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Effect of gasoline pool fire on liquid hydrogen storage tank in hybrid hydrogen–gasoline fueling station

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ABSTRACT

Multiple-energy-fueling stations, which can supply several types of energy such as gasoline, CNG, and hydrogen, could guarantee the efficient use of space. To guide the safety management of hybrid hydrogen–gasoline fueling stations, which utilize liquid hydrogen as an energy carrier, the scale of gasoline pool fires was estimated using the hazard assessment tool Toxic Release Analysis of Chemical Emissions (TRACE). Subsequently, the temperature and the stress due to temperature distribution were estimated using ANSYS. Based on the results, the safety of liquid hydrogen storage tanks was discussed. It was inferred that the emissivity of the outer material of the tank and the safety distance between liquid hydrogen storage tanks and gasoline dispensers should be less than 0.2 and more than 8.5 m, respectively, to protect the liquid hydrogen storage tank from the gasoline pool fire. To reduce the safety distance, several measures are required, e.g. additional thermal shields such as protective intumescent paint and water sprinkler systems and an increased slope to lead gasoline off to a safe domain away from the liquid hydrogen storage tank.

Abbreviations: FCV, fuel cell vehicle; HAZID, hazard identification study; CE, cold evaporator; FDMA, Japan Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications; TRACE, Toxic Release Analysis of Chemical Emissions; R.T., room temperature.

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Introduction

Hydrogen has been considered a promising energy carrier from the viewpoint of reduction in carbon dioxide emissions and efficient storage and transportation of energy. Moreover, hydrogen could be produced using renewable energy sources such as wind or solar energy, in which case it is referred to a renewable hydrogen or green hydrogen [1].

One of the rising technologies that utilize hydrogen is the fuel cell vehicle (FCV). A Japanese motor corporation has been selling commercial FCVs since December 2014, and other companies are poised to enter the FCV market as well. Therefore, it is necessary to establish hydrogen infrastructure, particularly hydrogen fueling stations. Specific safety measures and over-conservative approaches might increase the operational costs considerably. Thus, to make hydrogen fueling stations more economical, it is necessary to optimize these safety measures.

Many researchers have conducted risk assessments and analyses with respect to hydrogen fueling stations [2–20]. However, the characteristics of these stations differ depending on the country and location. Because each country has its own regulations regarding the construction and operation of hydrogen fueling stations, the availability of national spaces might determine the size of the stations. As Japan has limited space, multiple-energy-fueling stations, which can supply a few types of energy such as gasoline, CNG, and hydrogen, could ensure the efficient utilization of space.

Nakayama et al. identified three worst-case scenarios in a Japanese hybrid hydrogen–gasoline fueling station through hazard identification study (HAZID) [21]: (i) A massive gasoline pool fire forms at a gasoline dispenser, and the cold evaporator (CE) is damaged by thermal radiation. Large amounts of hydrogen then leak from the damaged CE area and ignite. Eventually, a catastrophic hydrogen explosion occurs. (ii) A massive kerosene pool fire forms at a kerosene dispenser, and the CE is damaged by thermal radiation. Large amounts of hydrogen then leak from the damaged CE area and ignite. Eventually, a catastrophic hydrogen explosion occurs. (iii) A liquid hydrogen trailer crashes into a gasoline tank truck while moving in the station. Large amounts of liquid hydrogen then leak from the trailer and ignite. Eventually, a fatal hydrogen explosion occurs. The present paper focuses on scenario (i); scenarios (ii) and (iii) will be discussed in a later paper.

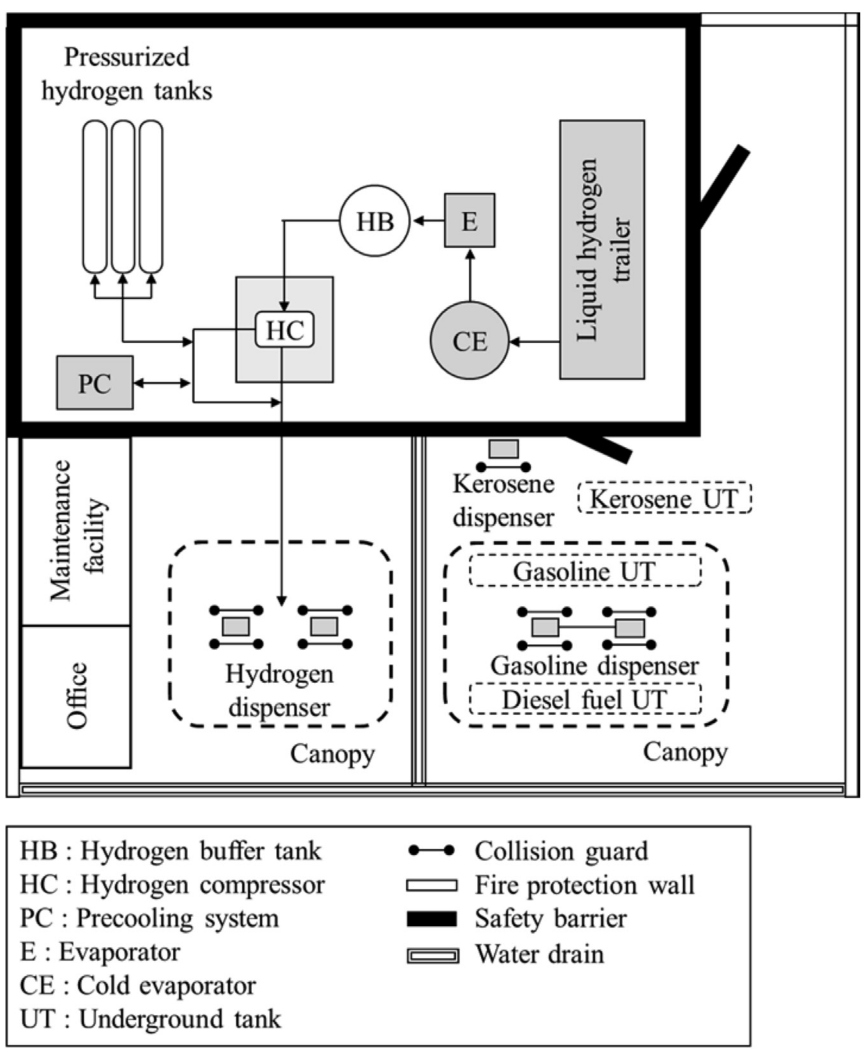


Fig. 1 – Layout of hybrid station with gasoline and liquid hydrogen supply systems [21].

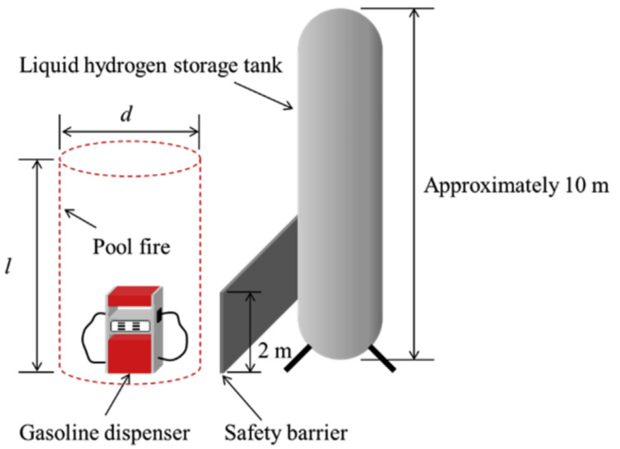
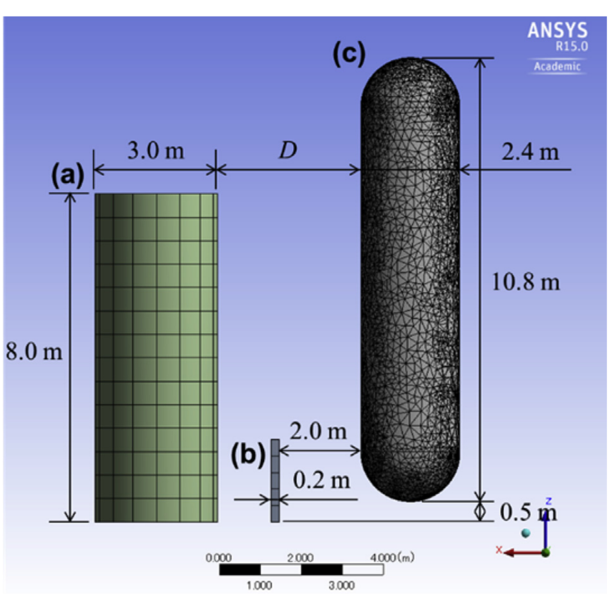


Fig. 2 – Relative positions of liquid hydrogen storage tank, safety barrier, and gasoline dispenser.

