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Spatial and Radiative Characteristics of Large Scale Hydrogen Jet-fires

Paola Russo[a,*], Francesco Marra[a], Michele Mazzaro[b], Francesco Pilo[c], Danilo Marini[a], Chiara Vianello[d], Giovanni Pulci[a]

[a] Dipartimento Ingegneria Chimica Materiali Ambiente, Università degli Studi di Roma La Sapienza, via Eudossiana 18, 00184 Roma, Italia
[b] Corpo Nazionale dei Vigili del Fuoco Direzione Centrale Prevenzione e Sicurezza Tecnica, Largo S. Barbara, 2 00178 Roma, Italia
[c] Corpo Nazionale dei Vigili del Fuoco Comando Venezia Via Motorizzazione 7 37100 Mestre (VE), Italia
[d] Dipartimento di Ingegneria Industriale, Università degli Studi di Padova, Via Marzolo 9, 35131 Padova, Italia.
paola. russo@uniroma1.it

Hydrogen refuelling stations carry the risk of hydrogen leakage from flanges, holes, broken pipes, etc., and the possibility of ignition is high due to the low minimum ignition energy of hydrogen. The length of these hydrogen jet flames may have an impact on damage and should be included in risk assessments. The risk assessment of typical hydrogen refuelling infrastructure is highly dependent on separation distances. These distances are estimated partially by jet flame lengths. The use of reliable physical models, engineering models, and risk analysis tools is hence required for safely operating this infrastructure. Generally, the physical models are adapted from hydrocarbon fuels, and they have to be validated for hydrogen especially in the range of operating pressures of FCEVs and refuelling infrastructures.
To fill this gap, large scale hydrogen jet-fires tests were conducted in open space at various hydrogen pressures (up to 450 bar) and orifice diameters (1-5 mm). The jets were visualized by a thermal camera (up to 2000°C) and radiation flux sensors facing the jet at different distances were located. Results showed that the hydrogen flames can cover distances of about tens meters, and cause life-threatening conditions by the flame itself and thermal radiation.

1. Introduction

Fuel Cell Hydrogen vehicles represent a valid alternative to replace current internal combustion engines. Fuel Cell Electric vehicles (FCEVs) have been under development for more than 15 years, with Toyota, Hyundai and Honda being the primary OEMs leading development of technologies. More recently, other car manufacturing groups (e.g. BMW and Daimler) have been promoting their prototype vehicle designs or technological advancements. As of June 2018, there were estimated to be globally 6500 FCEVs on the road. As the vehicle costs become more competitive and the refuelling infrastructure develops, consumer uptake is calculated to increase more quickly. It is projected that by 2030 there will be 1.6m FCEVs in the UK with annual sales of more than 300,000 (H2Mobility, 2019).
The build-up of a sufficient hydrogen refuelling infrastructure is essential to make larger-scale deployment of hydrogen powered motor vehicle possible. To this aim, in Italy the regulation on fire prevention for H_2 refuelling station has been recently revised (DM October 23, 2018) to be consistent with the new technological standards. In particular in these infrastructures operating pressure up to 100 kPa have to be reached to deliver hydrogen to the new FCEVs at pressure up to 70 kPa, which is needed to ensure greater quantity of stored gaseous hydrogen and less refill time.
In hydrogen refuelling infrastructure there is a fundamental issue concerning the safety of people, which is generally accomplished by specifying prescriptive separation distances. For hydrogen various methods and tools for determining safety distances were adopted. Among them the risk-informed method combines elements from a quantitative risk analysis and data obtained from a deterministic approach (LaChance et al.,

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2009a; Russo et al., 2018). The general QRA framework for hydrogen uses a combination of probabilistic and physical models, with the aim of assessing the likelihood and impacts of various hydrogen release and ignition scenarios, which can lead to thermal and overpressure hazards. Generally, the physical models are adapted from hydrocarbon fuels, hence, they have to be validated for hydrogen especially in the range of operating pressures of FCEVs and refuelling infrastructures.

