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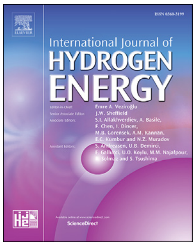

Temperature rise of hydrogen storage cylinders by thermal radiation from fire at hydrogen-gasoline hybrid refueling stations

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ABSTRACT

This study focuses on two types of hydrogen-gasoline hybrid refueling stations, and a risk assessment study on thermal radiation is carried out with a fire at each hybrid station. One of the hybrid stations has bare hydrogen storage cylinders, and the other has container walls around the cylinders. We calculate radiative flux to the cylinders from the fire occurring at the gasoline refueling machines in each hybrid station. Additionally, we calculate the temperature rise of the cylinders based on the obtained radiative flux. To evaluate a dangerous case for hybrid stations, we calculate the radiative flux and temperature rise using a large scale and high temperature fire. Based on our analysis, we find that the container walls can greatly insulate the radiative flux. Therefore, we show that we are able to keep the temperature of the cylinders below the hazardous temperature of 358 K by installing container walls around them.

Introduction

Hydrogen is expected to be the next generation energy across the globe. In Japan, hydrogen has been used in numerous fields, the most well-known being hydrogen Fuel Cell Vehicles (FCVs). Owing to support by the Japanese government, car companies have also been developing FCVs. In order to get FCVs into mainstream use, we must build a network of hydrogen refueling stations. For this reason, many risk assessment studies for a safe design of hydrogen refueling stations have been conducted [1–8]. Due to these studies, effective steps to protect the stations have been proposed when a fire occurs from hydrogen supply system or hydrogen leaks from that system. As a result, safety standards for hydrogen refueling stations have been established. Presently, not only those separated hydrogen refueling stations, but also hydrogen-gasoline hybrid refueling stations are also being built. The hybrid stations pose a higher risk compared to

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Nomenclature

A	Surface area, m^2
c	Specific heat capacity, J/(kg K)
F	View factor
G	Radiosity, W/m^2
J	Irradiation, W/m^2
M	Mass, kg
q	Radiative flux, W/m^2
T	Temperature, °C
t	Time, s
Greek	
ε	Emissivity
σ	Stefan-Boltzmann constant, $W/(m^2 K^4)$

separate stations. However, the number of risk assessment studies for the safe design is not sufficient [9]. We consider that the most dangerous situation at a hybrid station to be a fire originating at the gasoline refueling machines. Due to thermal radiation from the fire, the temperature of a high-pressure hydrogen storage cylinder increases, making the cylinder rupture likely. Thus, the risk assessment study to protect the storage cylinders from the fire occurring at the gasoline refueling machines in a hybrid station is important considerably. Sakamoto et al. [10] simulated the thermal radiation irradiated from a fire to a large liquid hydrogen storage cylinder. Therefore, the impact of the distance between the fire and large liquid hydrogen storage cylinder on user safety was clarified. However, an effective way to protect gaseous hydrogen-filled cylinders used for the FCV refueling process has not yet been proposed. As a result, the installation standard of the cylinders is not established, and the installation method varies from station to station. Specifically, many hybrid stations completely cover the cylinders with container walls, while other hybrid stations install the cylinders bare. We believe that a unified installation standard for the cylinders is needed. In this article, we attempt to elucidate the fire propagation and heat transfer dynamics in hydrogen-gasoline hybrid refueling stations. To achieve this, we investigate two separate fire propagation cases, one in the absence and one in the presence of container walls around the cylinders. From these investigations, we evaluate the temperature rise of the cylinders by the thermal radiation, and show the effect of container walls on the fire propagation mechanism.

Analytical model and method

Analytical models and conditions

Fig. 1 shows two hydrogen-gasoline refueling stations where fires have broken out at each gasoline refueling machine. The hybrid station in Fig. 1(a) has installed 9 bare hydrogen storage cylinders. The hybrid station in Fig. 1(b) has installed the 9 cylinders which are completely covered by 5 container walls. Each analytical model was assumed to be closed by a black-body surface (boundary surface). In each cylinder in Fig. 1, numbers were allocated to each cylinder sequentially from the lower left as shown in Fig. 1(a) and (b). Additionally, each container wall was named sequentially from the wall on the fire side as shown in Fig. 1(b).

In this study, to assume as a large scale fire, the diameter and height of the fire were set to 8.0 m and 12.0 m. The distance between the fire and cylinders 1, 4 and 7 was set to 15.0 m based on a regulation in Japan (High Pressure Gas Safety Act). The diameter and length of each cylinder were set to 0.44 m and 5.0 m, respectively. In the analytical model shown in Fig. 1(b), the thickness of the container walls for thermal insulation was defined as 1.6×10^{-3} m.

Subsequently, the conditions of the fire, cylinders, container walls and black-body surface are shown in Table 1. The fire source was defined as gasoline, and the material of cylinders and container walls were defined as steel. The emissivity of the fire, black-body surface, cylinders, and container walls were set to 1.0, 1.0, 0.7 and 0.7, respectively. The initial temperature of the fire was set to 1473 K, and the initial temperatures of cylinders, container walls and black-body surface were defined as 313 K. Since the emissivity of fires and black-body surfaces were 1.0, their temperatures were defined as constant. Based on the conditions, we calculated the radiative flux to the cylinders and container walls, and then we obtained the temperature rise of each cylinder using the mass and specific heat capacity in Table 1.

Calculation methods of radiative flux to and temperatures of hydrogen storage cylinders

We defined an irradiated hydrogen storage cylinder as targeted element i, and the fire, the black-body surface and the other cylinders radiating to the targeted element i as elements j. The radiative flux transferred to the targeted element i from the elements j is shown as follows:

$$q_i = G_i - J_i \tag{1}$$

where q_i is the radiative flux to the targeted element i, G_i is the irradiation from the elements j, J_i is the radiosity from the targeted element i. The irradiation in Equation (1) is given as:

$$G_i = \frac{\sum_{j=1(j\neq i)}^{N} A_j F_{ji} J_j}{A_i} \tag{2}$$

where F_{ji} is the view factor from the element j to the targeted element i, J_j is the radiosity from the element j, A_i and A_j are the surface areas of the targeted element i and the element j, and N is the number of elements. The irradiation can be transformed as follows by applying the interrelationship of view factors for Equation (2).

$$G_i = \sum_{j=1(j\neq i)}^{N} F_{ij} J_j \tag{3}$$

The radiosity in Equation (1) is given as:

$$J_i = (1-\varepsilon_i)G_i + \varepsilon_i \sigma T_i^4 \tag{4}$$

where ε_i is the emissivity of the targeted element i, σ is the Stefan-Boltzmann constant, and T_i is the temperature of the