Table 1 – Properties of gasoline and pool fire.		
Chemical composition [mol%]	Gasoline density [g/cm^3]	Gasoline flow rate [L/min]
Octane 87.7 and n-heptane 12.3	0.61	50

Japan's High Pressure Gas Safety Act requires a 2-m-high safety barrier to be installed in the hybrid hydrogen–gasoline station to cover the valves. Unfortunately, a 10-m-high liquid hydrogen storage tank would not be covered by this safety barrier. Thus, a pool fire of gasoline or kerosene would directly affect a liquid hydrogen storage tank. The Japan Fire and Disaster Management Agency (FDMA) of the Ministry of Internal Affairs and Communication [22] has recommended a 3.9 m safety distance between liquid hydrogen storage tanks and gasoline dispensers. This safety distance was determined considering two main assumptions. One is that the outer material of the tank has no temperature distribution and is uniformly heated. The other is that the safety measures can function properly at 650 °C to keep the internal pressure constant within tolerance levels. Based on these two assumptions, the safety distance was calculated to ensure that the temperature due to pool fire thermal radiation would not reach 650 °C within 30 min. However, temperature distributions generate thermal stress and cause tanks to fracture more easily. Thus, it is important to consider not only the strength decrease due to high temperatures but also the thermal stress due to temperature distribution. Although several researchers have conducted pool fire analyses [19,20,23–29], they have focused on temperature rather than temperature distribution.



$D = 3.5, 5.0, 6.5, 8.0, 11.0, 14.0$ m

Fig. 3 – Finite element model and mesh: (a) gasoline pool fire; (b) safety barrier; (c) liquid hydrogen storage tank.

In this study, to aid the safety management of hybrid hydrogen–gasoline fueling stations, the temperature and thermal stress due to temperature distribution were analyzed using the codes Toxic Release Analysis of Chemical Emissions (TRACE) and ANSYS. Based on the analysis results, the safety of liquid hydrogen storage tanks was discussed.

Worst accident scenario

Fig. 1 shows the layout of a hybrid hydrogen–gasoline fueling station. As mentioned in the previous section, two of the three worst-case scenarios are due to pool fires of gasoline or kerosene. In these scenarios, a massive gasoline/kerosene pool fire forms at a gasoline/kerosene dispenser, and the CE is damaged by thermal radiation. Large amounts of hydrogen then leak from the damaged CE area and ignite. The CE in the paper published by Nakayama et al. [21] indicates the liquid hydrogen storage tank. Eventually, a catastrophic hydrogen explosion occurs. In this study, the gasoline pool fire was selected for analysis.

Pool fire simulation

Estimation of shape and dimensions of gasoline pool fire using TRACE

Fig. 2 illustrates the dimensions and relative positions of the liquid hydrogen storage tank, safety barrier, and gasoline dispenser. To estimate the size of the pool fire (height l and diameter d), the properties of gasoline and pool fire were assumed as listed in Table 1. Although gasoline generally consists of many kinds of chemicals, the two main components were used. In this study, the wind effect was not taken into account. The dimensions l and d were calculated using TRACE 9.0, which is a set of consequence assessment solutions that allow rapid visualization of a potential failure involving airborne hazardous material [30]. The average

