NATURAL AND FORCED VENTILATION OF BUOYANT GAS RELEASED IN A FULL-SCALE GARAGE: COMPARISON OF MODEL PREDICTIONS AND EXPERIMENTAL DATA*

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ABSTRACT

An increase in the number of hydrogen fueled applications in the marketplace will require a better understanding of the potential for fires and explosion associated with the unintended release of hydrogen within a structure. Predicting the temporally evolving hydrogen concentration in a structure, with unknown release rates, leak sizes and leak locations is a challenging task. A simple analytical model was developed to predict the natural and forced mixing and dispersion of a buoyant gas released in a partially enclosed compartment with vents at multiple levels. The model is based on determining the instantaneous compartment over-pressure that drives the flow through the vents and assumes that the helium released under the automobile mixes fully with the surrounding air. Model predictions were compared with data from a series of experiments conducted to measure the volume fraction of a buoyant gas (at 8 different locations) released under an automobile placed in the center of a full-scale garage (*6.8 m x 5.4 m x 2.4 m*). Helium was used as a surrogate gas, for safety concerns. The rate of helium released under an automobile was scaled to represent *5 kg* of hydrogen released over *4 h*. CFD simulations were also performed to confirm the observed physical phenomena. Analytical model predictions for helium volume fraction compared favorably with measured experimental data for natural and forced ventilation. Parametric studies are presented to understand the effect of release rates, vent size and location on the predicted volume fraction in the garage. Results demonstrate the applicability of the model to effectively and rapidly reduce the flammable concentration of hydrogen in a compartment through forced ventilation.

1.0 INTRODUCTION

Substantial efforts are being directed towards the development of hydrogen-fueled automobiles as an approach for reducing the amount of carbon-dioxide generated by transportation systems and for reducing the dependence on fossil fuels. The US Department of Energy [1] has estimated that a transition to hydrogen as the main automotive fuel could be accomplished by the middle of the century. Hydrogen is clearly regarded as an energy carrier for future vehicles and offers the possibility of reducing pollution and securing the energy supply, especially when produced with renewable energy source.

Accidental release from a hydrogen-fueled application in a real world environment and the potential for subsequent fire and explosion can result in significant structural damage to surrounding buildings and loss of life and injury [2]. Ensuring the safety of hydrogen systems operated in a partially enclosed compartment (e.g. hydrogen-fueled vehicles parked inside a garage), is a key factor in ensuring a smooth transition towards a hydrogen-fueled economy. Motivated by this need for understanding and improving the safety of hydrogen systems, we examine the release and dispersion of a buoyant gas in a full-scale garage.

The volume fraction of hydrogen attained when it is released in a partially enclosed space depends on a number of factors. These include hydrogen release rate and duration (which in turn depends on initial pressure of the tank and size of the release port), location and cross-sectional area of the leaks in the compartment walls, and ventilation. These variables are generally not known a-priori in an accident scenario. An effective mitigation technique will attempt to reduce the envelope of flammable concentrations as quickly as possible to reduce the risk of potential fires and explosions. In this paper, we attempt to address these issues through a combination of experiments, numerical simulations and analytical models aimed at predicting the time-dependent concentration of a buoyant gas released in a partially enclosed compartment with natural and forced ventilation.

There have been only a limited number of studies that consider the natural and forced ventilation of a buoyant gas released under an automobile, parked in a realistic, full-scale garage. Concentration measurements during the release of helium underneath a wooden mock-up of an automobile placed inside a full-scale garage were reported by Swain [3]. These experiments have been simulated and substantial differences between model codes and experimental data was reported [4]. Release and dispersion in real scale enclosures using hydrogen has been reported [5] and modeled using a number of Computational Fluid Dynamics (CFD) software tools [6]. The experiments were performed in enclosures with well defined leaks, and did not consider the un-certainty associated with leak location and leak area distribution associated with realistic full-scale garages. Lowesmith et al. [7] have reported large scale experiments to study the accumulation of hydrogen mixtures released in a ventilated enclosure and have compared the results with a mathematical model. These experiments did not account for the mixing associated with the release under an automobile. Ventilation studies with various combinations of hydrogen release rate and ventilation speeds conducted in a rectangular enclosure with well defined leaks have been reported in [8].

The effect of releasing the buoyant gas under an automobile, on the flow field and concentrations attained inside the compartment has also not been studied extensively. Research indicates that vertical stratification can occur when buoyancy forces dominate and the release of the buoyant gas is not obstructed by the presence of an automobile [9,10,11]. On the other hand, when momentum forces dominate or when the flow is obstructed, the buoyant gas can get well-mixed with the surrounding air [12]. Turbulent mixing under the vehicle and the release of the buoyant gas as multiple plumes in and around the vehicle has been observed and reported in experiments [10]. The role of clutter in the garage on the flow field, and the transition from a stratified flow field to a fully mixed flow field has not been investigated adequately in the literature.

