European Train the Trainer Programme for Responders

Lecture 9

Hazard distances from hydrogen flames and fire fighting

LEVEL I

Firefighter

The information contained in this lecture is targeted at the level of Firefighter and above.

This topic is also available at levels **I-III**.

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

Disclaimer

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Summary

This lecture is focused on ignited hydrogen releases. A useful terminology has been introduced at the start. Then a classification of different types of hydrogen fires is provided

Keywords

Hydrogen fire, flame length

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1. Target audience

The information contained in this lecture is targeted at LEVEL 1: Firefighter. Lectures are also available at levels II, III and IV: crew commander, incident commander and specialist officer.

The role description, competence level and learning expectations assumed at crew commander level are described below.

1.1 Roll description: Firefighter

A firefighter is responsible and expected to be capable of carrying out operations safely in personnel protective equipment including breathing apparatus using equipment provided, like vehicles, ladders, hose, extinguishers, communication and rescue tools, under any climatic conditions in areas and to emergency situations which can be reasonably anticipated as requiring a response.

1.2 Competence level: Firefighter

Trained in the safe and correct use of PPE, BA and other equipment which it is expected they will operate first responders must be supported by appropriate knowledge and practice. Behaviours that will keep them and other colleagues safe should be described by Standard Operating Procedures (SOP). Practiced ability to dynamically assess risk to self and others safety is required.

1.3 Prior learning: Firefighter

EQF 2 Basic factual knowledge of a field of work or study. Basic cognitive and practical skills required to use relevant information in order to carry out tasks and to solve routine problems using simple rules and tools. Work or study under supervision with some autonomy.

2. Introduction and objectives

Frequently, the term ‘safety’ is referred to as a ‘non-technical’ barrier to the emerging FCH technologies. However, there are several engineering challenges to be addressed before rolling out these technologies to the market. One of them is the reduction of hydrogen jet flame length from the current value of 10-15 m from FC vehicle on-board storage to allow the evacuation and rescue of passengers and their safeguarding by responders. Another important unresolved problem is to increase the fire resistance rating of on-board hydrogen storage tanks from 1-7 minutes (current value for type IV vessels) to allow the longer time for blow-down of tanks. This would prevent severe damage of civil structures such as garages during accidental hydrogen release. Additionally, it would exclude even a chance of large hydrogen-air clouds formation inside tunnels, which can lead to fatalities throughout the entire length of the tunnel in the case of fires. The higher fire resistance rating of hydrogen storage tanks would permit safe evacuation of civilians from an accident scene, providing life safety of passengers and responders [1].

Without a doubt, Responders will have to deal with incidents or accidents involving hydrogen flames because hydrogen fire is a typical scenario of many accidents. Knowledge of the possible hydrogen flame length and related separation distances are of key importance for Responders. There will also be a thermal radiation from a fire, which can cause harm to humans and damage to structures, buildings, equipment, etc. at the distances beyond the flame length. Several factors that affect the extent of a jet fire and the associated radiative heat flux, including hydrogen storage pressure and a leak size, will be discussed in the present lecture. Methods of hydrogen fire detection, the techniques of hydrogen fires mitigation and extinction are considered in this lecture as well.

By the end of this lecture a Responder/a trainee will be able to:

- Distinguish between different types of hydrogen fires:
  from microflames to jet fires and fireballs,
- Evaluate hydrogen flame lengths with the aid of nomograms, dimensional and dimensionless correlations,
- Assess the average location of jet flame tip,
- Predict the determination separation distances to protect people and structures,
- Explain the effect of different factors on the flame length of jet fire: nozzle size and shape, jet attachment, buoyancy, barriers, or walls,
- Compare the flame lengths and heat fluxes of jet fires on hydrogen and other common fuels (CNG and LPG),
- Explain the pressure effects of hydrogen jet fires,
- Identify the main hydrogen fires detection methods,
- Recognise the mitigation techniques for hydrogen fires,
- Implement the hydrogen fires extinction practices,
- Appreciate the main safety challenges related to the current state of FCH technologies.

3. Main terminology

In order to fully understand hydrogen fires and other related phenomena (such as microflames, quenching, lift-off, blow-off and blow-out phenomena, thermal radiation, flame visibility, flame length and speed, impinging jet fires, etc.) it will be useful to learn a few definitions listed below. Please pay attention to the dimensionless numbers, which will be frequently used in the present and further lectures.

Blow-down is a process where the storage pressure decreases with time during a leak [1].

Blow-off is the flame extinguishment at a high velocity without a lift-off [2].

Blow-out is the flame extinguishment at high velocity with a lift-off [2].

Blow-out limit is a fuel flow velocity limit beyond which a lifted flame blows out [2].