The jet flame has been examined in several studies (Hottel and Hawthorne, 1949; Becker and Liang, 1978; Kalghatgi, 1984). However, few investigations have examined the flames produced by the release of high-pressure hydrogen. Schefer et al. (2007) performed experiments to characterize the dimensional and radiative properties of large-scale, vertical hydrogen-jet flames. The flame length results showed that lower-pressure engineering correlations based on the Froude number and a nondimensional flame length also apply to releases from storage vessels at pressures up to 413 bar. Similarly, radiative heat flux characteristics of these high-pressure jet flames obey scaling laws developed for low-pressure, smaller-scale flames and a wide variety of fuels. Mogi e Horiguchi (2009) conducted an experimental study on the high-speed hydrogen jet diffusion flame formed by the leakage of high-pressure compressed hydrogen. Hydrogen jets were horizontally released from circular orifices with diameters ranging from 0.1 to 4 mm, and the release pressure varied from 0.01 to 400 bar (gauge). The flame sizes were measured, and experimental equations were obtained for the length and width of the flame. The flame sizes depend not only on the orifice diameter but also on the release pressure. The radiation from the hydrogen flame could be predicted from the flow rate of the gas and the distance from the flame.

From the work of Schefer et al. (2007), it is known that very large (vertical) jet flames may be produced (up to 10 m for a 5 mm orifice under 300-413 bar). Further evidence was provided by Mogi and Horiguchi (2009) with smaller diameters and similar pressure range for horizontal jet fires. Proust et al. (2011) presented an original set of data about the blowout of a high pressure hydrogen reservoir (from 900 bar down) through orifices ranging from 1 to 3 mm. The horizontal jets were ignited and the flame geometry and radiative properties were investigated. About the geometry of the flame, the ratio L/D was found (6/1) exactly the same than found by Schefer's team (2007) and Mogi and Horiguchi (2009). But the flame length does not always compare well to the correlations proposed by those authors.

From previous studies it is expected that the downstream region from the hydrogen jet flame is particularly susceptible to thermal hazards. However, thus far, there have been few systematic researches on the temperature properties of the hydrogen jet flames and radiation in the downstream region.

Therefore, a campaign of large scale hydrogen jet-fires tests was conducted in open space at various hydrogen pressures (up to 450 bar) and orifice diameters (1-7 mm). The temperatures downstream the orifice were measured by K-type thermocouples that were installed in a stainless wire gauze. The jets were visualized by a LWIR camera (up to 2000°C) and radiation flux sensors facing the jet at different distances were located. In this work we presented the results of flame shape and radiation of the jet fires.

Results of these tests will be also utilized for validation of CFD models in the Horizon 2020 Hytunnel-CS project. The project aims to conduct internationally leading pre-normative research to close knowledge gaps and technological bottlenecks in the provision of safety and acceptable level of risk in the use of hydrogen and fuel cell cars as well as hydrogen delivery transport in underground transportation systems.

2. Experimental procedure

The tests were carried out at the National Fire Service test facility in Marco di Rovereto (TN), Italy. A picture of the flow delivery system is shown in Fig. 1. The hydrogen was provided by a storage tube trailer supplied by Linde. The trailer consisted of 16 high-pressure hydrogen storage tubes (Fig. 2). The volume of each tube was 50 L at a nominal pressure of 450 bar. The tube trailer was connected to the orifice (1-7 mm bore hole) via a 12 m pipe with a constant internal diameter of 7 mm in order to minimize head losses. The jet was directed horizontally at approximately 1 m above the ground level. The igniter was a continuous propane air burner. On the jet axis, K-type thermocouples were aligned and three radiant flux meters were installed (CAPTEC: sensing element of 30 x 30 mm, sensitivity 3 μV/(W/m^2) at a radial distance of 2 m from the jet centreline and at a axial distance of 2, 2.9 and 3.8 m from the orifice (Fig. 3). The radiometers were mounted on a tripod and orientated towards the projected flame centre. A LWIR camera (FLIR A655SC) which streams full-frame 16-bit data at 50 Hz was installed at about 10 m from the jet centreline so as to visualize the flame. Tests were carried out by changing both orifice diameter (1, 3, 5 mm) and pressure in the range 120-450 bar.