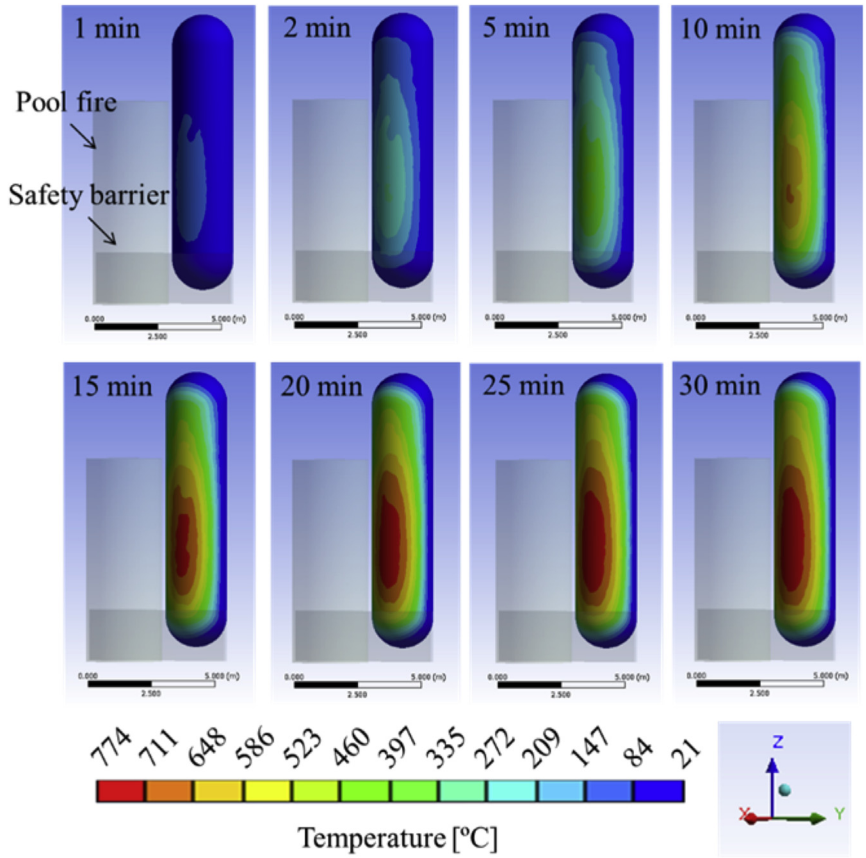


Fig. 4 – Effect of thermal radiation on temperature distribution of liquid hydrogen storage tank at D = 3.5 m and $\varepsilon = 0.7$.

values during the 30 min pool fire were 8 m and 3 m, respectively. The pool fire size varies depending on the calculation method adopted [22,31]. The values of l and d calculated by the FDMA are 5.5 m and 3.6 m, respectively [22]. Therefore, compared with the FDMA values, d is larger, and l is smaller in the values calculated using TRACE. Considering the existence of the safety barrier in the worst-case accident scenario, the height may be more influential than the diameter in determining the effect of the pool fire on the liquid hydrogen storage tank. Thomas [31] reported that many observations of pool fires demonstrate an approximate ratio of flame height to diameter, which is given for circular pool fires as follows:

$$l/d = 42\left(m\Big/\rho_0(gd)^{1/2}\right)^{0.61} \tag{1}$$

The value of d is assumed as 3 m. m is the mass burning rate (0.0719 kg/m^2 s at $d = 3$ m), ρ_0 is the air density (1.2 kg/m^3 at 20 °C and 1 atm), and g is the acceleration due to gravity (9.81 m/s^2). Substituting the values in Eq. (1), we obtained the ratio l/d and l as 2.69 and 8.07 m, respectively. The value of l calculated using Eq. (1) agrees well with that using TRACE.

Model

Analyses of the thermal radiation and thermal stress were conducted using the commercial finite element software package ANSYS 15.0 [32]. Fig. 3 shows the finite element model and mesh for the gasoline pool fire, safety barrier, and liquid hydrogen storage tank, and Table 2 lists their materials, emissivity (ε), and initial or constant temperatures. The liquid hydrogen tank has a double-shell structure with an insulating layer in between. Thus, fracture of the outer material of the tank might just lead to a loss of insulation and increased boil-off, instead of leading to fracture of an inner material of the tank and subsequent explosion. However, if the reason for a pool fire is earthquake, the boil-off function might not work properly.

Table 2 – Materials, emissivity, and initial or constant temperatures of gasoline pool fire, safety barrier, and liquid hydrogen storage tank.