In this paper, we build upon published work on this subject by conducting detailed concentration measurements during the release of helium under an automobile parked in a garage. Helium is used as a surrogate gas for safety reasons. A simple analytical model is developed to predict the natural and forced mixing and dispersion of the buoyant gas in a partially enclosed compartment with vents at multiple levels and to simulate the experimental setup. The model is based on determining the instantaneous compartment over-pressure that drives the flow through the vents. Experimental data on helium volume fraction are compared with the results of the simple analytical model. CFD simulations are performed to further validate the analytical model and to explain the physical phenomena. The effect of forced ventilation on volume fraction is studied through experimental measurements and analytical modeling and the result from these studies are compared and contrasted.

2.0 EXPERIMENTS

The experiments were conducted inside a single car garage that is part of the National Institute of Standards and Technology (NIST) Indoor Air Quality and Ventilation Test House. Fig. 1 shows an exterior front (top left sub-figure) and rear (top right sub-figure) views of the garage, where the experiments were performed. Photographs indicating the important features of the garage are shown in the bottom right and left sub-figures (Fig. 1). The interior dimensions of the garage were 6.8 m (W) x 5.4 m (L) x 2.4 m (H), and it was equipped with a manual metal garage door with dimensions of 2.8 m (W) x 2.1 m (H). The garage door was located approximately in the center of front wall of the garage (distance between the garage door and the left and right walls was 1.5 m and 1.1 m respectively). There was a rear door leading to the outside of the test garage (Fig. 1 top and bottom right sub-figures), and a side door leading to the interior of the house. Each door measured 0.91 m (W) x 2.0 m (H). An exhaust fan with a louver measuring 0.76 m x 0.76 m (not used in the current experiment), was installed on the right wall of the garage. There was a window with dimensions of 0.9 m (W) x 1.16 m (H) on the back wall of the garage. For this test series, the louver and the fan outlet were sealed using aluminum duct tape, and the window was always closed. A mid-size passenger sedan was parked in the middle of the garage, i.e. centered over the release location, and helium gas was released under the automobile to simulate the release from a hydrogen fueled automobile. During the experiment, the four car windows were rolled up and closed, and the front hood and rear trunk were also closed.

Figure 1. Front view (top left sub-figure) of the garage showing a parked automobile, and rear view (top right sub-figure) showing a wooden door and ventilation fan in the NIST Indoor Air Quality and Ventilation Test House facility. Bottom left sub-figure shows the manually operated metal garage door, while the bottom right sub-figure shows the rear door that leads to the outside of the garage.

In order to estimate air-leakage rates through the garage envelope, door fan tests under controlled pressurization and de-pressurization conditions (as specified in the ASTM E779-03 standard) were performed using an INFILTEC Model E3 blower door fan[i], coupled with a digital micro-manometer Model DM4 for pressure (relative standard uncertainty of *1 %*) and flow measurements (relative standard uncertainty of *1.5 %*). The blower fan was mounted in the rear or side door, using an aluminum door panel with a nylon cover to seal the opening. A pressure differential (typically between *10 Pa* and *70 Pa*) was imposed across the door boundary, and the flow through the fan was measured. Average differential pressures ΔP (Pa) as a function of air flow rates Q (m^3/s) were plotted, and the data pairs were correlated using a power law :

[i] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

$$Q = C(\Delta P)^n \tag{1}$$

where, values of C, a leakage coefficient and n, the pressure exponent, were obtained through a least-square fit of the fan test data. The pressure exponent n varies between 0.5 (turbulent flow) and 1.0 (laminar flow). The Effective Leakage Area (ELA), defined as the equivalent orifice area that would provide the same flow rate through the building envelope for a given imposed reference pressure differential can be obtained from this data as follows.

$$Q = ELA\sqrt{2\frac{\Delta P}{\rho_0}}, \tag{2}$$

where, ρ_0 is the air density. Equations (1) and (2) were combined to obtain the ELA for the garage using a commonly used reference pressure differential of *4 Pa*.

Two 1A cylinders of helium were connected to each side of a switchable, dual-manifold high-pressure regulator to provide a continuous supply of helium for the experiments and while providing a safe means of changing out the depleted cylinders. The regulated flow was connected through a valve to a dry test meter (equipped with a pressure gauge) in order to control and measure the helium volumetric flow rate into the garage. The measured flow rates were corrected for pressure and temperature. The helium release rates was set to simulate the flow of *5 kg* of hydrogen over a *4 h* period, requiring a volumetric flow rate of $0.0042\ m^3/s$ (measurements were made at regular intervals in time, and ranged between $0.0040\ m^3/s$ - $0.0045\ m^3/s$. Helium was released into the garage from an open box having dimensions of *0.30 m x 0.30 m x 0.15 m*. The flow entered the box near the bottom and then passed through a support screen (diffuser) on which a *0.10 m* layer of *12 mm* crushed stone was held in place by a covering wire mesh screen before exiting into the garage. Helium volume fractions were monitored using thermal conductivity sensors, calibrated using the procedure described in [14, 15]. Eight sensors were mounted using a custom-built brackets attached to a metal rod at heights of *0.305 m, 0.610 m, 0.914 m, 1.219 m, 1.524 m 1.829 m 2.134 m* and *2.388 m* from the garage floor, respectively. The rod was placed at a co-ordinate location of (*1.37 m, 6.29 m*) with its origin at the lower front left corner of the garage. The sensor voltage outputs were digitized and saved at one second intervals using a data acquisition system. Temperatures were manually recorded at regular time intervals using thermocouples and ranged between $28.0\ ^0C$ to $30.4\ ^0C$ in the garage, $30.4\ ^0C$ to $32.0\ ^0C$ outside the house, and $22.9\ ^0C$ to $24.1\ ^0C$ inside the house. Wind and humidity measurements were not made during this set of experiments.

