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Proposal for ventilation performance improvement measures considering the ship's kinetic characteristics in case of hydrogen leakage

Byeol Kim[1] · Kwang-Il Hwang[†]

Abstract: The goal of this research was to propose the shape of a hydrogen fuel storage room according to the roof apex angle considering structural and kinetic characteristics and to analyze the effect of improving ventilation performance accordingly. The computational fluid dynamics (CFD) method was used to analyze the ventilation flow rate of the exhaust vent and average hydrogen concentration value by applying ship motion conditions in the proposed model. Consequently, compared with the flat roof model, the proposed model increased the ventilation flow rate by up to 106% and decreased the hydrogen concentration by up to 28%. Similarly, even in mechanical ventilation, the ventilation flow rate increased by up to 19.02% and the hydrogen concentration decreased by up to 32.97%. The proposed model with a roof apex angle of 120° for both mechanical and natural ventilation was ascertained as the most effective model for hydrogen exhaust. The numerical results are expected to be helpful for research on the design of hydrogen tank storage room shapes and ventilation systems to improve the ventilation performance of hydrogen-powered ships.

Keywords: Hydrogen leakage, Ventilation, Computational fluid dynamics, Hydrogen fuel storage room

1. Introduction

In line with greenhouse gas emission regulations and energy paradigm shifts in shipping and shipbuilding, the need for environmentally friendly and energy-saving ships such as hydrogen ships is increasing [1][2]. Hydrogen fuel is not only eco-friendly, because it does not emit nitrogen oxides (NOx) and sulfur oxides (SOx), but also has advantages such as high energy efficiency and fast charging speed; therefore, it is emerging as a fuel to replace existing ship fuel oil [3][4]. However, the issue of securing safety in using hydrogen as an energy source has been raised due to its low gas density, difficulty in being detected because it is colorless and odorless, and large potential for fuel explosions [5][6]. If hydrogen leaks from the hydrogen tank, hydrogen supply pipeline, and valves due to sealing problems or damage caused by external shocks, the possibility of fire or explosion is high if it cannot be quickly exhausted to the outside [7].

Accordingly, certain research has been conducted on ways to effectively discharge hydrogen when it leaks from a hydrogen ship. Hwang *et al.* [8] studied the position of the exhaust port to effectively discharge hydrogen when it leaks from the hydrogen

tank storage room in a hydrogen fuel cell ship. Their results indicated that the higher the location of the exhaust port, the more effective it was in discharging the remaining hydrogen concentration in the storage room. Hwang *et al.* [9] conducted a numerical simulation to examine the location and size of the supply port to effectively discharge hydrogen from a hydrogen fuel cell ship. They observed that the smaller the size of the supply port, the more advantageous it was for the rapid hydrogen release. However, they indicated that the higher the position of the air supply port, the higher was the hydrogen concentration by inhibiting the distribution of the air current formed in the space. Lee and Cho [10] analyzed the effect of the area of the supply and exhaust ports on the ventilation performance when hydrogen leaked from a hydrogen tank storage room. They suggested that increasing the area of the inlet port was more effective for hydrogen leakage than increasing the area of the exhaust port. Previous studies have confirmed that to effectively exhaust hydrogen, the location and area of the supply and exhaust ports had to be reviewed when hydrogen leaked from ships.

However, previous studies have identified the following

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limitations. First, the kinetic characteristics of ships are factors that affect hydrogen diffusion; however, identifying studies evaluating ventilation performance considering these characteristics are difficult. Second, although the shape of the space affects ventilation performance, previous studies did not consider this.

The objective of this study was to propose the shape of the hydrogen fuel storage room based on the roof apex angle to improve the ventilation performance by considering the kinetic characteristics of the ship. Simulated using ANSYS FLUENT 19.2, the study showed the effect of improving the ventilation performance according to the proposed shape and ventilation method.

2. Methodology

Figure 1 illustrates the flowchart of the overall methodology. This included the shape of a hydrogen fuel storage room according to the roof apex angle as a measure to improve the ventilation performance considering the ship's motion. In addition, the hydrogen dispersion behavior of the proposed model using the ventilation method was analyzed to confirm the effect of improving ventilation performance. Accordingly, the shape of the fuel storage room and optimal ventilation conditions were selected.

