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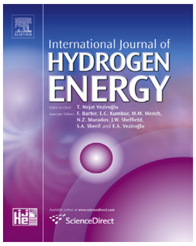

Assessment of similarity relations using helium for prediction of hydrogen dispersion and safety in an enclosure

Jiaqing He [a,b], *Erdem Kokgil* [b], *Liangzhu (Leon) Wang* [b], *Hoi Dick Ng* [a,*]

[a] *Department of Mechanical and Industrial Engineering, Concordia University, Montréal, Québec, H3G 1M8, Canada*
[b] *Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Québec, H3G 1M8, Canada*

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ABSTRACT

The ability to predict the concentration of hydrogen in a partially confined space is significant to the safe use of hydrogen-related products such as fuel cell vehicles. Hydrogen release and subsequent dispersion are frequently investigated using commercially-available computational fluid dynamic (CFD) models once those are calibrated with available experimental data. Due to the explosion safety concerns of using hydrogen, accidental scenarios are often replicated with helium as a hydrogen simulant in experiments. Currently, there is no validated, theoretical analogy to correlate the helium data in order to predict the spatial and temporal distribution of hydrogen in the enclosure. The aim of this paper is to assess different theoretical relationships for the similarity between hydrogen and helium leakage in an enclosure. Experiments were first carried out to obtain measured data with helium leakage in a set of scenarios and to validate the present CFD model. Three methods, namely equal volumetric flow rate, equal buoyancy and a newly proposed correlation derived from equal concentration, were employed to determine the equivalent hydrogen release rate, using which the validated CFD model was then used, with the physical property values for hydrogen, to stimulate hydrogen dispersion as compared to that of helium. The accuracy of these different methods at different stage of release and location is discussed. The present result thus provides a guide when using helium experiment to validate hydrogen simulation in different scenarios, which is of importance to the investigation of hydrogen safety.

Introduction

Hydrogen is considered as one of the leading fuels for a renewable and environment friendly energy carrier in the near future [1–6]. In particular, fuel cells using hydrogen present significant advantage in reducing carbon emissions generated by transportation systems and have higher efficiency when compared with traditional fossil fuels [7–10]. However, the high-pressure storage and use of hydrogen pose unique challenges due to its ease of leaking, low-energy ignition, a wide range of combustible fuel-air mixtures, high

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[*] *Corresponding author*. Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Blvd. West, Montréal, Québec, H3G 1M8, Canada. Fax: +1 (514) 848 3175.

E-mail address: hoing@encs.concordia.ca (H.D. Ng).

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Nomenclature

b	plume radius, m
B	buoyancy flux, m^4/s^3
C	volumetric concentration
g	gravity, m/s^2
$\dot{m}$	mass flow rate, kg/s
n	correlation exponent
Q	volumetric flow rates, m^3/s
u	plume vertical velocity, m/s
v	air entrainment velocity, m/s
z	height, m
Greek letters	
α	entrainment ratio
ρ	density, kg/m^3

buoyancy and diffusion rate in air [11–16]. As such, the ability to predict the behavior of leaked hydrogen in an enclosure under different scenarios is of great importance.

An extensive wealth of studies on hydrogen release and dispersion can be found in the literature. For example, fundamental investigations on hydrogen dispersion and explosion predictions in simple geometries, like an enclosure or tunnel, have been carried out experimentally (e.g. [17–23], etc.) and with Computational Fluid Dynamics (CFD) (e.g. [24–36], etc.). Current research efforts, both experimental and computational, are starting more toward engineering aspects of real hydrogen vehicles and refueling station systems in practical environment and scenarios [37–45]. Although CFD tools have the potential to predict hydrogen dispersion and explosion with reasonable accuracy, those often required inter-comparison between different models, extensive calibration and validation efforts together with experiments [31–35]. Due to safety concerns, large-scale experimental data of hydrogen release remain scarce [42–46]. Hence, most of current hydrogen experiments against which CFD models were validated, are limited to small volumes or scaled experiments in simple enclosure geometries.

To alleviate any concern of accidental combustion while obtaining large-scale experimental data for CFD model calibration, helium was considered as a hydrogen stimulant due to the similar low densities of the two gases [47–51]. Swain et al. [47–49] used helium to simulate leakage scenario experimentally and to predict using a calibrated CFD model with helium data the spatial and temporal distribution of leaking hydrogen gas in equivalent accidental settings. The studies conducted by Swain et al. [47–49] formed the methodology referred to as the hydrogen risk assessment method (HRAM). This method consists of the following four steps: 1) Simulate the leakage scenario with helium; 2) calibrate a CFD model of the leakage scenario using the helium experimental data; 3) predict the distribution of hydrogen using the calibrated CFD model; and 4) assess the risk from the numerically simulated concentration of hydrogen leakage [49].

Helium is also used in a number of recent studies as a surrogate gas to analyze the dispersion behavior of hydrogen in a 1/4-scale and a realistic full-scale residential garage parked with a hydrogen-fueled vehicle [50–53]. The effects of injected volume, location and characteristics of leakage source (i.e., jet or plume) within the enclosure on the dispersion and mixing dynamics are investigated. The presence of ventilation is also considered using different combination of vent size, number and location.

For the aforementioned studies, the similarity is often assumed with helium released in an equal volumetric flow rate as with hydrogen. However, it has been found that there exists a difference between hydrogen and helium concentrations before the plume becomes stable, particularly during the initial release of the gases [47,48]. Currently, the equivalent behavior between the two gases only relies on numerical or experimental results, and the similarity is not backed up by a theoretical correlation. Therefore, the objective of the present study is to report an analysis of helium and hydrogen similarity for the commonly used method of equal volumetric flow rate, and two new methods based on the theoretical plume characteristics, and to compare the three methods by measurements and CFD simulations. Experiments using time-resolved measurements of helium concentrations at multiple heights in a sub-scaled garage model during the releases phase were conducted to obtain helium concentration data at a set of initial conditions. These experimental data were used to validate the CFD model in the present study. The validated CFD model was then used, with the physical property values for hydrogen, to simulate hydrogen release and dispersion while using the three different methods to determine the equivalent hydrogen release rate as compared to that of helium. A numerical resolution study was also presented to ensure the convergence of the numerical results using the chosen mesh size for the simulations.

Theory

From the previous work by Swain et al. [49] where the hydrogen risk assessment method (HRAM) is introduced, it shows that, in simple geometric enclosures, helium can be used to simulate leakages of hydrogen and to predict the hydrogen concentrations near the ceiling. The method to assess the risk of hydrogen leakage relies on a CFD model calibrated by the data from helium experiments. The similarity between hydrogen and helium is obtained based on $Q_{H_2} = Q_{He}$, where Q_{H_2} and Q_{He} are volumetric flow rates of hydrogen and helium, in m^3/s, respectively. Most current studies using helium as a surrogate to validate hydrogen simulation models are also formulated by assuming the same volumetric flow rate of both gases. Nevertheless, Swain et al. [48] observed that, before the plume becomes stable during the development stage, the helium concentration can be significantly different from that of hydrogen using the aforementioned analogy.

In order to use helium accurately as a surrogate gas for hydrogen, it is necessary to assess the similarity between the hydrogen and helium plumes. Inspired by the ideal plume theory in the field of fire science [54], the ideal plume models of hydrogen and helium can be developed as shown in Fig. 1. Similar to that of a fire plume, the buoyancy flux of a buoyant gaseous plume, B in m^4/s^3, can be defined by: