed with air) (approximately 0.019 mJ), any ventilation method that has the potential to release electrical energy, such as forced ventilation with fans, could result in an explosion [6,14].

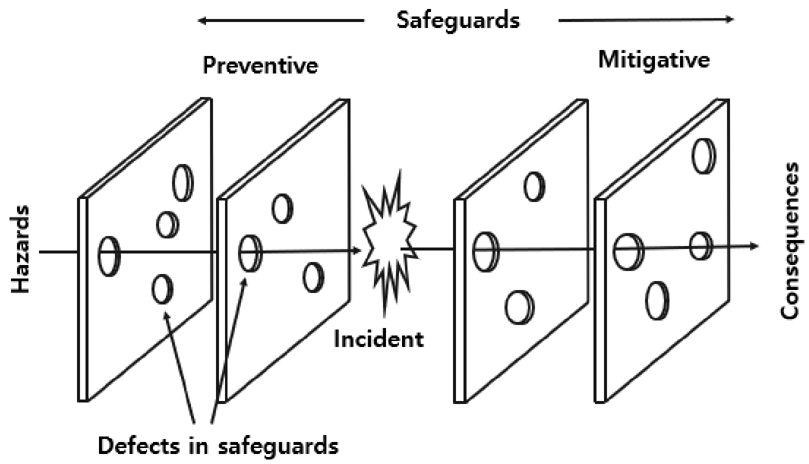


Figure 1. The Swiss cheese model, illustrating how multiple defects in safeguards can lead to major accidents [15]

Studies so far have been made to design so that the concentration of hydrogen does not exceed the allowable value in the event of hydrogen leakage through continuous ventilation. But, as described above, consideration should be given to contingency plans to safely eliminate leaks in situations where ventilation is restricted(Failure of ventilation system, etc.) and concentrations have already built up. This study aims to experimentally investigate the ventilation effectiveness using natural ventilation by opening a vent that can serve as an explosion panel in the event of an emergency situation; a scenario is assumed in which a hydrogen leak occurs (duet for example, irreversible damage to a storage container) that results in an accumulating hydrogen concentration. This suggests proposed a practical and novel method for future design and parameters of safety functions that protect hydrogen facility areas with an upper explosion vent applied in a confined space composed of high-pressure facilities.

2. HYDROGEN LEAK TEST

The goal of this experiment was to determine the extent to which an internal hydrogen concentration could reach below a reference value in the event of a hydrogen leak in a confined space that is mitigated via deployment of an upper natural vent. The experimental variables comprised the variation of the leakage flow rate, as adjusted by varying the leakage pressure and the size of the leakage hole, and a variation in the aperture of the vent.

The experimental setup consisted of a 4.2 × 2.8 × 2.8 m rectangular concrete structure with an internal volume of 20.3 m^3 (Fig. 2). The hydrogen supply system possessed a flow rate range of 2,000–5,000 slm, a power supply of +15 VDC to +24 VDC, an operating temperature of 5–50˚C, and a hydrogen concentration sensor (2 V/175 mA), with the details listed in Table 1. A total of six hydrogen concentration sensors were installed to measure the gas concentration at the top, middle, and bottom of the system. The locations of these sensors are shown in Table 2.