2.1 Mathematical model

The simulation was performed using the CFD code FLUENT 19.2 to evaluate the ventilation performance in the proposed model and ventilation method. Hydrogen release and dispersion can be described by the conservation equations of mass, momentum, and energy and the species transport equation, as shown in **Equations (1), (2), (3)**, and **(4) [11]**. The numerical analysis tool was verified through a previous study **[12]**, and the verification part was not included in this study.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\overrightarrow{\rho v}) = 0 \tag{1}$$

where ρ is the density, t is the time, and $\vec{v}$ is the overall velocity vector.

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \overrightarrow{vv}) = -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \rho \vec{g} + \vec{F} \tag{2}$$

where p is the pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\vec{g}$ is the gravitational acceleration, and $\vec{F}$ is the force vector.

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p))$$
$$= \nabla \cdot k_{eff} \nabla T - \sum_j h_j \vec{J_j} + (\overline{\tau_{eff}} \cdot \vec{v})) \tag{3}$$

where E is the total energy, k_{eff} is the effective conductivity, T is the temperature, h_j is the sensible enthalpy of species j, and $\vec{J_j}$ is the diffusion flux of species j.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J_i} + R_i + S_i \tag{4}$$

where Y_i, R_i, and S_i is the mass fraction of each species, net rate of the product of species i by chemical reaction, and the rate of creation by addition from the dispersed phase plus any user-defined sources.
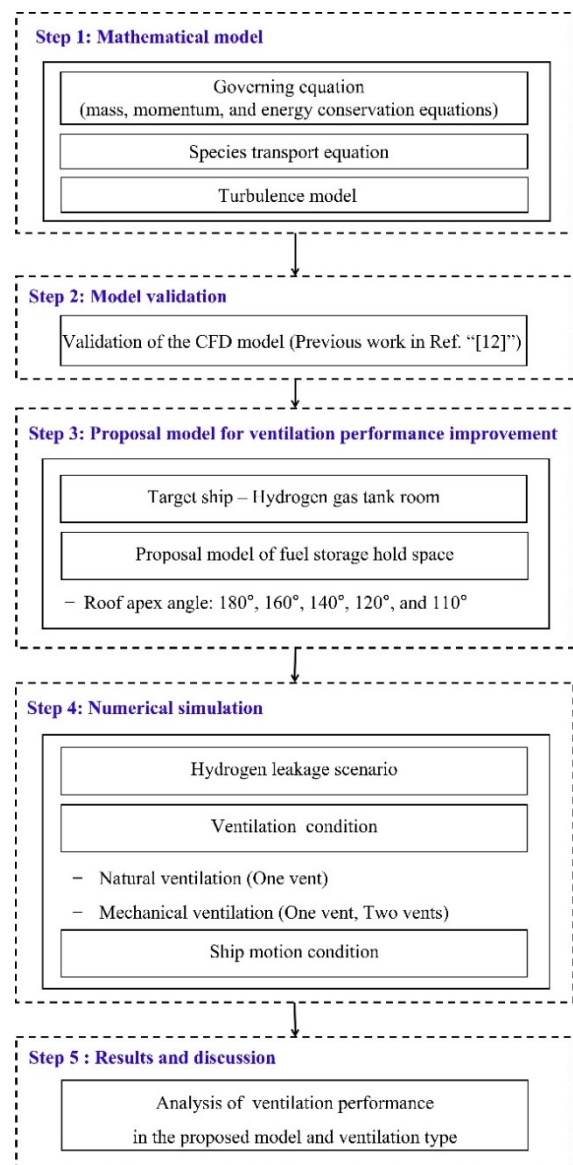