In order to assess a potential mitigation strategy for limiting the build-up of hydrogen, the built-in fan of an INFILTEC duct leakage tester (Model DL1-DM4-110) was used to provide forced ventilation in the garage (operated in the de-pressurization mode). The tester was placed on the ground outside the garage rear door (Fig. 1 top right sub-figure). A flexible aluminum trunk was used to connect the tester inlet with a circular vent hole located near the top of a piece of plywood that covered the garage rear door opening. Duct tape was used to seal the edges of the plywood and the rear door frame to minimize leakage. Two flow rates were used to characterize the dependence of the helium concentration on forced ventilation rate.

3.0 NUMERICAL SIMULATION OF HELIUM RELEASE IN VENTILATED COMPARTMENTS

Numerical simulations of helium release and mixing in the full-scale garage were performed using the NIST Fire Dynamics Simulator (FDS). FDS solves a form of the Navier-Stokes equations appropriate for low-speed, chemically reacting fluid flow [13]. The FDS solver is limited to low Mach number flows and uses a large-eddy sub-model for turbulence modeling in large-scale simulations. The equations describing the conservation of mass, momentum and energy are discretised on a rectilinear grid and second order accurate finite difference approximations of the equations were updated in time. FDS has been used by the fire protection community to simulate fires in large buildings and has also been validated with experiments in which helium was released into a 1/4-scale two-car residential garage [14,15]. In this paper we use the FDS model to predict helium release in a full scale garage with well defined leak locations for comparison with analytical model predictions.

4.0 ANALYTICAL MODEL OF HELIUM RELEASE IN VENTILATED COMPARTMENTS

Consider the case of a compartment of height H_c with a volume V in which a buoyant gas (helium) is leaking accidentally under an automobile. The compartment is assumed to be ventilated through two vents; "Vent 1" is located at the base of the compartment and is also referred to as the "lower" vent, while "Vent 3" is located at a height H above the floor, and is also referred to as the "upper" vent. The two vents have cross-sectional area a_1 and a_3, respectively. Here the suffixes 1 and 3 correspond to the respective vents. Note that subscript 2 will be used to denote intermediate level vents, consistent with our prior work in this subject [17]. Fig. 2 shows a schematic diagram of the compartment of height H_c with the two vents separated by a distance H. The formulation described in this paper is based on the concept of compartment over-pressure, and is more general than that discussed in [17] based on the height of the neutral plane. The formulation also allows us to consider vents that are separated by a height H, and is more general than one where the vents were located at the floor and ceiling of the compartment (separated by the height of the compartment H_c).

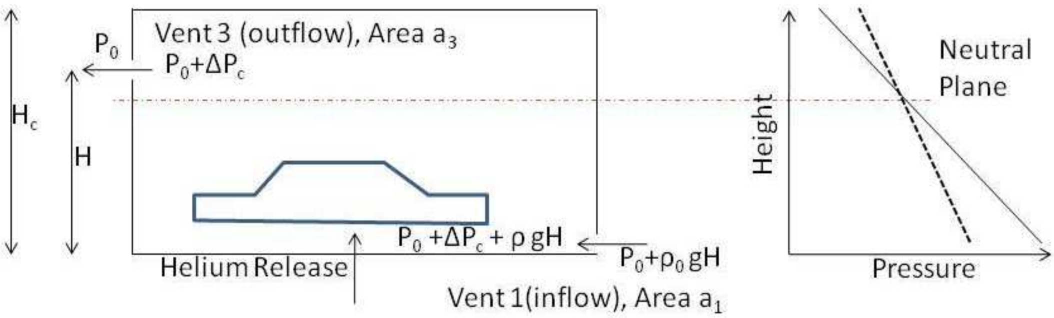

Figure 2. Schematic diagram of the geometry studied via analytical modeling, showing helium released under an automobile and dispersed through two vents in a compartment. Pressure changes with height, within the compartment (dashed line) and outside of the compartment (solid line) are indicated.

The helium gas released upwards under an automobile strikes the under-carriage of the automobile, and breaks up into multiple jets. Rapid mixing will occur under the automobile. Most of the helium will escape from under the vehicle through the wheel wells and the perimeter of the vehicle as multiple plumes rising towards the ceiling. This mixing of helium and air under the vehicle, and its subsequent release in the form of multiple independent plumes, results in a well mixed helium air mixture in the compartment. Turbulent mixing under an obstruction resulting in a well mixed hydrogen air mixture in the compartment has been observed in full-scale experiments [11, 12] as well as through CFD simulations [16].

