INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 13134–13145

Available online at www.sciencedirect.com

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

Investigation of ignited hydrogen leaks from tube fittings

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ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form
31 July 2015
Accepted 3 August 2015
Available online 28 August 2015

Keywords:
Hydrogen safety
Numerical simulation
Non-premixed combustion
Leak
Compression fitting

ABSTRACT

A combined experimental and numerical investigation of ignited hydrogen leaks from a compression fitting attached to a steel tube was conducted for a range of hydrogen mass flow rates controlled between 0.033 slpm and 1.0 slpm. Horizontal and vertical fitting orientations were considered in this study. The experiments involved temperature measurements of the fitting surface as well as thermal imaging of the corresponding flow field. The numerical simulations, which were performed using a commercial computational fluid dynamics (CFD) software, provided steady-state temperature distribution in the flow domain as well as in the fitting and the steel tube. It was observed that as the fitting and the tube were heated by the mass-flow controlled flame, the hydrogen leak path contracted, which resulted in a steady ignited leak and a maximum temperature of the fitting below 320 °C across the considered cases.

Introduction

The demand for clean energy sources is resulting in increased use of hydrogen as an energy carrier. Hydrogen is an attractive fuel source for power production; where it produces clean emissions when combusted and is well suited for fuel cell applications. However, widespread adoption of hydrogen requires thorough consideration of related safety aspects. Fuels such as LNG and propane have undergone decades of use and have well-established safety practices, while hydrogen safety when used as a fuel is a less-established, but continually developing field.

Hazardous hydrogen events include loss of containment incidents and vessel explosions. A study of industrial accidents in Europe since the beginning of the 20th century, performed by Gómez-Mares et al., concluded that 65% of accidents were in the form of jet fires, 92% of which initiated a secondary event [1]. Jet fires escalate via radiation and/or flame impingement, leading to one or more secondary events, such as pool fire, boiling liquid expanding vapour explosion (BLEVE), mechanical explosion, toxic release, or enlarged jet fires [2].

The significance of large-scale jet fires has resulted in several studies analyzing and predicting such events. Experimental measurements of large-scale, vertically oriented ignited hydrogen jets was performed by Schefer et al. [3]. The authors measured the flame length and the radiative flux in order to verify the correlations and scaling laws of high-pressure jets. Horizontally oriented, transient hydrogen jets ignited at different ignition times and positions were investigated by Grune et al. [4] in terms of the pressure loads and heat

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http://dx.doi.org/10.1016/j.ijhydene.2015.08.006

Nomenclature

c	specific heat, J/kg·K
D_{leak}	leak diameter, m
Da	Damkohler number, –
E	total energy, J/kg
Fr_{den}	exit densimetric Froude number, –
g	gravity acceleration, m/s^2
h	enthalpy, J/kg
k	thermal conductivity, W/m/K
Nu_D	Nusselt number, –
P	supply pressure, barg
Pr	Prandtl number, –
q	heat flux, W/m^2
Q	hydrogen leak rate, slpm
Ra	Rayleigh number, –
Re_D	Reynolds number, –
Sc	Schmidt number, –
t	time scale, s
t_{mix}	mixing time scale, s
t_{rxn}	reaction time scale, s
T	fitting temperature, C
T_g	gas temperature, C
T_s	surface temperature, C
$u_{i,j,k}$	velocity components, m/s
$x_{i,j,k}$	spatial coordinates, –
Y	mass fraction, –
Greek	
δ_{ij}	Kronecker symbol
ε	surface emmisivity, –
μ	dynamic viscosity, Pa·s
ρ_∞	ambient air density, kg/m^3
ρ_{exit}	exit air density, kg/m^3
Constants	
σ	Stefan–Boltzmann constant, 5.67×10^{-8}[W/m^{2}K^4]

releases associated with the deflagrating hydrogen-air clouds. In 2009, Landucci et al. assessed the effects of flame impingement upon storage tanks, developing a lumped model approach to predict a time to failure [5]. In 2011, Papanikolaou et al. used experimental and numerical methods to determine ventilation requirements to avoid hydrogen accumulation in a stationary fuel cell system [6]. Willoughby and Royle [7] and Schefer et al. [8] compared performance of inclined fire barriers as protection devices against hydrogen flames. Effectiveness of various ventilation techniques at reducing hydrogen concentration in an enclosed space as well as the resulting effects on deflagration were experimentally investigated by Meriolo et al. [9] and Ekoto et al. [10]. Molkov et al. developed a numerical experiment in 2014 to simulate a moderate scale ignited hydrogen release in a vented enclosure [11]. Péneau et al. [12] numerically investigated transient supersonic hydrogen releases, while Chernyavsky et al. [13,14] numerically and experimentally investigated subsonic and buoyant hydrogen gas release.

The aforementioned studies generally focus on unscheduled hydrogen releases from high-pressure vessels and with large mass flow rates, or do not analyze combustion effects. The flames observed are typically on scales of 1–100 m in length. Few resources, however, are available to quantify the effects of small-scale ignited hydrogen releases. These characteristically small flames can occur in areas that impinge upon other equipment, such as hydrogen fuelling infrastructure, or balance of plant components in motive or stationary fuel cell systems.

A study by Butler et al. [15] was performed to uncover the lower limit of a hydrogen leak that can support a stable flame (quenching limit). A section of the experimentation was dedicated to leaks from 3.2, 6.4, and 12.7 mm compression tube fittings (see Fig. 1). The fittings were subjected to three leak scenarios: under-tightening of the fitting, over-tightening of the fitting, and mechanical damage to the sealing ferrule. The quenching limit was independent of the failure modes and fitting orientation, with a hydrogen flow rate at 0.028 mg/s for the 6.4 mm fitting. These results are an order of magnitude smaller than the limits of propane and methane [15].

Hydrogen possesses a unique array of properties causing the leak propensity, and making it unusually hazardous as a fuel. Hydrogen has the lowest molecular weight among common fuels, the lowest quenching distance (0.51 mm), the smallest ignition energy in air (28 mJ), the lowest autoignition temperature by a heated air jet (640°C), the highest laminar burning velocity in air (2.91 m/s), and the highest heat of combustion (119.9 kJ/g) [15]. Hydrogen-air combustion flames have an adiabatic flame temperature of 2117°C [16]. Hydrogen flames are also undetectable to the human eye at low levels. Small quenching distances are important for leak scenarios; a flammable hydrogen–air mixture cannot burn when flowing through narrow channels (<0.51 mm in diameter) as all heat from a flame is conductively transferred to the channel walls. The mixture can only burn externally. The weakest flames recorded to date have been hydrogen flames from hypodermic needles, producing a mere 0.25 W [17].

It is also known that a sustained hydrogen leak has the potential to self-ignite. The mechanisms by which autoignition occurs have recently been reviewed by Astbury et al. [18] and Sánchez et al. [19]. Astbury reviewed the commonly postulated ignition mechanisms: the Reverse Joule–Thomson Effect, electrostatic ignition, diffusion ignition, sudden

Fig. 1 – Typical compression tube fitting showing the main leak site.