Figure 1: Flowchart of the overall methodology

2.2 Computational domain

2.2.1 Target model

The purpose of this study is to propose the shape of a hydrogen fuel storage room to improve the ventilation performance, and the target model is based on the concept design of a fuel gas supply room (FGSS room) of a hydrogen-powered ship. Hydrogen leakage is highly likely to occur from the hydrogen tank and piping connections, and component equipment other than hydrogen tanks can influence the analysis of the diffusion behavior and act as a variable in shape selection [13]. Therefore, only a hydrogen tank (total internal volume of 21 m^3) in a rectangular parallele-pipe-shaped (15 m long × 6 m wide × 7 m high) hydrogen fuel storage room was considered for simplification, as shown in **Figure 2**. The hydrogen tank was assumed to be that of a Type C LNG Tank among the independent fuel tank types stipulated by the IMO, and the detailed specifications are summarized in **Table 1 [14]**.
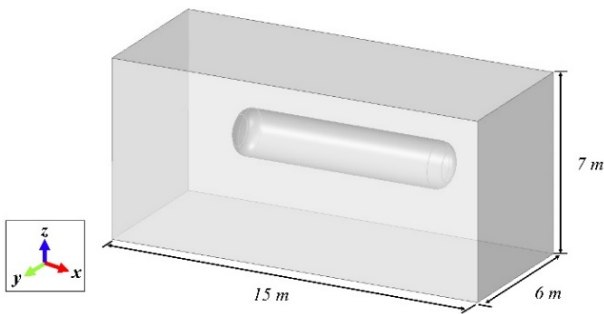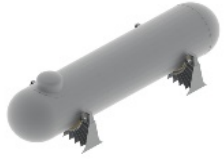

Figure 2: Geometric shape of a hydrogen fuel tank room

Table 1: Specifications of a Type C LNG Tank

Contents	Feature
Tank geometrical shape	
Tank type	IMO Type C Double Shell
Gross volume [m^3]	21
Net volume [m]	19
Tank dimension [m]	1.8 (I.D) / 8.823 (L)

2.2.2 Proposed model

A model was proposed from a structural perspective to improve the ventilation efficiency of a hydrogen gas tank room. According to a study by Perén *et al.* **[15]**, the roof inclination angle during natural ventilation significantly affected on air flow, and the ventilation volume tended to increase by 22% at 45°

compared with that when the roof inclination angle was 0°. Therefore, this study proposed a geometric shape based on the roof apex angle, as shown in **Figure 3**.
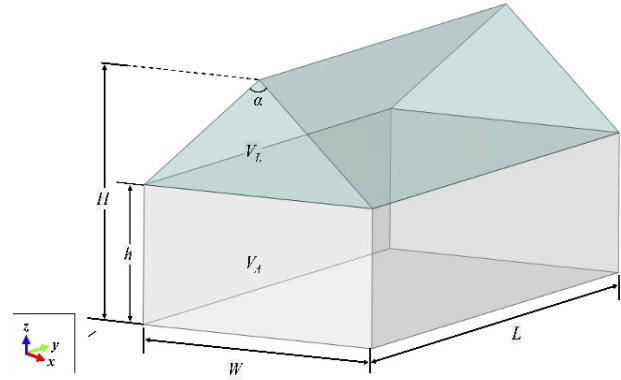

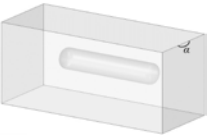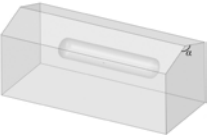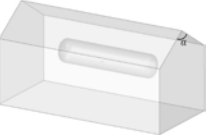**Figure 3:** Geometric shape of the proposal model
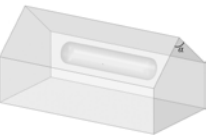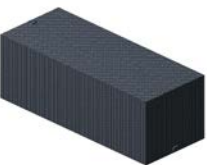
The volume of the model is determined by the cross-sectional area and length of the room, and the cross-section is represented by the side height (h), width (W), roof apex angle (α), and height of the ridge (H). It is divided into the available volume (V$_A$) used to place structural equipment other than hy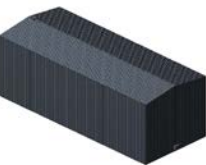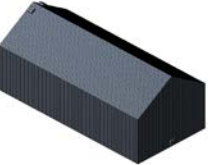drogen tanks and the load volume (V$_L$) that acts as a load factor due to ventilation. The effective volume is determined by the height (h) and width, and the load volume is defined as the roof space. In this study, the length (L) and height (H) of the ridge were fixed at 15 m and 7 m, respectively, and the width was adjusted to maintain the same total volume of approximately 630 m^3. **Table 2** lists the detailed dimensions of the proposed model for the hydrogen tank storage room based on the roof apex angle.