Figure 1: Picture of the flow delivery system

Figure 2: The storage tube trailer supplied by Linde.

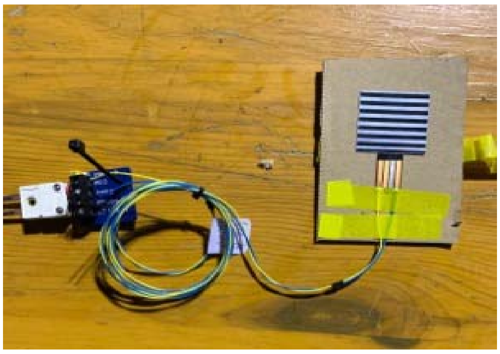

Figure 3: The Captec Radiant Flux sensor.

3. Results

Digital IR images of the flame were obtained to characterize the flame structure and length. An example of flame geometry extracted from the images recorded by the LWIR camera is presented in Fig. 4. The results refer to a flame at 325 bar and 3 mm orifice. It is observed that the flame has the largest width (W) closer to the tip of the flame than to the middle of the flame length (L). Moreover, the ratio L/W is approximately equal to 6 for all the flames analysed, and in agreement with Proust et al (2011) and Schefer et al. (2007).
It is also observed that the length of the flame increases with increasing the diameter of the orifice. Specifically, it increases from about 2.5 m to 6.2 m to 7.8 m when the orifice changes from 1 mm to 3 mm to 5 mm, respectively, at a pressure of about 320 bar in the storage tube. The calculated flame lengths were compared with the experimental results reported by Proust et al. (2011) and the correlations found by Mogi and Horiguchi (2009) and Shefer et al (2007). From comparison it results that measured lengths are in agreement with the experiments of Proust et al. (2011), and that both correlations well predict the experimental data except for orifice diameters equal to 5 mm and larger than it. For those diameters both correlations overestimate the length of the flame (i.e. for 5 mm orifice, a flame length of about 11 m is predicted). It is to underline that in the cited literature the flame length is obtained using visible flame emission and not IR emission like in this paper.
The maximum temperature inside the plume (at about 320 bar) is measured as high as 1600°C for 3 mm orifice and 1800°C for 5 mm, but it is much smaller for the 1 mm orifice (slightly higher than 1000°C). But this temperature is higher than for standard hydrocarbons.

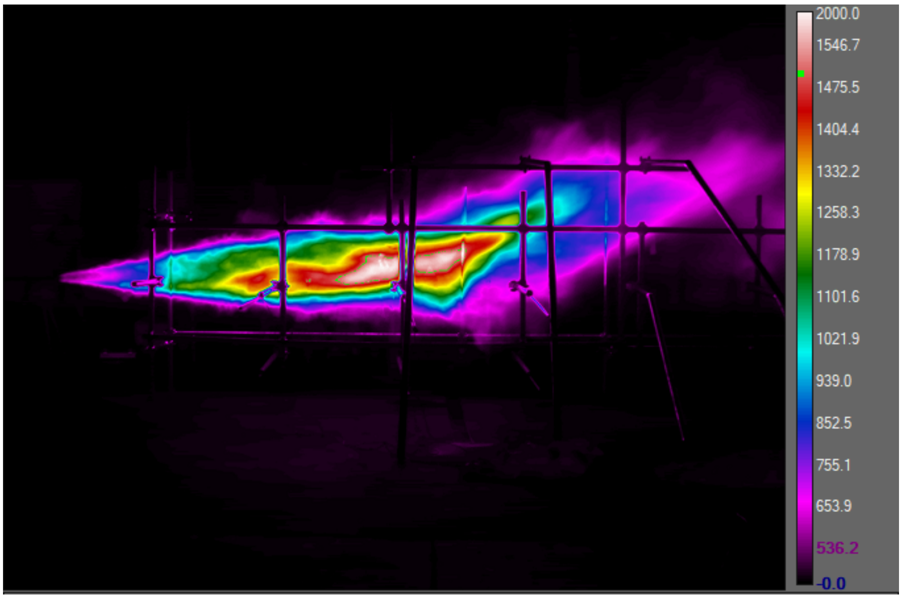

Figure 4: IR image of flame for test at 3 mm orifice and 325 bar (Temperature in K).