Owing to the lower density of gas mixture inside the compartment, the vertical pressure gradient inside the compartment is lower than the vertical pressure gradient outside the compartment. The difference in pressure across an opening leads to a buoyancy-driven flow. In general, the velocity v_j of a gas mixture through a vent j is related to the pressure drop ΔP using Bernoulli's theorem (and assuming that the flow through each opening is uni-directional at any given instant in time),

$$v_j = \sqrt{2\frac{\Delta P}{\rho}} \tag{3}$$

where, ρ corresponds to the density of the gas mixture moving through the vent. The volumetric flow rate Q_j through an area a_j can be defined as $Q_j = a_j v_j c_j$, where, c_j is the discharge coefficient that accounts for the reduction in the area of the streamlines through the vent. The discharge coefficient is a constant lying between *0.5* for a sharp expansion at the inlet and *1.0* for a perfectly smooth expansion.

Fig. 2 also shows the pressure distribution inside and outside the compartment as a function of height. The ambient pressure at the height of the upper vent outside the compartment is represented by P_0. The pressure inside and outside the compartment varies hydrostatically with height. As a consequence, the pressure at the height of the lower vent outside the compartment will be higher due to the weight of the fluid and will equal $P_0 + \rho_0 g\, H$, where g is the gravitational acceleration. If we let ΔP_c be the instantaneous compartment over-pressure due to the release of helium gas, then the pressure inside the compartment at the height of the upper vent is represented as $P_0 + \Delta P_c$, while that at the height of the lower vent is represented as$P_0 + \Delta P_c + \rho\ g\ H$. The pressure difference at the level of the lower vent ΔP_1 and upper vent ΔP_3can be written as

$$\Delta P_1 = \Delta\rho\ g\ H - \Delta P_c \tag{4}$$
$$\Delta P_3 = \Delta P_c \tag{5}$$

where, $\Delta\rho = \rho_0 - \rho$. Substituting equations (4) and (5) for pressure difference across each vent in equation 3 gives the instantaneous velocity through the lower vent (v_1) and upper vent (v_3).

We define $\dot{M}_{He}$ as the mass flow rate of pure helium gas (assumed to be constant over the duration of the release period) leaking into the compartment. The rate of accumulation of helium in the compartment is dependent on the rate at which helium gas is released into the compartment and the outflow of helium through the upper vent.

$$V\frac{d\,(\rho\, Y_{He})}{d\,t} = \dot{M}_{He} - \rho\, Y_{He}\ (\,a_3 v_3 c_3) \tag{6}$$

where, Y_{He} is the instantaneous mass fraction of helium. The ordinary differential equation above can be solved to obtain the instantaneous density of the compartment, and this in turn can be used to compute the mass fraction or volume fraction of helium in the compartment as a function of time. An additional equation is needed to predict the instantaneous over-pressure of the compartment, and to obtain the velocity v_3 in the mass conservation equation (6). Since the volume of the compartment is fixed, the volumetric flow rate into the compartment must equal the volume of gases entering of leaving the compartment through the vents, or

$$\dot{V}_{He} + a_1 v_1 c_1 = a_3 v_3 c_3 \tag{7}$$

where, $\dot{V}_{He}$ is the volumetric flow rate of pure helium gas released into the compartment and can be obtained by dividing the mass flow rate $\dot{M}_{He}$ by the density of pure helium gas ρ_{He}. Equations (6) and (7) form the system of equations that were solved to obtain the density ρ of the gas mixture in the compartment and the compartment over-pressure ΔP_c as a function of time. Equation (6) is an ordinary differential equation that was advanced in time using a second order Runge-Kutta (RK) method (midpoint method) to obtain the compartment density. This was followed by a Newton-Raphson iteration to solve the volume conservation Equation (7) to obtain the compartment over-pressure. In the case of forced ventilation through the upper or lower vent, the volumetric flow rate at the forced flow vents were set to fixed values (as specified in the experiment), and these values were used in Equations (6) and (7).

5.0 RESULTS AND DISCUSSION

In this section, we describe the results of the experimental study and compare the measurements with results of the analytical model. We first describe the results of the door fan test to obtain the vent cross-sectional area. This vent cross-sectional area was subsequently used in the analytical model to predict the natural and forced ventilation tests. Finally, we compare the experimental data with results of the analytical model. It should be pointed out that the model predictions for natural and forced ventilation of the compartment were made prior to experiments (using the measured leak areas) and the results of the blind calculations were compared with experimental data.

5.1 Fan Test Results

Four sets of air-leakage tests were conducted for the garage, two using the side door as the opening to mount the blower door fan, and two using the rear door. The two sets that used the side door had one set with the rear door closed and sealed from the outside using duct tape and one with the rear door closed but unsealed, and vice versa. In each set, both pressurization (moving air into the garage) and depressurization (moving air out of the garage) were used for the leakage tests. For a fixed differential pressure, 4 to 8 consecutive manual flow rate readings were recorded to obtain an average air volume flow rate. A least squares fit curve (relative uncertainty less than 5%) was subsequently used to obtain the values for the leakage coefficient C and the pressure exponent n. Table 1 summarizes the results. The leakage coefficient and the pressure exponent for each test were used to derive the volumetric flow rate ($Q_{4\ Pa}$) for a representative pressure differential of 4 Pa. The Air Changes per Hour (*ACH)* values for the compartment were computed using the expression, $ACH = 3600\ (\frac{Q_{4\ Pa}}{V})$ where, V is the volume of the garage ($88.1\ m^3$). The Effective Leak Area *ELA* was subsequently obtained from Equation (2).

Table 1. Summary of fan test performed in a garage attached to the NIST Indoor Air Quality and Ventilation Test House.

No.	Test	C	n	Q4Pa	ACH	ELA
1	Pressurization Test Side Door, Rear door un-sealed	0.022	0.64	0.0522	2.1	0.0202
2	De-pressurization Test Side Door, Rear door un-sealed	0.025	0.75	0.0699	2.8	0.0271
3	Pressurization Test Side Door, Rear door sealed	0.017	0.64	0.0423	1.7	0.0164
4	De-pressurization Test Side Door, Rear door sealed	0.024	0.72	0.0658	2.7	0.0255
5	Pressurization Test Rear Door, Side door un-sealed	0.031	0.50	0.0622	2.5	0.0241
6	De-pressurization Test Rear Door, Side door un-sealed	0.038	0.61	0.0894	3.6	0.0346
7	Pressurization Test Rear Door, Side door sealed	0.012	0.67	0.0305	1.2	0.0118
8	De-pressurization Test Rear Door, Side door sealed	0.013	0.86	0.0438	1.8	0.0170

Since the forced ventilation tests described in the following sections were performed on the rear door with the side door unsealed, the ELA value measured during these tests was used to obtain the size of the leaks for the analytical model. The ELA value for the pressurization test ($0.0241\ m^2$) and depressurization test ($0.0346\ m^2$) were averaged to obtain an effective leak area $ELA = 0.029\ m^2$. The door fan test does not provide the distribution of the leaks as a function of the height above the floor. The leak locations (leak area as a function of height above the floor) have a significant effect on the natural ventilation of the garage and the resulting concentrations of the buoyant gas that are obtained inside the garage. In order to estimate the area distribution of the leaks, photographs such as those shown in Fig. 1 were analyzed. Based on these photographs, it was decided to model the garage with two vents. The first vent (Vent 1) was located on one of the side walls at the level of the floor, while the second vent (Vent 3) was again located on the side wall at a height equal to half the height of the garage. Furthermore, *25 %* of the effective leak area was assigned to Vent 1 and the remaining *75 %* was assigned to Vent 3.

5.2 Natural and Forced Ventilation Tests

A series of tests were performed in a garage (attached to the NIST Indoor Air Quality and Ventilation Test House) to obtain volume fraction measurement during the release of helium under an automobile, with natural and forced ventilation. Table 2 summarizes the test conditions (release rate, duration) and parameters that were varied during this test series. The forced flow rate and the fan start time, used during the experiments have also been listed for those cases where forced ventilation was active. Each test condition was duplicated to ensure that the results were repeatable.

Table 2. Summary of Natural and Forced Ventilation Tests performed during the release and dispersion of helium under an automobile.

No.	Release Rate (m^3/s)	Release Duration (s)	Natural / Forced	Forced Flow Rate (m^3/s)	Fan Start Time (s)
1	0.004468	14396	Natural	-	
2	0.004326	13622	Natural	-	
3	0.004434	3628	Forced	0.0910	125
4	0.004239	3599	Forced	0.0922	101
5	0.004273	3618	Forced	0.1066	101
6	0.004283	3597	Forced	0.1071	0

Fig. 3 shows the helium volume fraction measurements recorded during the release of helium over a 4 h period in a full-scale garage, without any forced ventilation and comparison with analytical model. Measurements made with sensors located at various heights in the garage (Fig. 3 left sub-figure) and not affected by the presence of the automobile indicate that the helium volume fraction was relatively uniform in the entire compartment. The top six sensors (sensors located at *91.4 cm* above the floor and higher) showed helium volume fractions that were almost identical over the entire release duration. The maximum values measured at the end of the release phase (*14396 s*) by the six sensors ranged between *0.220* through *0.225*. The two bottom sensors located at heights of *61.0 cm* and *30.5 cm* measured helium volume fractions of *0.16* and *0.19*, respectively. These measurements indicate that a large volume of the garage had uniform concentration over the entire duration of the release phase.