Table 2: Detailed dimensions of the proposed model

Roof apex angle, α [°]	180	160	140	120	110
Height, h [m]	-	6.5	5.9	5	4.45
Width, W [m]	6	6.2	6.48	6.99	7.28
Available volume, V$_A$ [m^3]	630	605	574	524	491
Load volume, V$_L$ [m^3]	-	25.4	57.3	106	139

Table 3 summarizes the computing domain, hexahedral grid creation, number of nodes, and orthogonal quality generated for the five different types using ANSYS Meshing. The orthogonal quality is an index that evaluates the quality of a generated grid. The average orthogonal quality for each model was 0.991–0.993, which was within the excellent range **[11]**. In addition, the

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Table 3: Proposed model for a hydrogen tank room based on the roof apex angle

Roof apex angle, α [°]	180	160	140	120	110
Geometry					
Mesh					
Nodes	672,815	658,060	663,665	662,544	660,011
Orthogonal quality average	0.993	0.993	0.993	0.991	0.993

numbers of nodes at 180°, 160 °, 140°, 120°, and 110° depending on the roof apex angle were 672,815; 658,060; 663,665; 662,544; and 660,011, respectively.

2.3 Numerical simulation

2.3.1 Hydrogen leakage scenario

The worst scenario for a hydrogen leakage accident, in which the gas jet leaked from the flange connecting the hydrogen tank and the pipe, was considered in this study. The hydrogen leakage position is shown in **Figure 4,** and the hydrogen leaks horizontally. The flange size was set to DN250 (applicable pipe inner diameter: 273 mm), and the leak rate was set to 10% of the flange size. In general, high-pressure hydrogen is charged at 35 or 70 MPa; therefore, the pressure of the hydrogen tank was selected based on this. In addition, the hydrogen temperature was selected as 85°C according to the temperature range of 5–85°C, which was selected as the charge/discharge simulation temperature in IS WG24 **[16]**. To calculate the high-pressure hydrogen leak flow rate, the leakage was determined as either sonic or subsonic. If the tank pressure is higher than the critical pressure calculated according to **Equations (5)** and **(6)**, the gas is determined to leak at sonic speed, and if the tank pressure is lower than the calculated critical pressure, the gas is determined to leak at subsonic speed. The pressure is 7×10^7 Pa and the temperature is 85 ° C, is calculated as 1.376, and is calculated as 190,333 Pa, and the gas is determined to leak at the speed of sound. The leakage flow rate is calculated according to **Equation (7) [17]-[18]**. **Table 4** presents the hydrogen leakage scenario.
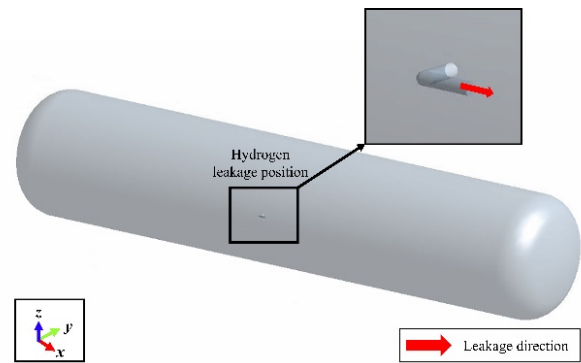

Figure 4: Geometric shape of the proposed model

$$P_c = P_a \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \tag{5}$$

where P_c is the critical pressure, P_a is the atmospheric pressure, and γ is the polytropic index of adiabatic expansion or the ratio of specific heats.

$$\gamma = \frac{C_p}{MC_p - R} \tag{6}$$

where M is the molar mass, C_p is the specific heat at constant pressure, and R is the universal gas constant.

$$W_g = C_d SP \sqrt{\gamma \frac{M}{ZRT}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \tag{7}$$

where W_g is the mass release rate of the gas, C_d is the discharge coefficient, S is the cross section of the opening, P is the pressure inside the container, Z is the compressibility factor, and T is the absolute temperature of the gas.

