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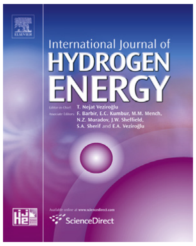

Review

Numerical study of hydrogen release accidents in a residential garage

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ABSTRACT

The increase in the number of applications using hydrogen in the marketplace will require a better understanding of the dispersion and accumulation associated with accidental leaks in a structure. Predict the evolution of the hydrogen concentration over time in a structure, with different flow rates and positions of leak is challenging. CFD modeling was employed extensively in a study designed to characterize possible modifications and costs associated with parking hydrogen-fueled automobiles in buildings. We describe our CFD approach in sufficient detail to justify the choice of model using the commercial software FLUENT, and we explored the relationship between leak positions, release rates, leak duration and hydrogen concentration. When the leak position is approaching to the center of the garage, there is encouragement of stable stratification. Hydrogen concentration is higher and leak scenarios are more dangerous when the leakage time is important and the flow rate is low.

Introduction

The approach in favor of sustainable development helps reduce energy consumption, pollution control and diversification of primary energy sources, development of renewable energy. Hydrogen is one of the new energy which may limit long-term releases of greenhouse gas emissions. Indeed, the hydrogen used in fuel cells or in an internal combustion engine is an energy carrier which provides electricity and heat with water as the only residue. But even the hydrogen is "extremely flammable" gas classified: it has a wide flammability range from 4% to 75%. Its ignition energy is about 10 times lower than that of classic hydrocarbons. By cons, the auto-ignition higher temperature is around 585 °C. The hydrogen combustion flame in air is almost invisible and extremely hot (2000 °C). It showed a very high potential explosion in confined areas. It is the lightest of all gases; it diffuses very easily in the air and has a high propensity to flee [1].

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Storing a hydrogen fuel-cell car in a garage can pose a safety hazard if there is a leak from the fuel storage system that would result in a buildup of a flammable mixture within the structure or within the vehicle. Research on hydrogen leaks is important to avoid accidental ignition, and set the margin of safety for leaks. Therefore, to ensure the safe use of hydrogen, it is necessary to predict and understand the characteristics of its leakage and dispersion [1,2]. The knowledge of the characteristics of hydrogen–air mixture accumulated and its evolution over time is important for risk assessment. Previous studies of indoor hydrogen leaks have employed simplified analyses, computational fluid dynamics (CFD) modeling, and laboratory testing. The study subjects included a hydrogen jet through a nozzle [3], the boundary layers [4,5], the transient dispersion in a vertical cylinder [6], dispersion and natural ventilation in a garage [7,8] in a tunnel [9] and in domestic rooms [10], the effects of leakage and dispersion into the atmosphere [11]. Yassine Hajji et al. [1] studied by FLUENT the effect confinement on behavior of hydrogen for 1 h of the leak inside a prismatic cavity with an apex angle A. They have tested various values of A (A = 180°, 150°, 120° and 90°). They showed that the hydrogen concentration increases over time of leakage with formation of three layers where the flow degree of stratification varies from one layer to another and that the molar fraction is strongly influenced by the apex angle. Results have shown that an apex angle A of 120° can yield a lower molar fraction comparatively with A = 180°, 150° and 90°; which implies that 120° can be selected herein as an optimal apex angle. Lacome et al. [12] studied the temporal and spatial distribution of hydrogen released inside a cave sized to represent a single car garage with a single vent near the floor. Injected gas volume flow rates and durations were varied. Matsuura et al. [13] proposed an innovative risk mitigation control method employing forced ventilation based on the real-time sensing of leaking hydrogen. In Ref. [13], after clarifying the disadvantage of ventilation with a constant exhaust flow rate, a plot for the exhaust flow rates that we refer to as an acceptability diagram, is constructed to show acceptable exhaust flow rates for various inflow rates and leak positions. Assuming the real-time sensing of the hydrogen concentration and height-direction velocity, the volume flow rate of leaking hydrogen is then estimated. On the basis of the estimated leak flow rate and hydrogen sensor information near the roof, ventilation is controlled considering the acceptability region. The forced ventilation method ventilates hydrogen within about 10 s, one side of the space is completely open, and a hydrogen buoyant plume is subjected to cross flows during forced ventilation. William Pitt et al. conducted experimental studies to characterize the behavior of helium in a residential garage at a reduced scale of 1/4, the hydrogen–air mixture when it is released in a two-car residential garage [14]; they have studied the distribution of the hydrogen fraction into the garage with and without vehicle, the combustion behavior of hydrogen–air mixture resulting in damage of the garage and the vehicle. Matsuura [15] clarified the effects of the geometrical configurations of ventilation systems on leaking hydrogen dispersion and accumulation in terms of natural and forced ventilation. It is found to be very critical to understand the condition of taking air from outside through door vents in order to do forced ventilation of hydrogen safety. Matsuura et al. [16], for the first time as far as the authors know, proposed a real-time sensing based adaptive risk mitigation algorithm for leaking hydrogen in a partially open space. So far, a period of the order of 1000 s. has been necessary for natural ventilation in a space having size and leakage condition as considered in the present study. The ventilation control method proposed by Ref. [16] is a method of ventilating hydrogen within approximately a few tens of seconds. Barley et al. [7] studied the effectiveness of natural ventilation provided by two vertically separated vents on the build up of helium in a real-scale enclosure. Parameters varied included helium volume flow rates and helium release distribution.

If one looks only at the energy point of view, hydrogen seems to be the miracle solution to overcome the current energy and environmental crisis. Indeed, hydrogen seems inexhaustible and is present everywhere in the form of water, so it can be produced in all countries, which solves the economic and socio-political tensions between countries. In addition, it creates a priori no pollution. Hydrogen therefore appears ideal, but this view is very simplistic and does not take into account the various difficulties mentioned above for the production, storage, distribution and use especially because several studies have shown that the dispersion and accumulation hydrogen in confined spaces are examples of the most dangerous scenarios. Using hydrogen in the study requires a properly prepared system to ensure the secure execution experiments. In this regard, the CFD (Computed Dynamic Fluid) is considered a cost-effective and safe approach. If the constituent factors, such as chemical, physical, and turbulence models, boundary conditions, etc, are safety modeled, and the numerical schemes are verified [17], the methodology provides much information on the integral linkages that increase the potential hazard. This important information is required for minimizing computation.

In this study, the dispersion of hydrogen in a prismatic garage is studied by using the commercial software FLUENT, considering the important factors that influence on the behavior of the hydrogen concentration and accumulation such as the leak position, leak duration and the mass flow rate.

Models description

Mathematical model

The continuity and the compressible Navier–Stokes equations with gravitational force, as well as the energy and the transport equations for the hydrogen mass fraction are used to be numerically resolved. Gas species diffuse according to Fick's Law. The ideal gas equation is used to close the system of the equations. In formulating the governing equations, hydrogen buoyant plume is classed as non-Boussinesq [18,19], and therefore the Boussinesq approximation is not used. Buoyancy effects resulting from density differences owing to thermal and chemical reasons are treated directly. The mixture model solves the continuity equation for the mixture, the momentum equation for the mixture, the energy equation for the mixture, and the volume fraction equation for the