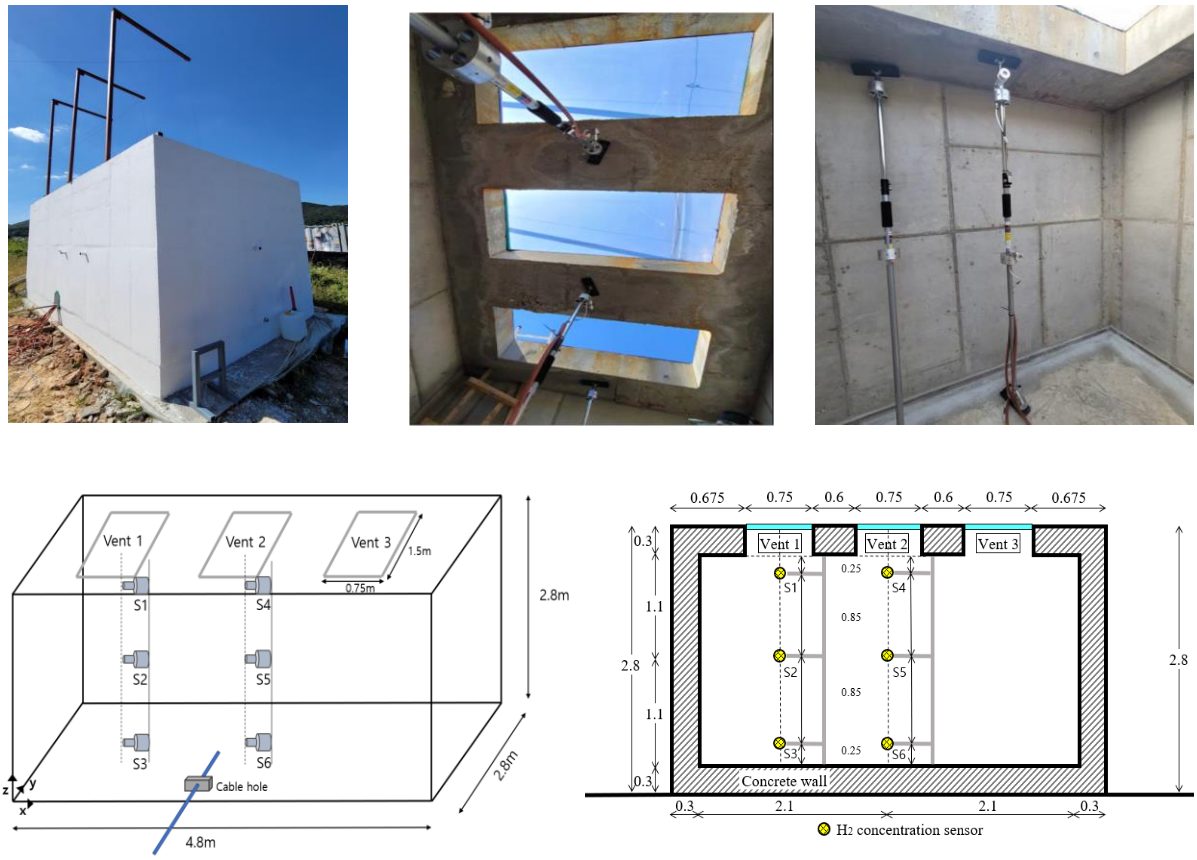


Figure 2. Photographs and schematics of the experimental setup

Table 1. Specifications of the experimental setup

Equipment	**Characteristics**
Hydrogen supply system (microbial fuel cell)	-Company: MKP, Hwaseong, South Korea -Model: TSM-D260 -Flow rate: 2,000~5,000slm -Working pressure: 8barg
Hydrogen concentration sensor	-Company: SGX Sensortech, Katowice, Poland -Model: VQ600

Table 2. The locations of six hydrogen concentration sensors (S1–S6) along three dimensions (X, Y, and Z) within a 4.2 × 2.8 × 2.8 m rectangular concrete structure

	X (m)	Y (m)	Z (m)
S1	1.05	1.4	1.95
S2	1.05	1.4	1.1
S3	1.05	1.4	0.25
S4	2.4	1.4	1.95
S5	2.4	1.4	1.1
S6	2.4	1.4	0.25

The average temperature on the day of the experiment was 23.5 °C and the average wind speed was 1.6 m/s. Three 0.75 × 1.5 m vents for natural ventilation were installed on the top of the concrete structure, which corresponding to the required minimum vent area (A_{v0} = 1.1 m^2) as presented in Eq. (1) of NFPA 68(2013).

$$A_{v0} = A_s \frac{\left[1-\left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma b}\right]}{\left[\left(\frac{P_{red}+1}{P_{max}+1}\right)^{1/\gamma b}-\delta\right]} \frac{S_u \rho_u}{G_u} \frac{\lambda}{C_d} \tag{1}$$

where A_{v0} is the vent area calculated in m^2, A_s is the enclosure internal surface area in m^2, P_{red} is the maximum pressure developed in a vented enclosure during a vented deflagration in bar-g, S_u is the fundamental burning velocity of gas-air mixture in m/s, ρ_u is the mass density of unburned gas-air mixture in kg/m^3, λ is the ratio of gas-air mixture burning velocity, G_u is the unburned gas-air mixture sonic flow mass flux in kg/m^2-s, C_d is the vent flow discharge coefficient, P_{max} is the maximum pressure in bar-g, and γb is the ratio of enclosure pressure prior to ignition in bar-g. The internal space was completely sealed off until the hydrogen reached the target concentration. The aperture of each vent comprised 12% of the floor area, and the experiment was conducted by varying the diameter of the leakage hole and the number of vent openings used. The set-up for nine cases we investigated is summarized in Table 3.