	Material	Emissivity	Initial temperature
(a) Gasoline pool fire	n-octane	1	1200 °C (constant)
(b) Safety barrier	Concrete	1	22 °C
(c) Liquid hydrogen storage tank	Structural steel thickness: 9 mm	0.2, 0.7	22 °C

Therefore, the worst possible scenario is that fracture of the outer material directly leads to fracture of the inner material, thus causing explosion. Considering this, the model used in this study was made of the only the outer material of the tank. The total number of nodes and elements were 46181 and 22320, respectively, and the distance between the pool fire and the liquid hydrogen storage tank (D) was varied as 3.5 m, 5.0 m, 6.5 m, 8.0 m, 11.0 m, and 14.0 m.

Results

Fig. 4 shows the effect of thermal radiation on the temperature distribution of the liquid hydrogen storage tank at $D = 3.5$ m and $\varepsilon = 0.7$. On the side near the pool fire, the temperature increases with the increase in exposure time, as shown in Fig. 4, whereas, on the opposite side, the temperature remains unchanged. This is because the tank is big, and therefore the heat is radiated before being conducted to the opposite side. Moreover, the temperature distribution on the tank induces thermal stress. Fig. 5 shows the relations between the maximum temperature T_{max} on the hydrogen tank and the exposure time t at different distances for the emissivity values $\varepsilon = 0.7$ and $\varepsilon = 0.2$. As D increases, the maximum temperature and temperature increase rate decrease, as shown in Fig. 5a and b. It can be inferred that smaller values of ε result in slower increases in temperature. Fig. 6 shows the von Mises stress distribution on the hydrogen tank at the exposure time of 30 min for $D = 3.5$ m and $\varepsilon = 0.7$. The maximum von Mises stress $\sigma_{v,max}$ occurs on the flanked material and not on the front side. This location may correspond to the largest temperature gradient. Fig. 7 shows the relations between the maximum von Mises stress on the hydrogen tank and the exposure time at different distances for$\varepsilon = 0.7$ and $\varepsilon = 0.2$. As D decreases, the maximum von Mises stress increases because of the higher temperature gradient.

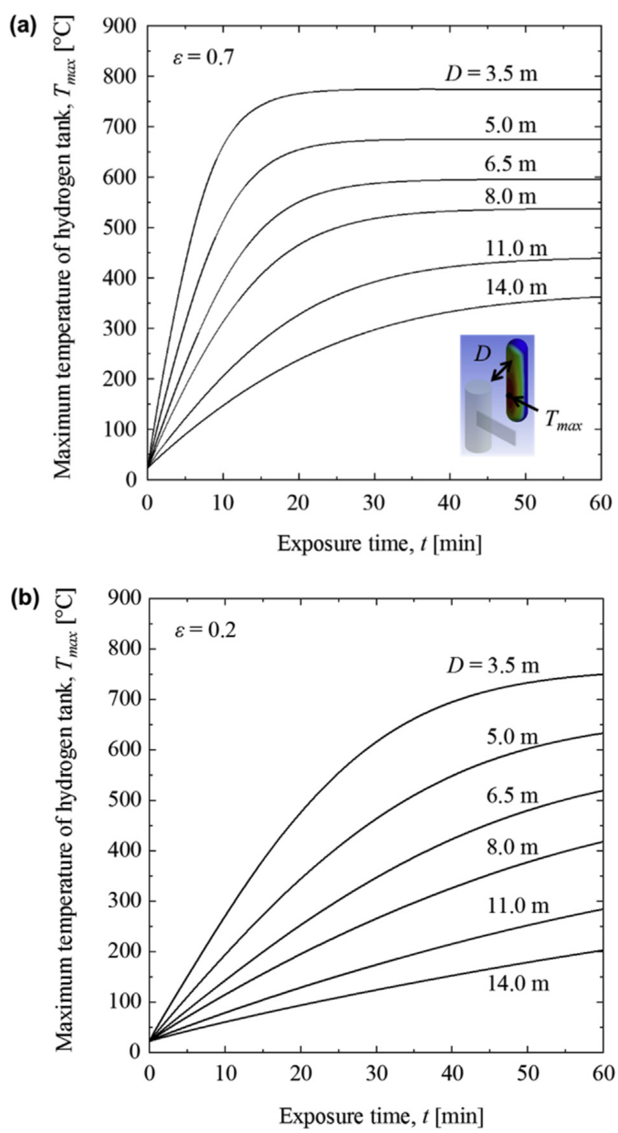


Fig. 5 – Relations between maximum temperature on hydrogen tank and exposure time at different distances for (a) $\varepsilon = 0.7$ and (b) $\varepsilon = 0.2$.

