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Dispersion of hydrogen leaking from a hydrogen fuel cell vehicle

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ABSTRACT

Hydrogen will be an important energy carrier in future energy supplies. Since hydrogen is portable and has a reasonable energy density, hydrogen will be especially important for transportation. However, a vital issue for hydrogen fuel cell vehicles (HFCV) is the safety concerns when hydrogen is leaking from a damaged vehicle after an accident. This paper describes simulations of the use of a portable blower to disperse hydrogen around a leaking vehicle when the blower is in front of the vehicle so that first responders can safely approach the vehicle. The simulations compare well with previous experimental results for a blower in front of the vehicle. The calculations predict the hydrogen concentration distributions around a vehicle for various scenarios to find the most effective solution to provide safe hydrogen levels around the vehicle. The models show that a ground effect blower with the diffuser flush to the floor more effectively removes most of the hydrogen to create a safety envelope around the vehicle. The results also show that the first responders should not approach the vehicle from the side opposite the blower where the hydrogen concentrations would still be close to the lower flammability limit even with a blower.

Introduction

Hydrogen fuel cell vehicles are a promising future solution for transportation systems in the future low-carbon society, because the vehicle itself discharges zero carbon dioxide. However, there are some important problems with HFCVs that need to be solved, of which safety is the most significant with hydrogen as an energy carrier especially for transportation systems. When a car accident happens with a fuel cell vehicle, the most dangerous problem after the accident is hydrogen leakage. The hydrogen concentration around a leaking car will quickly reach dangerous levels that exceed the lower hydrogen flammability limit of 4% mole fraction in air which creates a serious explosion hazard. Therefore, measures must be taken to reduce the hydrogen concentration to ensure the safety of drivers, passengers and first responders.

Some experiments have been done to examine the physics of hydrogen leaks and the key parameters that influence the leaks, as well as methods to reduce the hydrogen concentrations around a leak.

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Houssin-Agbomson et al. [1] observed the influence of the height of the release point in an enclosure on the flow regime and the influence of the flow rate on the maximum concentration in the enclosure.

Gupta et al. [2] ran a series of helium dispersion experiments and found that the risk during an accident with leakage is more influenced by the total volume of gas released than the flow rate and that flow rate variations can change the decay rates of the gas concentrations.

Tamura et al. [3] experimentally investigated methods to disperse hydrogen from around a car that could be used by first responders after fuel cell vehicle accidents. They showed that forced air flows of 10 m/s with or without a duct effectively dispersed the hydrogen for a hydrogen leak rate of 2000 NL/min with hydrogen concentrations near the car and in the vehicle interior being less than the lower flammability limit of 4 vol.% hydrogen.

Numerical simulations have also been used to investigate hydrogen leaks as a less expensive and less dangerous method than experiments.

Molkov et al. [4] modeled passive ventilation of a sustained gaseous release in an enclosure with one vent using Computational Fluid Dynamics (CFD) simulations compared against measured helium concentrations. They developed a criterion for mixture uniformity based on three dimensionless ratios for the ratio of the entrainment rate to the mass flow rate of the mixture out of the enclosure, the ratio of the enclosure surface area to the vent area, and the ratio of the release source diameter to the vent height.

Tran et al. [5] numerically simulated the mixing and dispersion of helium injected into an air-filled cavity to reproduce the results of experiments by Bernard-Michel et al. [6] The simulation results were reasonably close to experimental data, but some aspects of the model still needed to be improved.

Numerical simulations are a powerful tool for research, but there are few numerical studies of hydrogen dispersion. This study simulates hydrogen dispersion around a vehicle for the same conditions as in the experiments by Tamura et al. [3] when the blower is in front of the vehicle. The simulation results compare well with the experimental data for two cases. Then, the hydrogen dispersion is simulated with a smaller, more portable blower that directs the air right along the floor to evaluate better methods for hydrogen dispersal. Xie et al. [7] did a similar study for a fan blowing from the side of the vehicle and showed that a smaller blower with higher velocities provided better hydrogen dispersion efficiencies, but a smaller blower would be most effective when the leak position was accurately known, which is not the case in most accident situations. The present study assumes that the blower is in front of the vehicle which has three advantages in that accurate knowledge of the leak location is not so important because the vehicle is not as wide as it is long, the blower blows the hydrogen towards the back of the vehicle rather than the side so that the higher hydrogen concentrations are further from the doors that the first responders would use to reach the occupants if necessary and the blower blows the hydrogen away from the hot engine compartment.

Model and theory

A transient, three-dimensional model was used to model the hydrogen leaking around a vehicle. The simulation solved the Navier–Stokes equations with the energy equation, the species transport equation and the standard k-ε turbulence model [8]. The gases were modeled as incompressible ideal gases since the compressibility effects are important only over a very small region hear the leak point. Calculations using the compressible gas model yielded essentially the same results.

The equations were solved by Fluent 6.3 in a three-dimensional region around and under the car that extended far enough from the vehicle so that the outer boundaries did not affect the flows around the car. The space was assumed to be symmetric since the leak and all the boundary conditions were symmetric. The total computational region was 3 m high, 5 m wide and either 11.67 m long for the 2 m case or 14.67 m long for the 5 m case. The car was modeled as a 4.67 m long, 0.848 m wide (half of the vehicle width due to symmetry) and 1.845 m high block. Since the air was blown from the front, the sloped windshield was also included with the windshield starting to slope at a height of 0.9 m and extending back 1.6 m from the front as shown in Fig. 1. Initial calculations showed that the sloped front had a large effect on the flow going under the vehicle. The bottom of the car was 0.16 m above the ground and the exit was 5 m beyond the back of the car. Two of the experiments of Tamura et al. [3] were modeled with a blower placed either 2 m or 5 m in front of the car with the blower centerline aligned with the car centerline. The cases model first responders using a blower to disperse the hydrogen before approaching the car to evaluate the efficacy of the blower arrangement and the time needed to disperse the hydrogen near the vehicle to below the lower flammability limit. The space under the car was meshed with hexahedrons while the space around the car was meshed with tetrahedrals. Fig. 1(a) shows the elements on the symmetry plane. Fig. 1(b) shows an expanded view of the elements on the symmetry plane under the car near the leak point which were hexahedrons. Case 1 (2 m) had a total of 1.03 million elements, while case 2 (5 m) had 1.04 million elements.

The equations were solved using the density solver with the second order upwind scheme for all the advection terms. The standard k-ε turbulence model was used with the standard wall functions.

The boundary conditions used the velocity inlet condition for the hydrogen leakage point and the blower, symmetry for the symmetry plane, and the pressure outlet (pressure = 0) condition for the exit and all other surfaces. According to Gupta et al. [2], the total volume of gas flowing into the area is more important than the instantaneous flow rate or the velocity, so the hydrogen inlet conditions were specified to give the same total volumetric flow rate. The hydrogen leak was directly underneath the middle of the car (hole center was 2.335 m from the front of the car) at ground level with the flow directly upwards as in the experiments. An actual leak would flow downwards from the bottom of the car, but the flow