Table 3. Cases for nine scenarios investigated in our experiment

	Size of leakage hole (inches)	Vents in the open position	Total vent area (m^2)	Vent area as a ratio of the floor area (%)	Leak flow rate (L/min)
Case 1	1/2	Central only	1.125	12	600
Case 2		Both sides	2.25	24	
Case 3		All	3.375	36	
Case 4	1/4	Central only	1.125	12	200
Case 5		Both sides	2.25	24	
Case 6		All	3.375	36	
Case 7	3/8	Central only	1.125	12	400
Case 8		Both sides	2.25	24	
Case 9		All	3.375	36	

3. EXPERIMENTAL RESULTS

3.1 Leak characteristics of hydrogen

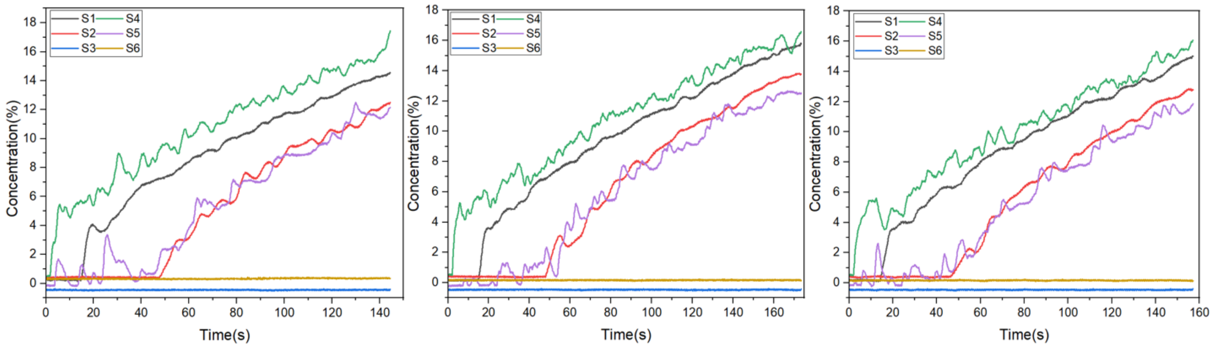
The diffusion characteristics inside the confined space were analyzed as a function of the inlet diameter to investigate the leakage characteristics of hydrogen. The flammable range of hydrogen is generally known to be 4–75 vol% [11], and keeping the concentration safely below the flammable range is an effective way to prevent explosions. NFPA 86 specifies that flammable vapor concentrations should be limited to within 25% of the lower flammability limit (LFL). Hydrogen ignites at 10 vol% or less, at which it exhibits no explosive pressure but rapid diffusion; at 20 vol% or more, a powerful explosion with dangerous pressures occur [16]. Therefore, the hydrogen concentrations acquired via leakage in this experiment were set to 1 vol% (25% of LFL), 4 vol% (LFL), 8 vol%, and 15 vol%.

The changes in hydrogen concentration obtained from each of the six sensors are shown in Fig. 3. Figure 3a–i correspond with Cases 1–9, respectively. For the subsonic release of hydrogen, a clear stratification is observed from the upper part of the confined space [17]. Thus, the central top sensor (S4) reached the target concentration the fastest in every case, forming an explosive atmosphere. The current design of gas and dust explosion mitigation systems assumes that the combustible mixture inside an enclosure displays a uniform concentration gradient; however, in practice, stratification and concentration gradients occur, and resulting explosions can be more dangerous [18]. Therefore, the time to reach the target hydrogen concentration at S4, which represented the starting point for an accident, was measured (Table 4). The hydrogen concentration of 1% (25% of LFL) was reached in less than 6 s in all cases. The theoretically combustible concentration of 4% was reached on average in 4.4 s for Cases 1–3, 81.4 s for Cases 4–6, and 21.3 s for Cases 7–9. To reach a hydrogen concentration of 8% (which is close to the concentration where flame start to spread rapidly), the average time was 40.6 s for Cases 1–3, 326.6 s for Cases 4–6, and 88.7 s for Cases 7–9. Lastly, the average time to reach a 15% hydrogen concentration (the most dangerous concentration used in the experiment, which involves dangerous pressures) was 136.6 s for Cases 1–3, 829.3 s for Cases 4–6, and 264.2 s for Cases 7–9. The time to reach concentrations of 4% to 15% varied significantly, depending on the size of the leakage hole.