Discussion

Safety criteria

To evaluate the safety of the liquid hydrogen storage tank, tolerance ranges need to be set up for temperature and stress. Fig. 8 shows the stress–strain curves of structural steel (JIS SS400) at different temperatures, provided by Furumura et al. [33]. It can be observed that clear yielding points exist at room temperature (R.T.), 100 °C, and 200 °C, whereas no clear yielding points exist at 300 °C, 400 °C, 500 °C, and 600 °C. To investigate the effect of temperature on yield strength, 0.2% proof strength was used instead of yield strength for temperatures over 300 °C. Fig. 9 shows effect of temperature on yield strength or 0.2% proof strength and tensile strength of structural steel (JIS SS400), as given by Saito [34]. The yield strength or 0.2% proof strength decreases as the temperature increases. In this study, the tolerance ranges for temperature and stress were set up as the shaded area in Fig. 9, which indicates temperatures lower than 500 °C and von Mises stresses lower than 150 MPa. When steels are subjected to the stress equivalent to the yield strength just once, fracture does not occur in general. However, when steels are repeatedly subjected to the mechanical stress equivalent to the yield strength, fatigue fracture generally occurs at 10^4–10^5 cycles. Moreover, the thermal fatigue life might be shorter than the mechanical fatigue life. To evaluate the liquid hydrogen storage tank safety more cautiously, the stress tolerance is set up to be within the range from 0 MPa to the yield strength. Moreover, 500 °C is selected as the maximum tolerance temperature because the yield strength decreases sharply between 500 °C and 600 °C in Fig. 9. In addition, heating over 500 °C might generate residual stresses. In this study, the safety of the liquid hydrogen storage tank was considered to be ensured if the maximum temperature and stress obtained from the ANSYS analysis of a 30 min pool fire were within the set tolerance ranges.

Safety distance

The minimum safety distance between a liquid hydrogen storage tank and a gasoline pool fire was calculated using the