5.3 Comparison of Analytical Model Predictions with Experimental Test Data

In this section we compare the results of the analytical model using the methodology developed in Section 4.0 with experimental measurements of helium volume fraction. The model predictions were made prior to conducting the experiments. The input parameters required for the analytical model were set as follows: volume of the compartment $V=89.0\ m^3$, height of the compartment $H_c=2.44\ m$, area of vent 1 $a_1=0.011\ m^2$, discharge coefficient for vent 1 $c_1=0.7$, area of vent 3 $a_3=0.031\ m^2$, discharge coefficient for vent 3 $c_3=0.7$, distance between upper and lower vent $H=1.2\ m$, volume flow rate of helium $\dot{V}_{He}=0.004211\ m^3/s$, mass flow rate of helium $\dot{M}_{He}=0.000694\ kg/s$, density of air $\rho_0 = 1.1847\ kg/m^3$, density of helium gas $\rho_{He} = 0.1649\ kg/m^3$. The volume of the garage does not account for the volume of the automobile that was parked inside the garage. The vent sizes were based on door fan test data explained in Section 5.1.

Fig. 3 right sub-figure shows comparison of the analytical model predictions for helium volume fraction with the average value of the measured experimental data (symbols). In order to compare the analytical predictions with measured experimental data, the average helium volume fraction in the garage was obtained from the experimental data. The data from sensors 1-8 was used for the averaging process. The maximum value of the average helium volume fraction measured at the end of the release phase was found to be *0.21*. It should be noted that this average value was very close to the value measured by the top six sensors located on the tree (sensors located at *91.4 cm* above the floor and height). Results indicate that the analytical model accurately tracks the experiments data over the entire duration of the release. The maximum value predicted by the analytical model at the end of the release phase was *0.214*, and this value over-predicted the experimental value by *0.4 %.*

5.4 Comparison with CFD simulations

The dimensions of the compartment used in the CFD simulations were *6.8 m x 5.4 m x 2.4 m*, with a total volume of *88.128 m^3*. Pure helium gas was uniformly released through a square cross-section of *0.3 m x 0.3 m* (area of *0.0784 m^2*) with a mass flux of *0.007715 $kg/m^2/s$*. The duration of the release was 4 h. A flat plate with dimensions of *1.8 m x 4.8 m x 0.05 m* was placed at a height of *0.30 m* above the floor to simulate the obstruction effect of the automobile. The compartment was vented through two rectangular vents located on one of the side walls. The lower vent located close to the floor had dimensions of *0.15 m x 0.05 m* with a cross-sectional area of *0.0075 m^2*. The upper vent located at a height of *1.2 m* above the floor had dimensions of *0.45 m x 0.05 m* with a cross-sectional area of *0.0225 m^2*. The computational domain was divided into eight meshes. Grid resolution in the computational domain was *5 cm* in the horizontal and vertical direction to resolve the flow through the plume region. Typical computational time (CPU time) of a simulation performed on an eight processor machine was approximately *680 h*. Numerical results indicate that the helium volume fraction in the garage was very uniform, except for a small region of the domain under the flat plate. Fig. 3 (right sub-figure) shows the numerically predicted helium volume fraction (dashed line) averaged over the eight sensors (averaging process was similar to that of the experimental data).

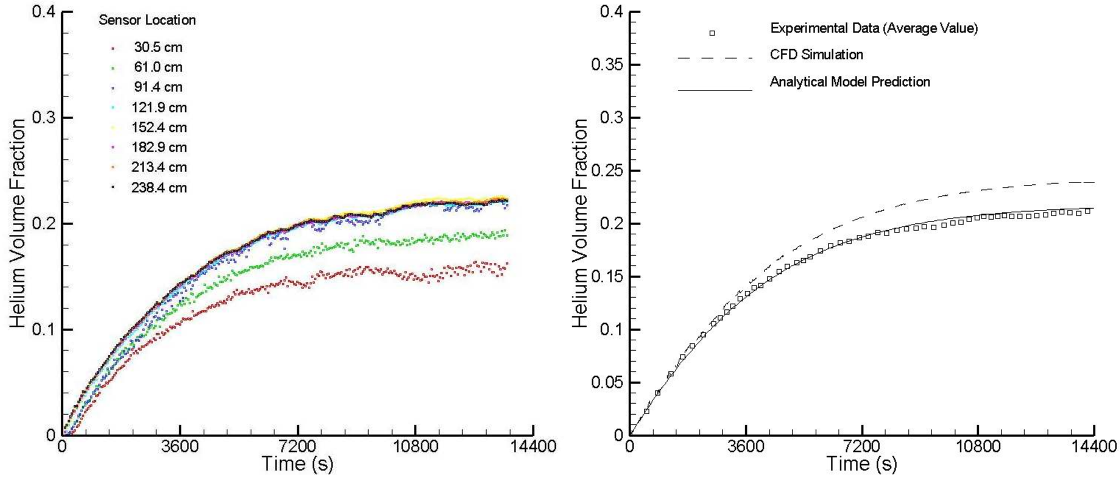

Figure 3. Helium volume fraction measurements (left sub-figure) recorded during the release of helium over a 4 h period, under an automobile parked in the center of a full-scale garage, without any forced ventilation. The right sub-figure shows comparison of model predictions (solid line) with average helium volume fraction measurement in the garage.