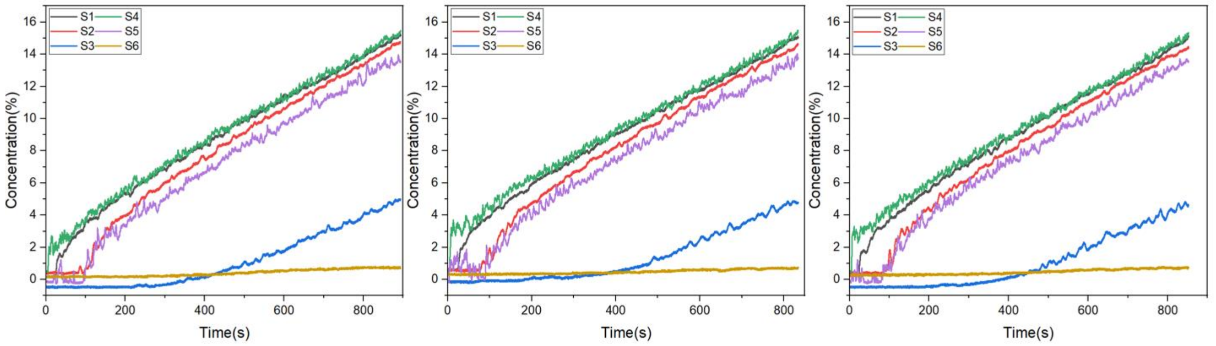
Figure 3. Sensor concentration in Cases 1–9, corresponding with (a)–(i), in the event of a leak

	1/2 Inch				**1/4 Inch**				**3/8 Inch**			
	Case 1	**Case 2**	**Case 3**	**Avg**	**Case 4**	**Case 5**	**Case 6**	**Avg**	**Case 7**	**Case 8**	**Case 9**	**Avg**
1%	1.9	2.05	2.1	2.0	5.9	4.9	5.1	5.3	4.4	5	6.2	5.2
4%	4.4	3.7	5.25	4.4	105	71.2	68.2	81.4	27.6	23.8	12.4	21.3
8%	29.3	48.4	44.2	40.6	363.8	304	312	326.6	87.6	86.2	92.4	88.7
15%	127	144.5	138.4	136.6	851.6	811.2	825	829.3	259.2	265.7	267.6	264.2

1/2 Inch

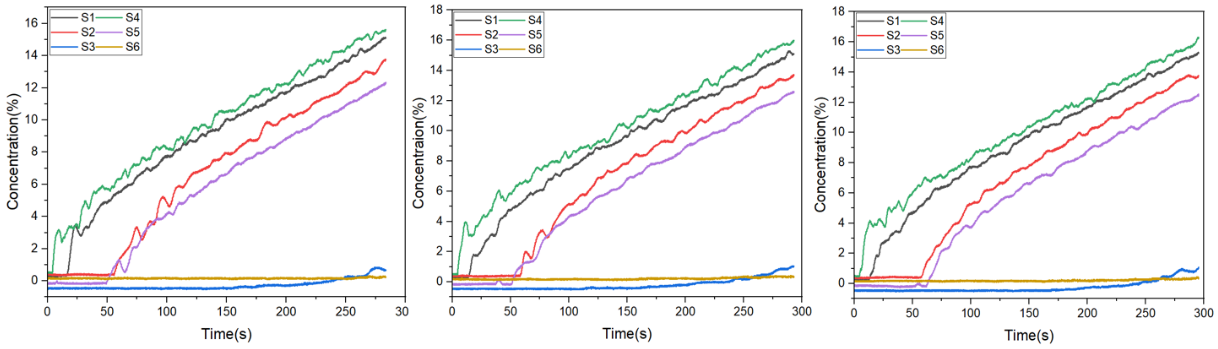


1/4 Inch



(d) (e) (f)

3/8 Inch



(g) (h) (i)

Table 4. The time to reach specified hydrogen concentrations (sec) at the central top sensor (S4) of the enclosure

Furthermore, hydrogen stratifies differently depending on the outflow velocity. When the outflow velocity of hydrogen is slow, the concentration of hydrogen tends to expand from the ceiling downward, and the explosive cloud takes a relatively long time to form. In contrast, if the outflow rate is high, an explosive cloud will form quickly and uniformly in space [19]. The results of this experiment confirmed that higher outflow velocities resulted in greater concentration differences resulted in greater concentration differences between sensors (Fig. 3). From a safety perspective, this means that even if the flow rate is constant, the intensity and shape of an explosion may differ depending on the size of the leakage hole and the leakage pressure. It is crucial that safety measures that take this phenomenon into account.

