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A CFD simulation of hydrogen dispersion for the hydrogen leakage from a fuel cell vehicle in an underground parking garage☆

Jongrak Choi [a], *Nahmkeon Hur* [a,*], *Seongwon Kang* [a,*], *Eun Dok Lee* [b], *Kwang-Bum Lee* [b]

[a] *Department of Mechanical Engineering, Sogang University, Sinsoo 1, Mapo, Seoul 121-742, Republic of Korea*

[b] *Department of Advanced Vehicle Safety Research, Korea Automobile Testing and Research Institute, Samjon 625, Songsan, Hwaseong, Gyeonggi 455-871, Republic of Korea*

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ABSTRACT

In the present study, the dispersion process of hydrogen leaking from an FCV (Fuel Cell Vehicle) in an underground parking garage is analyzed with numerical simulations in order to assess hazards and associated risks of a leakage accident. The temporal and spatial evolution of the hydrogen concentration as well as the flammable region in the parking garage was predicted numerically. The volume of the flammable region shows a non-linear growth in time with a latency period. The effects of the leakage flow rate and an additional ventilation fan were investigated to evaluate the ventilation performance to relieve accumulation of the hydrogen gas. It is found that expansion of the flammable region is delayed by the fan via enhanced mixing near the boundary of the flammable region. The present numerical results can be useful to analyze safety issues in automotive applications of hydrogen.

1. Introduction

Recently, there has been a lot of interest in using hydrogen for automobiles such as a fuel cell vehicle (FCV). This is due to several advantages of hydrogen such as its regenerative feature, no production of carbon dioxide and a possible increase of the thermodynamic efficiency. Meanwhile, there have been many concerns on the safety of hydrogen in automotive applications. Hydrogen is a light gas with a relatively large flammable region and a fast flame speed [1]. Hydrogen has the flammable range of 4–74% and the detonation range [2] of 11–59% by volume. These imply that a hydrogen deflagration accident can incur more serious medical and economic loss compared to conventional fuels. These features raise several safety issues in production, transportation and storage of the hydrogen gas.

Thus, it is very important to assess the safety of hydrogen for automobiles in various situations. One of the most dangerous situations is a leakage of hydrogen from an FCV in an underground parking garage. Theoretically, it is

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* *Corresponding authors*. Tel.: +82 2 705 8637; fax: +82 2 713 8637.
E-mail addresses: nhur@sogang.ac.kr (N. Hur), skang@sogang.ac.kr (S. Kang).

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straightforward to do an experiment of a hydrogen leakage accident and measure the dispersion characteristics. However, an experiment of hydrogen leakage has a high risk because of the possibility of hydrogen deflagration. In order to avoid the high risk of a hydrogen experiment, a numerical simulation has become a very important alternative [3]. A simulation using computational fluid dynamics (CFD) techniques can provide detailed data such as the concentration of hydrogen, the flammable region, the spatial dispersion, etc.

There are several previous studies on hydrogen leakage phenomena in various situations [4–8]. Takeno et al. [9] performed an experimental study on hydrogen dispersion in case of leakage from a pressurized vessel. Liu et al. [10] proposed a numerical model for the dispersion process of hydrogen which produced results consistent with the data of Takeno et al. Vudumu and Koylu [11] carried out a numerical study of the mixing process of hydrogen from a modeled accident and assessed the flammability. They performed simulations for different geometries such as confined, partially closed and open areas and predicted the evolution of the flammable regions in time. Mukai et al. [12] investigated the dispersion phenomena of hydrogen from an FCV inside a tunnel and underground parking garage. For each case, they investigated the dispersion characteristics and the safety risk. Although several studies have been done for hydrogen leakage, most of studies have focused on the dispersion characteristics of hydrogen, and there are only few studies that focused on the temporal change of the flammable region in a closed area such as an underground parking garage. The evolution of the flammable region can strongly depend on the flow rate of hydrogen. Besides, there are only few studies which performed a quantitative analysis of the effect of a ventilation fan on flammable envelop size.