5.5 Effect of Analytical Model Input Parameters

In this section we examine the sensitivity of various analytical model input parameters (vent cross-sectional area, vent location, volumetric flow rate and volume of the compartment) on the predicted values of helium volume fraction over the entire release period. These parameters are difficult to measure accurately and the parametric studies help us in determining the important parameters.

The base case results discussed in Section 5.3 did not account for the effect of the volume occupied by the vehicle. The volume of the vehicle is estimated to occupy *10 %* of the volume of the garage. Fig. 4 left sub-figure shows the effect of reducing the volume of the garage by *10 %* and *20 %*. The volume of the garage was reduced by decreasing one of the horizontal dimensions, while keeping the vertical dimensions un-changed. The cross-sectional area of the vents and separation distance was not changed during this study. Predicted results indicate that volume fraction measured at the end of the release phase did not change substantially when the volume of the garage was reduced. Reducing the volume of the garage reduced the length of the transient phase, and the predicted volume fraction quickly approached the steady state value.

Fig. 4 (right sub-figure) shows the effect of increasing the distance between the lower and upper vents on helium volume fraction. Increasing the separation between the lower and upper vents reduces the helium volume fraction over the entire release duration. As discussed, the door fan test provides an estimate of the effective leak area and does not provide the distribution of the leaks determined from photographic and visual observations. This parametric study helps in understanding the relative importance of the location of the vents.

The largest effect on predicted helium volume fraction was obtained by increasing the release rate (results not shown due to lack of space). As expected, increasing the release rate increases the predicted values of helium volume fraction in the compartment. Increasing the cross-sectional area of either vents reduced the helium volume fraction in the garage. Changing the area of the lower vent had a larger effect on predicted volume fraction as compared to the upper vent. It should be noted that the area of the upper vent was three times larger than that of the lower vent for the base case. The role of wind and thermal effects has not been discussed systematically in this paper (since detailed wind measurements were not available in this test series for model validation), but have been studied parametrically elsewhere [17].

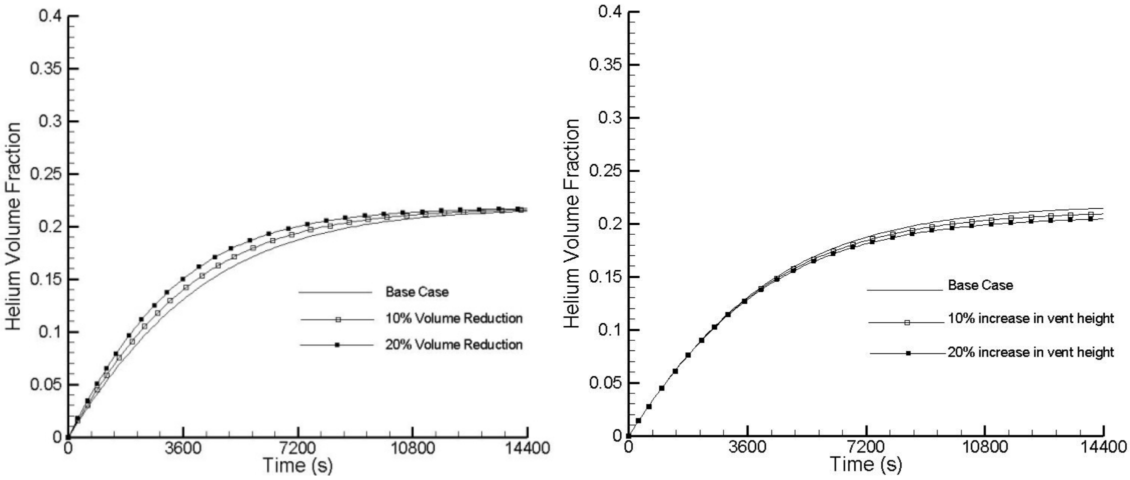

Figure 4. Effect of various model parameters on predicted values of helium volume fraction over the entire release period in the garage.

5.6 Forced Ventilation

Fig. 5 shows the helium volume fraction measurements under forced ventilation condition, recorded during the release of helium over a *4 h* period under an automobile parked in the center of the garage. During this test, the garage was ventilated with an exhaust fan operating at a rate of $0.0910\ m^3/s$. Exhaust fan was turned on at *125 s* after the initial release of helium, when the helium volume fraction measured by any of the sensors reached a value of *1 %* (25 % of lower flammability limit). Helium volume fractions under forced ventilation condition (Fig. 5) were significantly lower than that for natural ventilation, for all the sensors used in the current study.

Results for forced ventilation show that the helium volume fractions measured by the top six sensors (sensors located at *91.4* cm above the floor and higher) were almost identical over the entire release duration. The maximum values measured at the end of the release phase (*3628 s*) by those six sensors ranged between *0.03* through *0.04*. The two bottom sensors located at heights of *61.0 cm* and *30.5 cm* measure helium volume fractions of *0.02* and *0.03*, respectively. These measurements again show that a large volume of the garage had uniform concentration over the entire duration of the release phase.