3.2 Ventilation characteristics

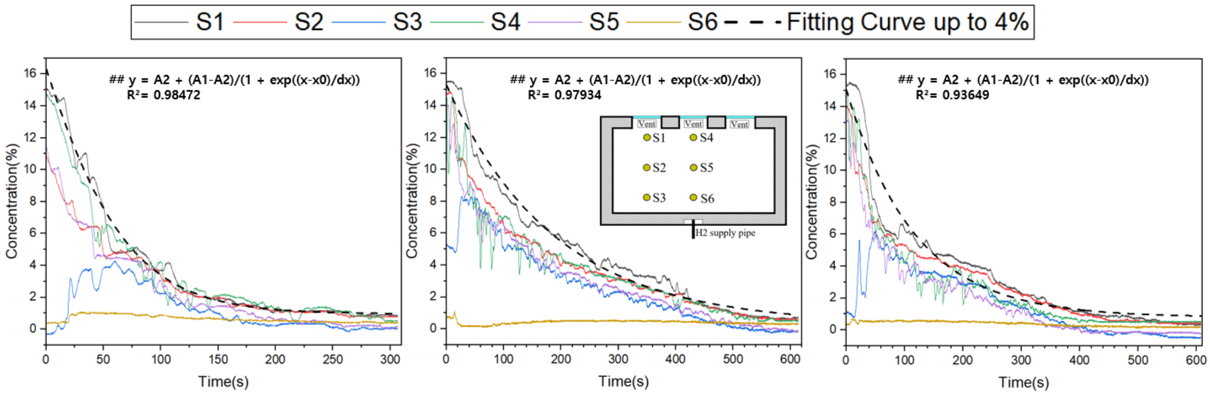
Venting experiments were conducted with different vent areas to measure the time required to reduce explosive hydrogen concentrations to acceptable ones. The vent areas applied were 0.75 m^2, 1.5 m^2, and

2.25 m^2, which accounted for 12%, 24%, and 36% of the floor area, respectively. For these experiments, we selected two target hydrogen concentrations to be reached via ventilation: 4 vol% (LFL) and 1 vol% (25% of LFL). The ventilation time measurement was initiated when the vent was opened and the concentration values indicated by the topmost sensors (S1 and S4) were uniform at 15 ± 0.5%. Taking a conservative stance from a safety point of view, ventilation was ceased only when the detectable hydrogen concentration had dropped below the critical threshold throughout the entire confined space. In other words, ventilation was deemed adequate when all sensors indicated gas levels below the desired concentration, and the time measurement was terminated when the last sensor provided this reading. Based on the data from that sensor, a non-linear curve was fit to the LFL. The ventilation times of tests were compared using the hourly average readings of the six sensors.

The change in hydrogen concentration for a vent size corresponding to 12% of the floor area (the smallest aperture used in our tests) is shown in Fig. 4. The time to reach a concentration of 4 vol% was 108.8 s, 297.6 s, and 228.4 s across three cases, while the time to reach a concentration of 1 vol% was 266.6 s, 510.4 s, and 434 s (Table 5). This constituted a significant variation. In the case of natural ventilation, the time to mitigate hazardous gas levels is highly influenced by environmental factors such as external climatic conditions, temperature, humidity, and wind direction. In this case, the ventilation time cannot be predicted consistently, and the time to reach 4 vol% and 1 vol% is quite lengthy. Thus, we assessed that this vent size would not have adequate ventilation performance in case of an emergency.

Table 5. Time to reach the target concentration by case (s)