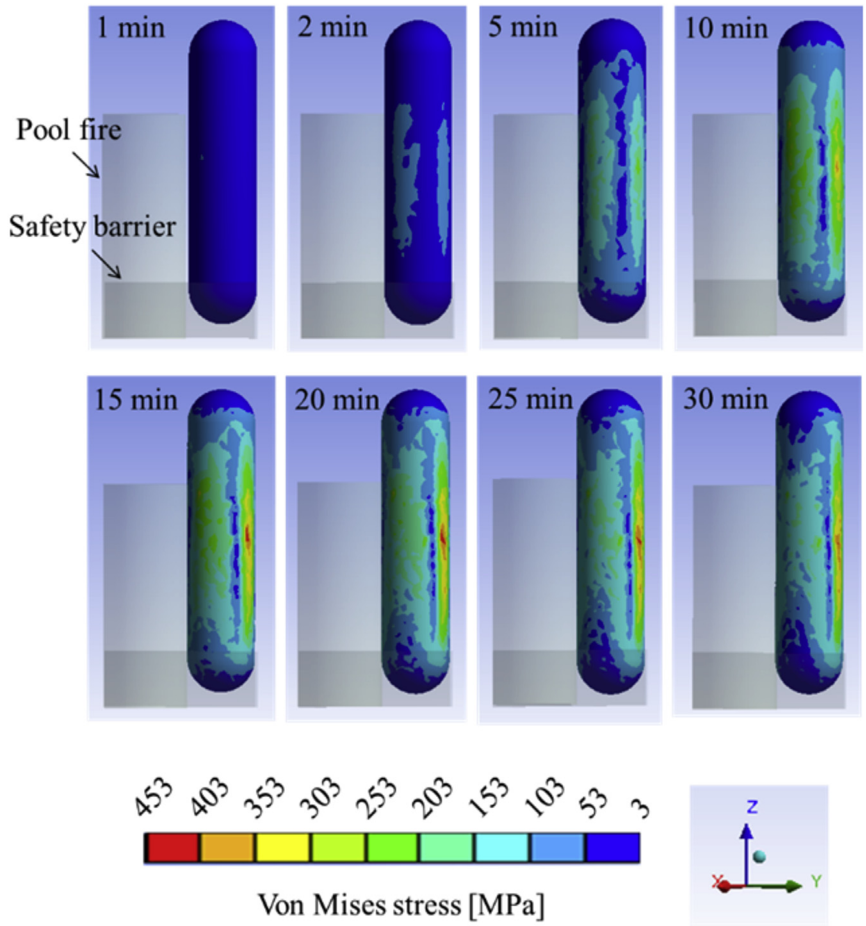


Fig. 6 – Distribution of von Mises stress on hydrogen storage tank at $D = 3.5$ m and $\varepsilon = 0.7$.

tolerance criteria defined in Section 4.1. Based on the temperature criteria, the safety distance was calculated as approximately 8 m and 5 m from Fig. 5(a) and (b), respectively, whereas, based on the stress criteria, it was calculated as approximately 14 m and 7 m, from Fig. 7(a) and (b), respectively. Therefore, for $\varepsilon = 0.2$ and 0.7, the minimum safety distances are approximately 7 m and 14 m, respectively. For efficient use of the small space in Japan, the surface of liquid hydrogen storage tanks should have lower emissivity. Thus, it is desirable that ε and D be less than 0.2 and more than 7 m, respectively. This D value of 7 m corresponds to a safety distance of 8.5 m between liquid hydrogen storage tanks and gasoline dispensers. These results were obtained considering the thermal stresses in addition to the maximum temperature. Moreover, the pool fire height in this study was larger than that calculated by the FDMA because of the difference in calculation methods. Therefore, compared with the 3.9 m safety distance recommended by the FDMA, the safety distance determined in this study is longer. The scenario analyzed in this study, 30 min of pool fire, is an extreme case. However, liquid hydrogen storage tanks in stations are high-hazard and should be carefully treated. Furthermore, the European Industrial Gases Association (EIGA) has recommended the minimum safety distance between liquid hydrogen storage and flammable gas storage as 8 m [35]. This value is nearly the same as the distance obtained in this study. To reduce the distance, various safety measures are required, e.g. additional thermal shields such as protective intumescent paint and water sprinkler systems and increased slope to lead gasoline off to a safe domain away from the liquid hydrogen storage tank.

Conclusions

In this study, the scale of gasoline pool fires in hybrid hydrogen–gasoline fueling stations was estimated using TRACE and, subsequently, the temperature and the stress due to temperature distribution were estimated using ANSYS. Based on the results, the safety of liquid hydrogen storage tanks was discussed. It was concluded that the emissivity of the outer material of the tank and the safety distance between liquid hydrogen storage tanks and gasoline dispensers should be less than 0.2 and more than 8.5 m, respectively. Moreover, additional safety measures are suggested to reduce the safety distance.

