INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 18530–18541

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Pressure peaking phenomenon for indoor hydrogen releases

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ARTICLE INFO

Article history:
Received 30 April 2018
Received in revised form
9 August 2018
Accepted 13 August 2018
Available online 6 September 2018

Keywords:
Pressure peaking
Hydrogen
Enclosure
Ventilation
Overpressure
Nomogram

ABSTRACT

The pressure peaking phenomenon can be observed when hydrogen is released in enclosures with vent(s). The unforeseen physical phenomena of pressure peaking has been described and explained. This phenomenon occurs for hydrogen releases in enclosures where the vent(s), volume, and leak rate are such that there will be no air ingress to the enclosure. Pressure peaking describes the physical phenomenon of a peak in the pressure transient during such a release for some release conditions in a vented enclosure. This phenomenon is pronounced only for gases lighter than air, e.g. hydrogen and helium. For particular release flow rates and vent sizes the peak can be an order of magnitude higher compared to the steady-state overpressure that is reached when the enclosure is fully filled with hydrogen over time. This finding is relevant to all hydrogen applications indoors from a fuel cell in an enclosure or laboratory scale storage up to a forklift in a warehouse. The peak magnitude depends on the release flow rate, hydrogen inventory, enclosure volume and the ventilation area, and potentially can exceed the maximum pressure which the enclosure can withstand. A look up nomogram for applicability of the developed theory that is based on vent area and leak rate has been created for sustained releases. Experimental evidence of the phenomena is described. Reduced analytical equations are presented for the case of a constant flow rate release, and the associated nomogram is presented for use by hydrogen safety engineers and regulators.

Introduction

As hydrogen and fuel cell applications become more widely used it is practical that their indoor use is considered and understood. Necessary indoor use of these systems is unavoidable, and examples include fuel cells or hydrogen storage in a confined space or enclosures, hydrogen vehicles in garages or maintenance shops, hydrogen powered forklifts in warehouses, production and storage in research laboratories, there are numerous applications. There is a clear need to understand the hazards associated with indoor use in order to provide guidance, inform standards, and ensure inherently safer design. The work presented here is motivated by the need to better understand the safety issues surrounding indoor use of hydrogen and fuel cell applications to inform engineers so that the effects of potential hazards may be mitigated against or prevented through design. The topic is timely and hence is the subject of on-going investigations by a number of research groups globally as evidenced by recent publications for example [1] and [2], it has been the subject of European research project HyIndoor [3].

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https://doi.org/10.1016/j.ijhydene.2018.08.096

Nomenclature

A	vent area (m^2)
C	coefficient of discharge
H	vent height (m)
M	molecular mass (kg/mol)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
n	number of moles
P	pressure (Pa)
R	universal gas constant
T	temperature
V	volume (m^3)
$\dot{V}$	volumetric flow rate (m^3/s)
V	velocity (m/s)
X	mole fraction
Y	mass fraction
Greek	
γ	ratio of specific heats
ρ	density (kg/m^3)
Subscripts and superscripts	
a	Air
atm	Atmospheric
encl	enclosure
h	Hydrogen
nozz	Nozzle
t	Time
max	Maximum
vent	Vent
Acronyms	
CFD	Computational Fluid Dynamics
PRD	Pressure Relief Device

From a safety perspective, a number of hazards arise following an unignited hydrogen release in a vented enclosure. Previous works e.g. Refs. [4,5] have focused on dispersion, and formation of a flammable atmosphere in an enclosure for comparatively small releases. Whilst the dynamics of hydrogen concentration are briefly discussed here, this work focuses primarily on overpressure development and tools that can be used to predict, and thus potentially avoid, excessive overpressure capable of demolishing a structure for releases indoors.

Previous work by the authors [6,7] has introduced the phenomena of pressure peaking during a non-reacting release from hydrogen storage through a pressure relief device (PRD) in an enclosure with a vent. The initial study was driven by the need to understand the potential safety issues associated with parking a vehicle in a garage with the aim of informing guidance, however the findings are applicable to any application where the vent(s), volume, and leak rate are such that there will be no air ingress to the enclosure. The initial work [6] described the case of a sustained release with a constant mass flow rate from 3 MPa storage through a 5.08 mm diameter PRD in a garage-like enclosure of volume 30.4 m^3 with a single brick-like vent of size 250 × 50 mm. Computational Fluid Dynamics (CFD) was used to demonstrate the occurrence of a peak in the pressure dynamics (pressure-time curve) following the injection of hydrogen in the enclosure. A system of equations was presented describing this phenomenon. It was demonstrated how the overpressure levels in the case chosen were capable of causing major damage and possible collapse within only 1 s even without ignition. This phenomenon was shown to be pronounced only for hydrogen and to some small extent for methane but not for other combustible gases with a molecular mass higher than air. It was shown in Ref. [6] that if the enclosure does not rupture first (i.e. collapse), the pressure within the garage, reaches a maximum level in excess of 60 kPa for 35 MPa storage. This maximum pressure then drops off and tends towards a steady state value, an order of magnitude lower, and equal to that predicted by the simple steady state estimations of pure hydrogen release from the enclosure i.e. 17 kPa [6].

Subsequent work [7] accounted for a decrease in tank pressure during hydrogen blow down and hence a decreasing mass flow rate. A blow down model developed at the University of Ulster and published elsewhere [8,9] was used to determine mass flow rate from a hydrogen storage tank and this mass flow rate was used as an input to the pressure peaking model. An attempt was made in Ref. [7] to correlate Air Change per Hour (ACH) with vent size and enclosure volume and use this to develop a nomogram for “safe” PRD diameters. In Ref. [7] a “safe” diameter was defined as that which, for a given enclosure volume and vent size, would result in a “pressure peak” or overpressure which was considered to be “safe” for the structure. Overpressure levels not exceeding 20 kPa where deemed to be sufficiently low to avoid serious structural failure. The “safe” diameters indicated in Ref. [7] are significantly smaller than those typically used in existing PRDs. However, as a PRD diameter is decreased the hydrogen will naturally take a longer time to blow down from the storage tank. Hence it is clear that the fire resistance of the tanks has to be increased in-line with the blow down time to avoid both catastrophic tank failure in fire, and destruction of the enclosure by the pressure peaking phenomenon. The nomograms presented in Ref. [7] give a “safe” diameter and subsequent blow down time for a specific enclosure volume, ACH, and hydrogen storage pressure and inventory. Whilst the authors do believe that the nomograms presented in Ref. [7] could be used as an engineering tool, neither the diameters nor the blow down times suggested may be feasible in practice for today's storage tanks, with their current level of fire resistance. The work in Ref. [7] rather serves to highlight the existing problem for the benefit of future tank design with increased fire resistance.

Both previous works [6,7] focused on the case of a malfunctioning PRD and hence a relatively high mass flow rate in an enclosure. In the case of [7] it is also noted that there is ambiguity in the literature regarding the method used to calculate ACH. The authors believe that the pressure peaking phenomenon is widely applicable and should be accounted for in design for all indoor hydrogen and fuel cell applications ranging from small fuel cell enclosures and laboratory applications to maintenance shops etc. Indeed, recent work [8] has validated the phenomenon in a laboratory scale enclosure