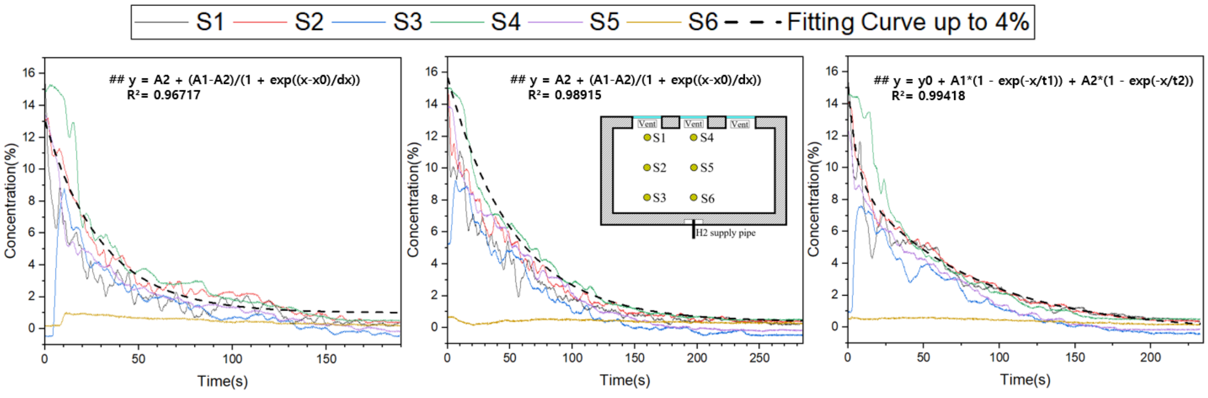
	12%			**24%**			**36%**		
	Case 1	**Case 4**	**Case 7**	**Case 2**	**Case 5**	**Case 8**	**Case 3**	**Case 6**	**Case 9**
4%	108.8	297.6	228.4	43.2	83.8	65.6	47.8	58.8	42
1%	266.6	510.4	434	139.8	156.6	157.6	161.2	134.4	141.2



(a) (b) (c)

Figure 4. Hydrogen concentration change over time for a vent area corresponding to 12% of the floor size: (a) Case 1, (b) Case 4, and (c) Case 7

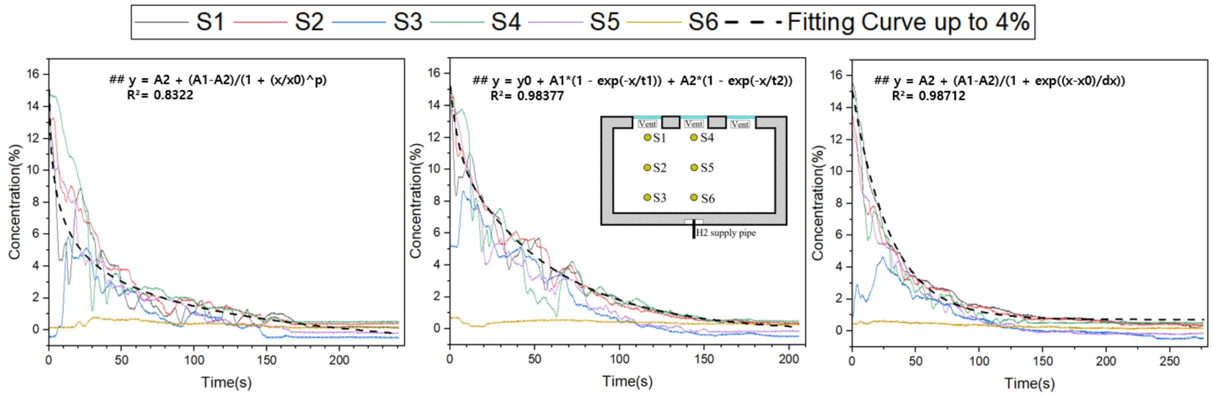
A plot of the indoor hydrogen concentration evolution for a vent size corresponding to 24% of the floor area is shown in Fig. 5. In this scenario, the times to reach a concentration of 4 vol% were 43.2, 83.8, and 65.6 s across three cases, and the times to reach a concentration of 1 vol% were 139.8 s, 156.6 s, and 157.6 s. For Case 2, the ventilation time was faster or similar to those of Case 3, Case 6, and Case 9, which had larger vent areas. This may be due to the difficulty in controlling the ambient environment of the test site, which was located outdoors and exposed to the effect of sudden wind or airflow changes. However, compared to our previous results for the 12% vent size, the ventilation time here was significantly reduced with a small deviation. This is because a larger vent aperture had a greater effect on constant fluidity (caused by principles such as the buoyant release of hydrogen and the difference in air pressure between the interior and exterior environment), rather than the effect caused by the external environment alone.