The emissivity coefficient of hydrogen flame is smaller than that of other gaseous fuel flames. However it cannot be ignored the fact that radiation from a hydrogen flame affects its surroundings in the case of a large flame. Therefore, the thermal radiation from the flame was measured in order to investigate its thermal effect on its surroundings.
As an example, radiative heat flux measurements for 1 and 3 mm orifice at a pressure of about 320 bar are reported in Fig. 5 and 6, respectively. For 1 mm orifice a maximum radiative heat flux of about 2 kW/m^2 is measured at a radial distance of 2 m from the jet centerline and at a axial distance of 2 m from the orifice along the jet axis. This value decreases to 1.5 and then to 1 kW/m^2 increasing the axial distance to 2.9 m and 3.8 m. These values are similar to the value of solar radiation. Therefore is not expected harm for long exposure of people to these values of radiative heat flux.
On the contrary for 3 mm orifice the radiative heat flux reaches a maximum value of 10 kW/m^2 at 2 m axial distance, and of about 9 kW/m^2 at 2.9 and 3.8 axial distance. In the literature 9.5 kW/m^2 is reported as the harm criteria for second degree burn after 20 second (LaChance et al., 2009b). Therefore, in this case, for people not in the flame, there is still a potential for exposure to high radiation heat fluxes for a sufficient time to

result in second degree burns. For 5 mm orifice (data not reported) heat fluxes as high as 16 kW/m^2 were measured, which overcome the harm criteria for 1% lethality (in 1 min).
The harm criteria for structures and equipment can also be expressed in terms of exposure to radiant heat flux or direct flames. 10 kW/m^2 is the heat flux able to ignite fuel oil for 120 s of exposure (LaChance et al., 2009b).

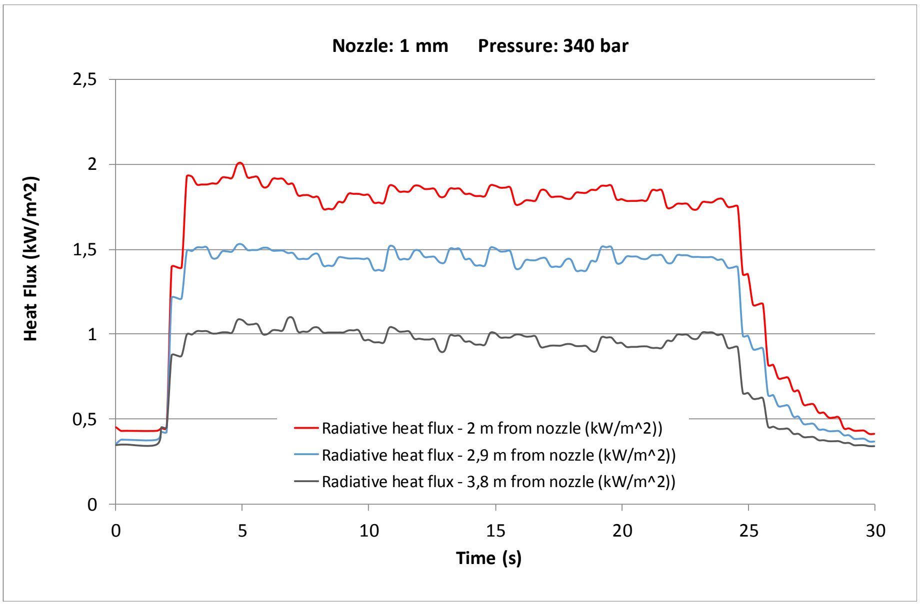

Figure 5: Heat Flux for 1 mm orifice at 340 bar.