Table 4: Hydrogen leakage scenario

Contents	Feature
Leak hole size [m]	0.0273
Pressure [MPa]	70
Temperature [℃]	85
Leak direction	Horizontal
Leak rate [kg/s]	1976.48
Volumetric flow rate [m³/s]	5.74

2.3.2 Ventilation condition

The ventilation flow rate is 5.25 m³/s when calculated to have a ventilation capacity of at least 30 times per hour according to regulations and 25.93 m/s when converted to speed **[19]**. **Equations (8)** and **(9)** are used to calculate ventilation rates. For natural ventilation, a type 2 ventilation method was applied and evaluated by applying it to the air supply inlet.

$$Q_{vent} = \frac{30V_{room}}{H} \left[\frac{m^3}{hr}\right] \tag{8}$$

where Q_{vent} is the ventilation requirement, V_{room} is the volume of the room, and H is the time.

$$V_{outlet\ velocity} = \frac{Q_{vent}}{3600 \cdot A_{outlet}} \left[\frac{m}{s}\right] \tag{9}$$

where $V_{outlet\ velocity}$ is the ventilation velocity requirement, and A_{outlet} is the ventilation area.
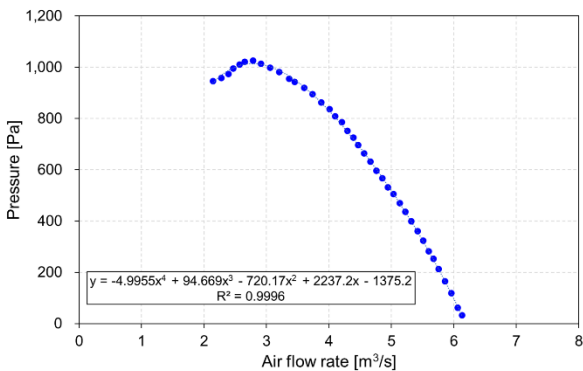

Figure 4: Fan modeling using a momentum source

In the case of mechanical ventilation, ventilation is performed using a blower. To consider this in the analysis, the blower characteristic curve was applied to the exhaust opening. **Figure 4** shows the characteristic curve of the blower fan prototype that satisfies the required ventilation as a polynomial expression. This was converted into a momentum source and applied in the

simulation **[20]**. The location of the air supply inlet was modeled to be at the bottom of the room, and the exhaust opening was at the top, opposite to the air supply inlet, according to the regulation **[21]**. When the number of exhaust ports was one, it was placed on the ceiling, opposite to the air supply inlet, and when the number of exhaust openings was two, they were placed on the roof surface of the ceiling.

2.3.3 Ship motion condition

Previous study confirmed that when the hydrogen leakage is in the longitudinal direction, it is affected by pitch motion [12]. Therefore, pitch motion was applied in the simulation. The motion occurs with an 8-s period according to **Equations (10)** and **(11)** [22].

$$T = \sqrt{\frac{2\pi\lambda}{g}} \tag{10}$$

where λ is the pitch angle, and g is the gravitational acceleration.

$$\lambda = 0.6(1 + f_T)L \tag{11}$$

where f_T is the ratio between draught at a loading condition and scantling draught, and L is the overall length.

3. Result and discussion

When a high-pressure hydrogen fuel tank leaks, a large amount of hydrogen (1,976 kg/s) leaks and the gas expands. Thus, when the thickness of the hydrogen gas layer on the ceiling increases and reaches the top of the vent, the gas is discharged outdoors through the vent. Therefore, to evaluate the effect of the ceiling apex angle of the proposed model on hydrogen ventilation, the ventilation flow rate of the exhaust opening and average hydrogen concentration in the room were confirmed.