(d) (e) (f)

Figure 5. Hydrogen concentration change over time for a vent area corresponding to 24% of the floor size: (d) Case 2, (e) Case 5, and (f) Case 8

Corresponding results for the largest vent area (36% of the floor size) is shown in Fig. 6. The times to reach a 4 vol% concentration in this scenario were 47.8 s, 58.8 s, and 42 s, and it took 161.2 s, 134.4 s, and 141.2 s to reach a concentration of 1 vol%. Compared to the aforementioned two scenarios, the ventilation time here was the shortest on average and the deviation tended to be smaller. However, Case 3 took up to 21.4 s longer to reach 1 vol% compared to Case 1, Case 4, and Case 7 under a 12% vent area. This was observed to be due to the sudden decrease in the concentration at S3 and an increase in the concentration at S1, which occurred simultaneously at approximately 145 s (Fig. 6g); the hydrogen in the vicinity of S3 stayed near S1 and the wall due to an unstable interior flow. These results corroborate those of previous studies. Matsuura [20] similarly reported that hydrogen inside a naturally ventilated enclosure is subject to large concentration instabilities due to shear layers generated near the vent edges, and that this possibility increases with the use of larger vents.



(g) (h) (i)

Figure 6. Hydrogen concentration change over time for a vent area corresponding to 36% of the floor size: (g) Case 3, (h) Case 6, (i) Case 9

To compare the ventilation times of all cases, a venting coefficient value was calculated according to the vent size (Fig. 7). The venting coefficient (K_v) is one of the design parameters of an explosion panel. It is a dimensionless value calculated using the outlet area (for pressure or smoke generated by an explosion or fire) and the internal volume of the enclosed space using the formula $K_v = V^{2/3}/A_v$, where V is the internal volume and A_v is the outlet area [21].

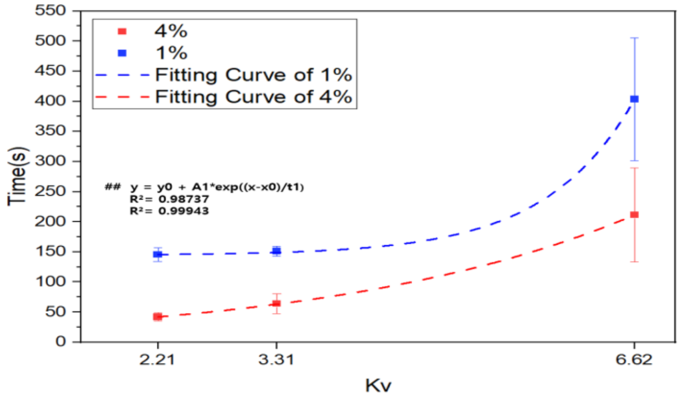


Figure 7. Time to target concentration based on venting coefficient (K_v)

Overall, as the vent size increased, the required ventilation time decreased and showed less deviation. Notably, the K_v was 2.21 in the case with the largest vent size, in which a 4 vol% LFL was reached in less than 1 min. Here, even the administrative concentration of 1 vol% was reached in a relatively short time of 145.6 s. However, when comparing these results to those obtained at K_v = 3.31, there is no significant difference. This suggests that ventilation performance improves as the vent aperture area increases, but this difference will decrease after a certain point.

To consider the overall hydrogen concentration inside the experimental setup, the average value of the concentration indicated by the six sensors is shown in Fig. 8 as a function of time. In the case of K_v = 6.62 as obtained for the smallest vent area, the hydrogen buoyant flow was strongly affected by the external flow. This resulted in a large deviation in the trend of a concentration decrease over time, and the time required for ventilation was long. In the case of K_v = 3.31 and K_v = 2.21, the hydrogen buoyant flow dominated the concentration decrease trend over time, and the deviation decreased. These overall data are shown in Table 6. This indicates that these set-ups were less affected by the airflow, and the reproducibility of the experiment improved.

Table 6. The time it takes for the average concentration reading of all sensors to reach the target concentration, according to vent size (s)

	Kv=6.62			**Kv=3.31**			**Kv=2.21**		
	12%			**24%**			**36%**		
	Case 1	**Case 4**	**Case 7**	**Case 2**	**Case 5**	**Case 8**	**Case 3**	**Case 6**	**Case 9**
4%	69	180	115.6	25.8	55	44.4	29	43.6	30.2
1%	184	454	341.8	123	134.6	126	110.6	109	101.4