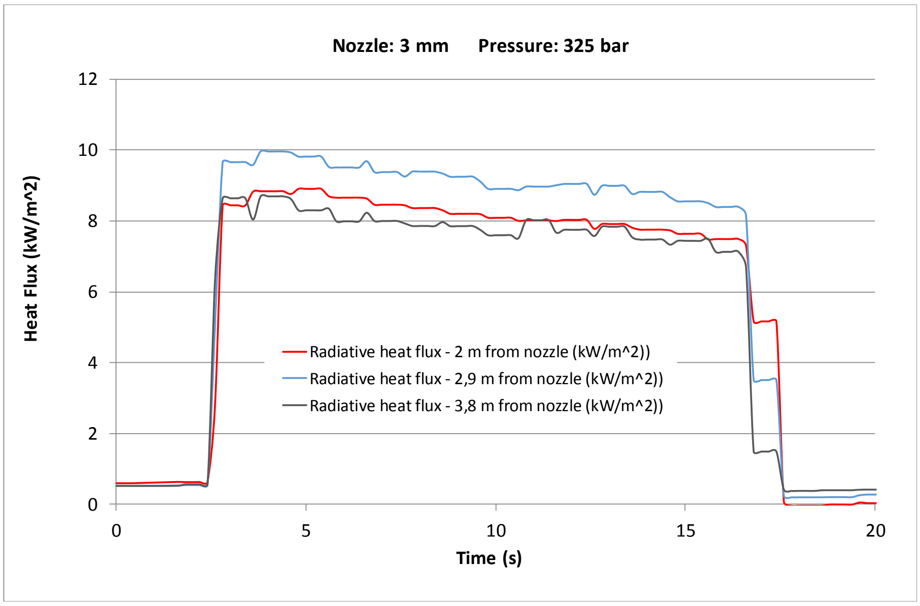

Figure 6: Heat Flux for 3 mm orifice at 325 bar.

In the literature empirical models are available for the calculation of the radiative heat flux. In particular, we compared the experimental results with the calculated values through the following correlation, reported by Mogi and Horiguchi (2009):

$$E\, r^2 = 6.0\, x 10^3\, m^{1.3} \qquad (1)$$

where E (W/m^2) is the radiative heat flux, r (m) is the distance between the radiometer and the flame axis and m (kg/s) is the mass flow rate.

This correlation refers to H_2 jet fire tests performed in conditions similar to those reported in this work: pressure in the range 0.1-400 bar, nozzle diameter from 0.1 mm to 4 mm; radiometers located at distances of 1.5, 2.5, and 3.5 m from the flame axis to measure the thermal radiation from the flame. As an example, for the test with 3 mm nozzle diameter and 325 bar at a distance of 2 m form the jet axis the empirical correlation gives E=7.44 kW/m^2, value that is slightly lower (about 10%) than the measured values.

4. Conclusions

The primary consequences from fire hazards are that people, components, or structures will be exposed to flames, high air temperatures, or high heat fluxes from fires. For jet fires generated from immediate ignition of hydrogen jets, it can result in direct flame contact or exposure to high radiant heat fluxes. Factors such as the diameter and pressure of the leak influence the potential harm to people and equipment. From the campaign of large scale hydrogen jet-fires tests reported in this work, the geometry of the jet flame and the heat flux radiation as function of orifice and pressure were evaluated.
It was found that at pressures higher than 300 bar and for 3 to 5 mm orifice the hydrogen flame can cover distances up to 8 m, and cause life-threatening conditions by the flame itself and thermal radiation. In particular, for 3 mm orifice and 320 bar the radiation from hydrogen jet flame can cause second degree burn at 2 m axial distance, while for 5 mm orifice 1% lethality is expected.
The experimental results are in good agreement with those predicted by empirical correlation reported in literature.

Acknowledgments

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