In the present study, we investigated the dispersion of hydrogen for a model parking garage that meets the official Korean regulations. There are two objectives: (1) to make a quantitative analysis based on detailed simulations of hydrogen dispersion and (2) to evaluate safety for a few situations of hydrogen leakage in a parking garage. We performed a parametric study by changing the flow rate of hydrogen leaking from a model vehicle and analyzed the dispersion phenomena based on the temporal evolution of the flammable region. We investigated the effect of ventilation fans with different discharge rates on the change of the flammable region.

2. Description of problem and cases

In the present study, we considered an underground parking garage and used a model that satisfies the official Korean regulations. Fig. 1(a) shows the configuration and dimension of computational domain. It is assumed that the parking garage has 12 slots and hydrogen leaks from an FCV parked at one of the corners away from the entrance. We assume that the location of the FCV with leakage is selected for the most dangerous situation in the given condition. The size of a parking slot is chosen as the smallest one allowed by the regulation based on the assumption that a smaller parking garage tends to be more dangerous than a larger one for the same hydrogen leakage rate; thus, the width of each parking slot is determined as 2.3 m. As shown in Fig. 1(b), an FCV is modeled as a typical shape of a small passenger car and hydrogen is assumed to leak from a pipe near the hydrogen tank in the rear. The leakage area is assumed as a square of 5 cm in length and the leakage velocity is set to satisfy the assumed volume flow rate of leaking hydrogen. Notably, the leakage velocity from a high pressure tank is typically sonic or supersonic and much larger than the leakage velocity we used, because of the relatively large leakage area considered in the present study. In practice, there is a high possibility of a blockage effect by the ground and the other parts located near the bottom of a vehicle. It is expected that the high initial momentum of the gas from the vessel is gradually diffused and damped up to the point where the gas leaves the bottom region of the vehicle. Thus, it is assumed for simplicity that the leakage flow rate rather than the velocity has the major effect on the long term evolution of the flammable region that is the main topic of the present study. Under an assumption that the buoyancy force is important in the present problem, the mass flow rate should be an important factor because it can significantly affect the local and global fraction of hydrogen in the garage at a specific time. The atmospheric pressure is assumed at the entrance of the parking garage and the no-slip condition is used at walls. The pressure value at the entrance is typically higher than the external atmospheric pressure. Since the accurate pressure value depends on the specific configuration of the vent, we conveniently assumed a relatively wide entrance door and vent to ignore the pressure drop and used the atmospheric pressure at the door in our model.

As shown in Fig. 2, two different configurations were considered based on the shape of the entrance and the existence of an indoor ventilation fan. In the first configuration, the size of the entrance is 5 m in width and 0.1 m in height (closed with a small opening) and there is no ventilation fan. We assumed this case as the worst case scenario for this model parking garage. In the second configuration, the size of the entrance is 5 m in width and 2.3 m in height (open) and there is an indoor ventilation fan running constantly. The effect of the ventilation fan is simulated by an additional source term to the momentum equation. The size and discharge rate of the ventilation fan is set based on the specification of several fans commercially available. The cases considered in the present study are described in Table 1. We considered several different leakage rates of hydrogen as the primary parameter. The unit of the leakage rate Q is the mass rate of hydrogen with the energy equivalent to a gasoline leakage regulated by U.S. FMVSS 301 [13]. This unit has been conventionally used in several previous studies for hydrogen and other explosive gases and is equivalent to $Q = 131$ L/min in the present study. For the case with the open entrance and ventilation fan, three different air volumes of the fan are considered. The flammable region at a given time is identified by the flammable condition of hydrogen. From Cengel and Boles [14], the flammable range is 4–74% by volume of hydrogen.

3. Computational setup

For simulating flows with hydrogen dispersion and identifying the flammable region, three basic conservation equations of