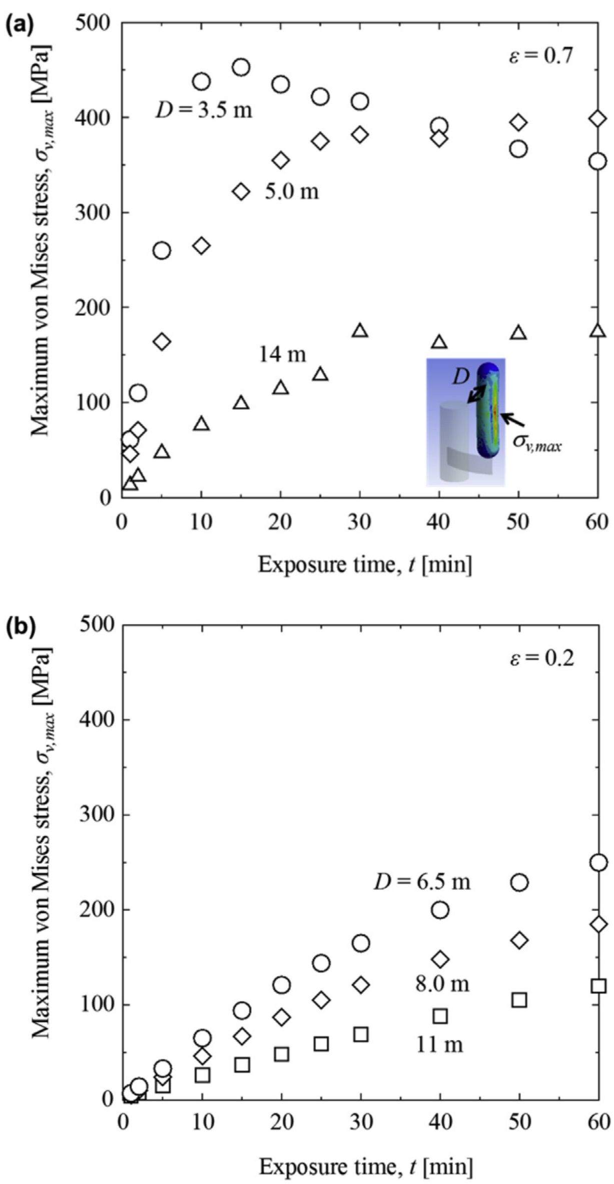


Fig. 7 – Relations between maximum von Mises stress on hydrogen tank and exposure time at different distances for (a) $\varepsilon = 0.7$ and (b) $\varepsilon = 0.2$.

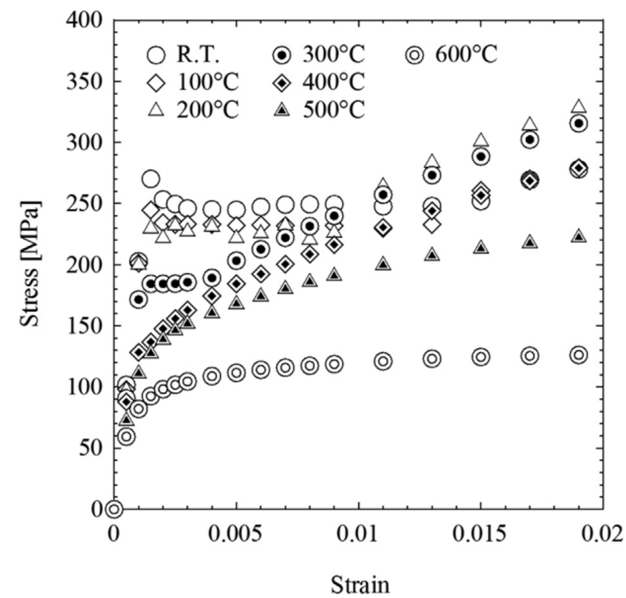


Fig. 8 – Stress–strain curves of structural steel (JIS SS400) at different temperatures [33].

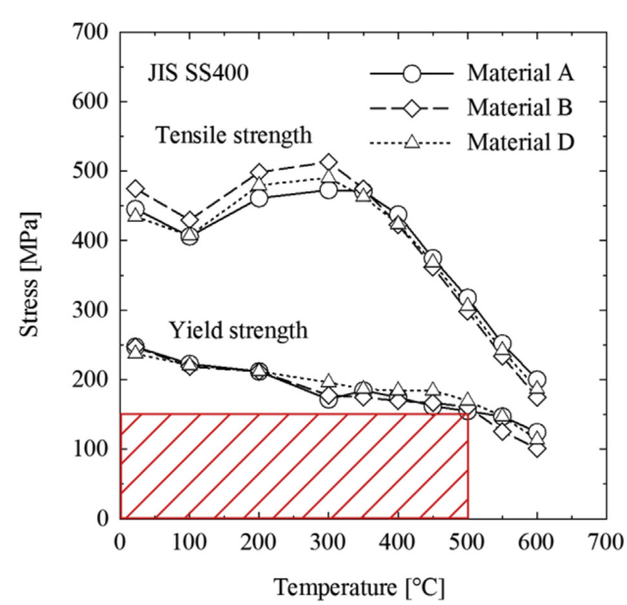


Fig. 9 – Effect of temperature on yield strength or 0.2% proof strength and tensile strength of structural steel (JIS SS400) [34] (Shaded area indicates tolerance ranges set up in this study).

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