The analytical model (predictions made prior to the experiment) was used to predict the helium volume fraction that was measured in the experiments under forced flow conditions. The various input parameters required for the analytical model were identical to those used for natural ventilation conditions. The vent sizes were obtained from the door fan test data explained in the previous section. Fig. 5 right sub-figure shows the analytical model predictions for helium volume fraction in the compartment over the entire release duration (solid line) for the forced flow conditions and comparison with the average value of the experimental data (symbols). The averaging process was identical to the one used for natural ventilation case. The maximum value of the average helium volume fraction measured at the end of the release phase for the forced ventilation case was found to be *0.036*. Results indicate that the analytical model accurately captures the trend of the experiments data over the entire duration of the release. The maximum value predicted by the analytical model (0.046) over-predicted the experimental value by *1.0 %*.

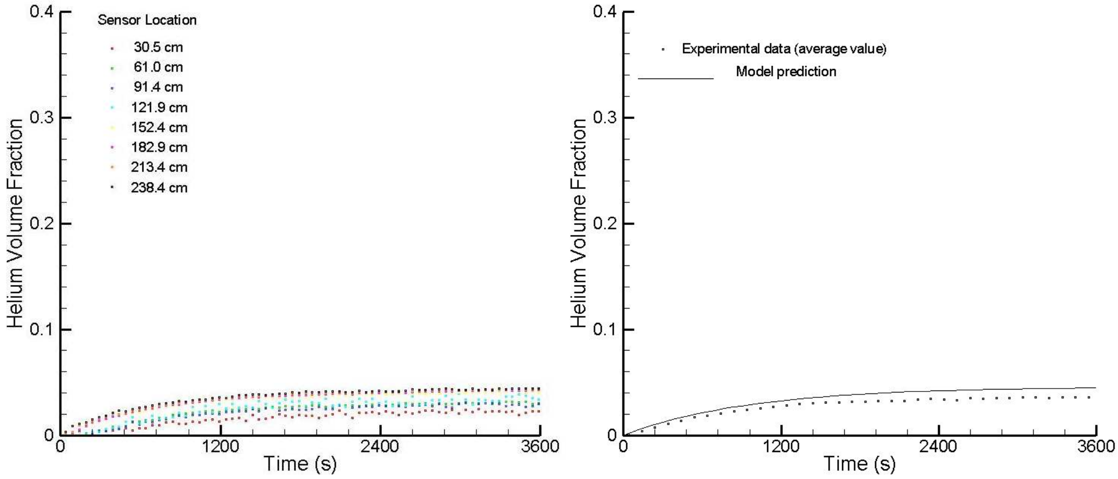

Figure 5. Helium volume fraction measurements (left sub-figure) recorded during the release of helium over a 4 h period, under an automobile parked in the center of a full-scale garage. The garage was ventilated with an exhaust fan operating at a rate of $0.0910\ m^3/s$. The right sub-figure shows comparison of model predictions (solid line) with average helium volume fraction in the garage.

6.0 CONCLUSIONS

A detailed experimental, numerical and analytical modeling study has been presented to better understand and improve the safety of hydrogen fueled applications operated in passively and actively ventilated compartments. A series of experiments were conducted to understand the dispersion of helium released under an automobile parked in the center of a full-scale garage. Helium was used as a surrogate gas, for safety concerns. The rate of helium released under an automobile was scaled to represent *5 kg* of hydrogen released over *4 h*. Door fan test were conducted to obtain the effective leak area of the compartment walls. Helium volume fraction was measured at *8* different heights in the garage.

A simple analytical model was developed concurrently, to predict the natural and forced mixing and dispersion of a buoyant gas released in a partially enclosed compartment with vents at multiple levels. The model is based on determining the instantaneous compartment over-pressure that drives the flow through the vents and assumes that the helium released under the automobile mixes fully with the surrounding air. CFD simulations were performed to confirm the observed physical phenomena. Analytical model predictions for helium volume fraction compared favorably with measured experimental data for both natural and forced ventilation over the entire release duration. Model results over-predicted the experimental data by *0.4 %* for natural ventilation conditions and *1.0 %* for forced ventilation conditions. Parametric studies were presented to understand the effect of release rates, vent size and location on the predicted helium volume fraction in the garage.

Model and experimental results clearly indicate that forced ventilation can effectively and rapidly reduce the flammable concentration of hydrogen in a compartment. Validation of the analytical model with experimental data allows the model to be used with confidence for predicting the volume fraction in partially enclosed spaces and for developing and improving hydrogen safety codes and standards. Although the model can predict the mixing effect caused by the presence of the automobile, the model is unable to predict the high volume fractions that are observed locally in the engine compartment or under the vehicle. The model also cannot predict the seepage of helium into the passenger compartment or the trunk. Developing simple rules or techniques for estimating the volume fraction in the passenger compartment is an important task that will be addressed in the future.

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