3.1 Natural ventilation performance of the proposed model

3.1.1 Ventilation flow rate

Figure 5 shows the ventilation flow rate at the exhaust opening based on the roof apex angle. As the roof apex angle decreased to 120 °, the ventilation flow rate increased, and the tendency to repeat the rise and fall according to the period could be confirmed. In particular, the largest difference occurred when the pitch angle at 34 s was -10°. When the apex angle was 180°, the ventilation flow rate was 0.21 ㎥/s, whereas when the apex angle was 160°,

140°, 120°, and 110°, the ventilation flow rate was 0.44 ㎥/s, 0.58 ㎥/s, 0.78 ㎥/s, and 0.68 ㎥/s, respectively, indicating an increase of 114.5%, 177.8%, 275.6%, and 226.9%, respectively. The rate of increase in ventilation flow compared with that at 180° is shown in **Figure 6** as a box plot graph. Although a large variation occurred in ventilation due to changes in exercise, the average ventilation increased by 40%, 59%, 106%, and 71% at 160°, 140°, 120°, and 110°, respectively, compared with that at 180°. Thus, even if the air supply was the same, a ventilation plan considering this was necessary because the difference in exhaust occurs depending on the motion period and shape of the space.
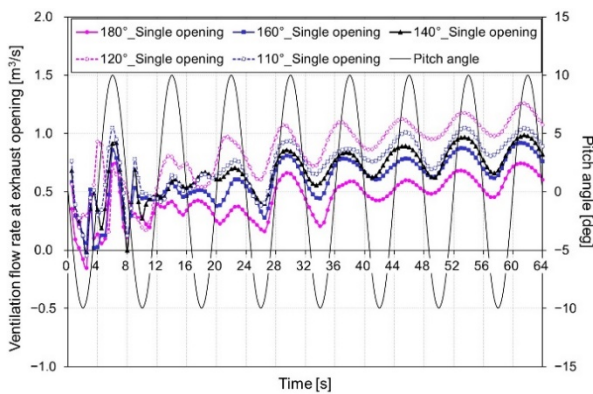

Figure 5: Ventilation flow rate at the exhaust opening based on the roof apex angle (Natural ventilation)
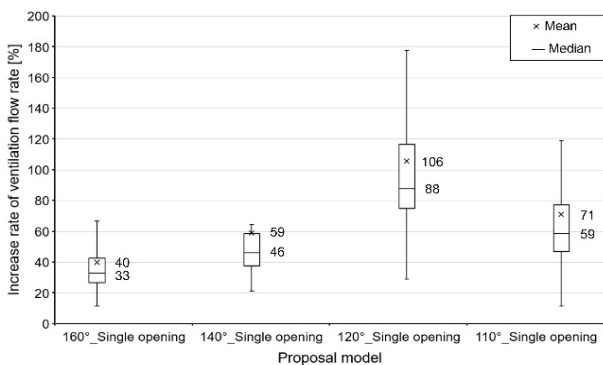

Figure 6: Increase rate of the ventilation flow rate based on the roof apex angle (Natural ventilation)

3.1.2 Hydrogen concentration

The average concentration of the hydrogen remaining in the room for each proposed model is shown in **Figure 7**. In addition, the decrease rate of hydrogen concentration compared with that at 180° is shown in **Figure 8** as a box plot graph. Overall, the average hydrogen concentration tended to be lower as the roof
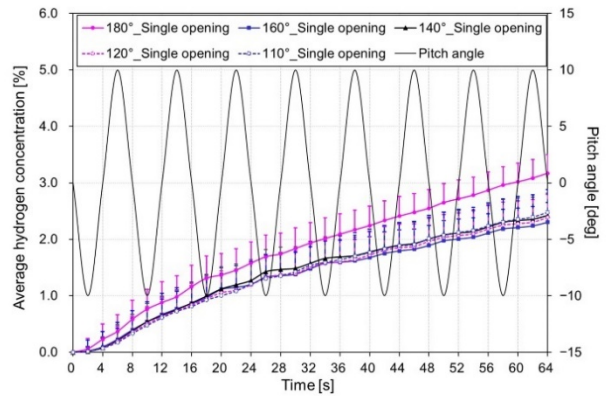

Figure 7: Average hydrogen concentration based on the roof apex angle (Natural ventilation)
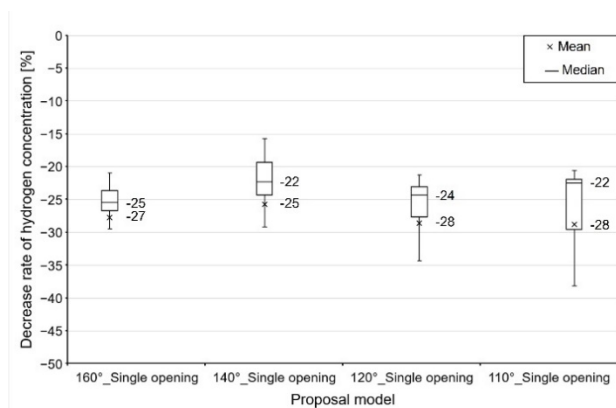

Figure 8: Decrease rate of hydrogen concentration based on the roof apex angle (Natural ventilation)

apex angle decreased, but no significant difference existed between 25 and 28% for each angle compared with that for 180°. This result is due to the failure to provide sufficient ventilation compared with the amount of hydrogen leakage. Therefore, mechanical ventilation method was applied, and the number of exhaust ports was added to confirm the ventilation performance.

3.2 Mechanical ventilation performance of the proposed model

3.2.1 Ventilation flow rate

The hydrogen leakage according to the ventilation conditions was analyzed by setting the roof apex angle to 120°, which is the most effective model for hydrogen exhaust during natural ventilation, as an experimental group and a roof apex angle of 180° as a control group. **Figure 9** shows the ventilation flow rate at the exhaust opening due to the installation of the blower, and **Figure 10** shows the increase rate of the ventilation flow rate by the number of exhaust openings in a box plot graph. Unlike natural ventilation (type 2 ventilation), mechanical ventilation (type 1
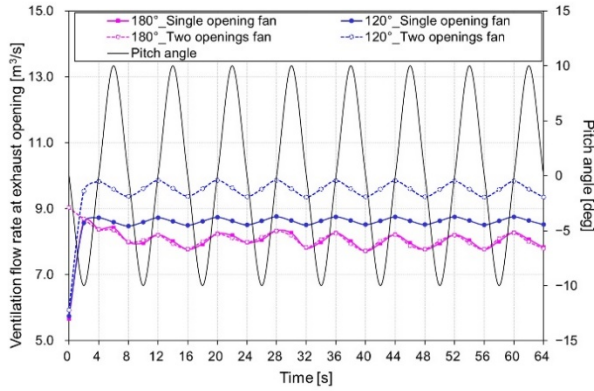
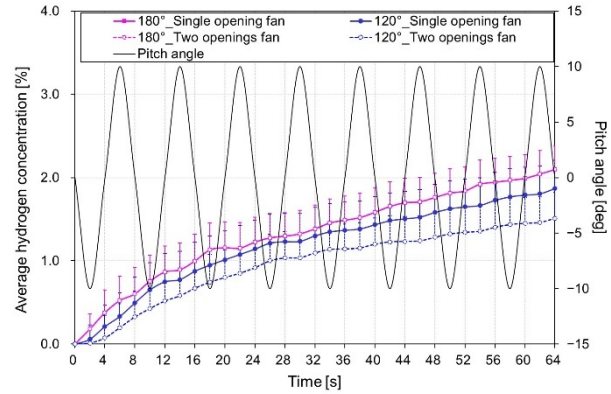**Figure 9:** Ventilation flow rate at exhaust openings based on the roof apex angle (Mechanical ventilation)

Figure 11: Average hydrogen concentration based on the roof apex angle (Natural ventilation)
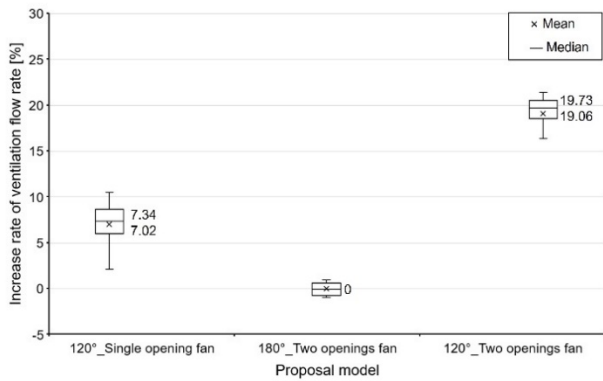