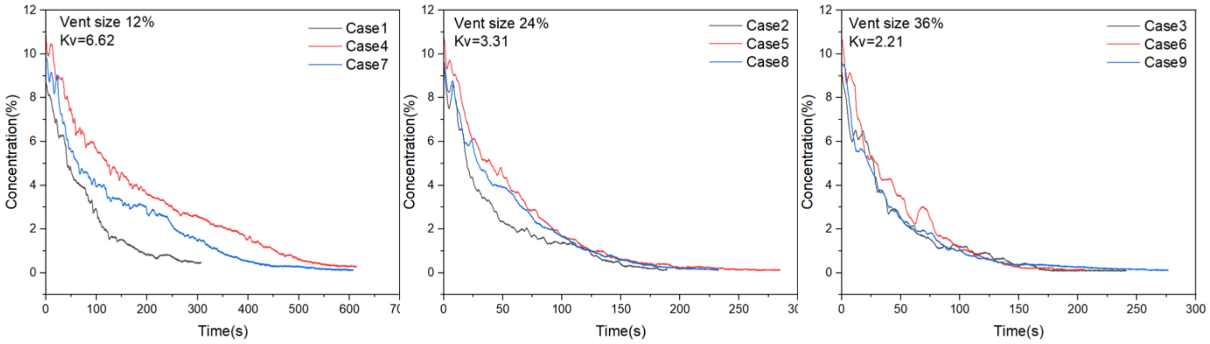


Figure 8. Change in average hydrogen concentration reading of 6 sensors inside a confined space, per case and over time

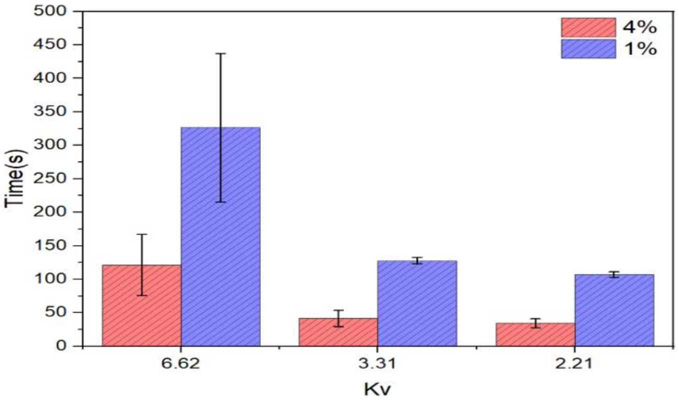


Figure 9. Time to reach the target hydrogen concentration by vent size as based on the venting coefficient (K_v) (average of six sensors)

Figure 9 shows the time that was required to reach a target hydrogen concentration, with vent size as a function of vent factor. If the K_v was less than 3.31, the internal hydrogen concentration fell below the LFL within 1 min. Moreover, at $K_v < 3.31$, the internal hydrogen concentration fell below 1% within 2 min on average, and it is considered that a first responder (manager or firefighter) could enter the confined space safely at this point. Thus, we established that the size of explosion panels should represent a K_v of 3.31 or less when considering the contribution of natural ventilation in the emergency use of such a panel.

4. CONCLUSIONS

This study experimentally investigated the efficiency of natural ventilation in mitigating the effects of a hydrogen concentration buildup in a confined space with limited ventilation by opening a vent that serves as an explosion panel. We reached the following conclusions.

The time to reach an explosive concentration differed significantly depending on the size of the hydrogen leakage hole: the larger hole, the faster the time to reach the explosive concentration. In addition, the stratification in a confined space varied by leakage rate depending on the size of the leakage hole and leakage pressure. Therefore, explosion safety measures that take this into account are necessary. As for ventilation time, it was difficult to predict the general ventilation time required to reach safe conditions in the case of the smallest vent area because it was highly affected by the external environment. The conservative ventilation time (to LFL) from a safety point of view was 108–300 s, i.e., a lengthy time of up to 5 min. The vent time required tended to decrease as the vent area increased. The ventilation time (to LFL) for the medium-sized and large vents were similar and in the range of 25–55 s. These experimental results revealed that it is reasonable to apply the area below Kv=3.31 (24% of the floor area) when designing a vent that can act as an emergency vent and an explosion vent at the same time. The findings can be useful information to design a confined space for hydrogen storage.

This study proposes a practical and novel method for future design and parameters of safety functions that protect areas where hydrogen is present. This can be applied as an emergency measure when designing a ventilation system for a confined space. The findings suggest that an appropriate safety response is required to prevent accidental combustion and explosion accidents from occurring by considering the ventilation time as a factor of vent size when applying emergency ventilation due to a leakage accident. One limitation of this study is that the experiment was conducted without any structures in the confined space. In practice, facilities that store hydrogen possess facilities such as low- and high-pressure storage containers, compressors, and pipes that make it easy to form hydrogen retention and concentration in case of a hydrogen leakage, which increases the required ventilation time and performance. Therefore, future experiments should be designed to simulate a realistic environment that considers internal obstacles.

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