Figure 10: Increase rate of the ventilation flow rate based on the roof apex angle (Mechanical ventilation)
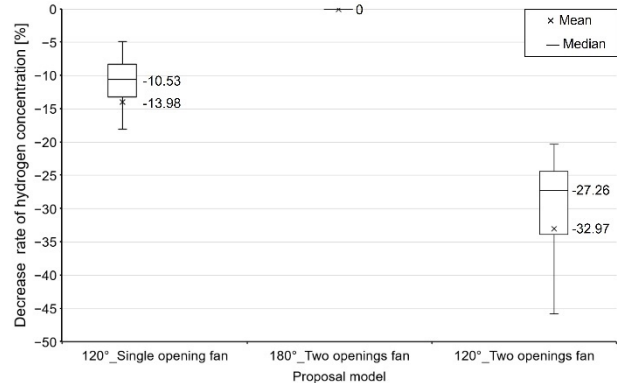

Figure 12: Decrease rate of hydrogen concentration based on the roof apex angle (Natural ventilation)

ventilation) had a constant ventilation volume. In addition, when the roof apex angle was 180 °, no difference existed in the amount of ventilation despite the increase in the number of exhaust openings. This implied that a stagnant area existed during hydrogen leakage; therefore, the effect of the number of exhaust openings and the blower was small. However, when the roof apex angle was 120 °, ventilation flow increased by at least 10% to a maximum of 13% with two openings compared to one. This implied that when hydrogen leaked, it accumulated on the roof side of the zone and was discharged through openings located on the roof side. In terms of ventilation, compared with a 180° single opening fan, the average increase was 7.02% for a 120° single opening fan and 19.02% for a 120° two openings fan. This confirmed that the amount of ventilation increased at 120°.

3.2.2 Hydrogen concentration

The average hydrogen concentration remaining in the room according to the ceiling apex angle and number of exhaust openings are shown in **Figure 11**. In addition, the reduction rate of hydrogen concentration compared with that at 180 ° is shown in **Figure 12** as a box plot graph. When the roof apex angle was 180 °, although the number of exhaust outlets increased, no difference was observed in hydrogen concentration because the amount of ventilation was the same. In addition, when the ceiling apex angle was 120 °, the hydrogen concentration decreased by a minimum of 16% to a maximum of 25% with two openings compared with that with a single opening. This can be attributed to the increase in ventilation due to the increase in the number of openings. The hydrogen concentration compared with that at the 180° single opening was reduced by an average of 13.98% in the case of a 120° single opening fan and 32.97% in the case of a 120° two openings fan. Thus, the hydrogen concentration value decreased due to the increase in ventilation when both natural and mechanical ventilation were at 120 °.

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4. Conclusion

The purpose of this study was to propose a shape and ventilation method for a hydrogen fuel storage area considering the structural and environmental characteristics of the ship to effectively discharge hydrogen during leakage and analyze the effect of improving ventilation performance. The results obtained in this study are summarized as follows:

1) Ventilation performance was compared according to the apex angle (160°, 140°, 120°, and 110°) of the ceiling of the hydrogen fuel storage room when natural ventilation was applied. The ventilation flow rate increased up to 106% (120°) depending on the ceiling angle, and hydrogen concentration decreased up to 28% (120°).

2) When mechanical ventilation was applied, hydrogen leakage analysis was performed on the model (120°), which is the most effective for hydrogen emission in natural ventilation and a ceiling apex angle of 180° (control group), and the ventilation flow rate and hydrogen concentration values were compared. As a result, the ventilation flow rate increased by up to 19.02%, and the hydrogen concentration decreased by up to 32.97%.

In summary, considering the characteristics of the ship, the ventilation performance was most effective when ceiling apex angle of the hydrogen fuel storage space was 120 °. However, when applying hydrogen leakage and ventilation scenarios, research on the quantification of hydrogen diffusion characteristics according to leakage and ventilation characteristics must be conducted by applying various conditions, such as the size of the leak port, leak amount, leak direction, and size of the ventilation port. These considerations can overcome the limitations of the application of various ship ventilation conditions.

Author Contributions

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