Deflagration is the process following the weak ignition in a combustible mixture, which propagates at a subsonic speed into fresh, unburned mixture [3].

Detonation is the process, in which the combustion wave propagates with a supersonic velocity in the unreacted medium [3].

Drop-back is the reattachment to the nozzle of a lifted flame by a decrease of lift-off velocity [2].

Effective diameter is the jet diameter at the location where expansion down to 1 bar takes place, in an under-expanded jet [4].

Expanded jet is the jet with a pressure at the nozzle exit equal to atmospheric pressure [1].

Fire-resistance rating is a measure of time for which a passive fire protection system can withstand a standard fire resistance test [1].

Flame lift-off is the condition, in which the flame and a burner become separated.

Flame speed is the velocity of the flame with the respect to a fixed observer [3].

Flashpoint is the lowest temperature, at which the fuel produces enough vapours to form a flammable mixture with air at its surface [1].

Froude number (Fr) is the dimensionless number equal to the ratio of inertial to gravity force [1].

Hazard distance is a distance from the (source of) hazard to a determined (by physical or numerical modelling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from “no harm” to “max harm”) to people, equipment or environment.

Laminar burning velocity is the rate of flame propagation relative to the velocity of the unburned gas that is ahead of it, under stated conditions of composition, temperature, and pressure of the unburned gas [1].

Lift-off height is the height from the nozzle exit to the base of a lifted flame [2].

Lift-off velocity is the fuel flow velocity causing a flame to be detached from the nozzle [2].

Mach number (M) is the dimensionless number equal to the ratio of the local flow velocity to the local speed of sound [1].

Maximum Allowable Working Pressure (MAWP) is the maximum pressure, to which any component or portion of the pressure system can be subjected over the entire range of design temperatures [5].

Normal Temperature and Pressure (NTP) conditions are: temperature 293.15 K and pressure 101.325 kPa [1].

Non-premixed flame (often called a *diffusion flame*) is the flame, in which the oxidiser and the fuel are not mixed prior to reaching a flame front. During combustion oxidiser combines with a fuel by diffusion. The flame speed is limited by the rate of diffusion.

Overpressure is the pressure in a blast wave above the atmospheric pressure, or the pressure within a containment structure that exceeds the maximum allowable working pressure of the containment structure [5].

Premixed flame is the flame, in which the oxidiser has been mixed with the fuel prior to the reaching the flame front. Combustion of premixed fuel and oxidiser forms a thin flame front due to the reactants being readily available.

Quenching gap is the spark gap between two flat parallel-plate electrodes at which ignition of combustible fuel-air mixtures is suppressed. The quenching gap is the passage gap dimension requirement to prevent propagation of an open flame through a flammable fuel-air mixture that fills the passage [1].

Reynolds number (Re) is the dimensionless number that gives a measure of the ratio of inertial to viscous forces [1].

Hazard (or separation) distance is a minimum distance, which separates "specific targets (e.g. people, structures or equipment) from the consequences of potential accidents related to the operation a hydrogen facility" [6].

Under-expanded jet is the jet with a pressure at the nozzle exit above the atmospheric pressure [1].

*Visible flame length i*s the centerline distance from the tip of the nozzle to the flame end [2]. Visible, infrared (IR) and ultraviolet (UV) digital images are often used for the measurement of flame length and the measured flame lengths vary between different images [8].

4. Types of hydrogen fires and flames

Hydrogen may burn in different combustion modes, which include flash fire, jet fire, deflagration, detonation, etc. Hydrogen fires can range from microflames with the mass flow rate of 10^{-9} kg/s to the high mass flow rate flames (hundreds of kg/s). Hydrogen releases may burn as laminar diffusion or turbulent non-premixed flames depending on the Reynolds number (Re) at a leak exit. Flames can be buoyancy-controlled and momentum-dominated. Most hazardous hydrogen releases will be in a momentum-dominated regime. The jet fires can be, depending on the leak exit conditions, subsonic (the Mach number $M<1$), sonic and highly under-expanded supersonic. In the scenarios, where a failure of storage tank is possible with the immediate release of hydrogen into the surrounding atmosphere large size fireballs (tens of meters) can be formed. The presence of obstacles, surfaces and enclosures affect the jet flame significantly. A special case is the fires involving liquefied hydrogen (LH_2). Currently, there is a little knowledge available on LH_2 fires. There is a knowledge gap with an indication that condensation and solidification of oxygen (from the atmosphere) in the case of LH_2 leak/spill at certain condition may lead to explosive mixtures.

5. Radiation heat fluxes from jet fires and fireballs

5.1 Radiation heat fluxes from jet fires

Hydrogen burns in a clean atmosphere with an invisible flame. It has a somewhat higher adiabatic premixed flame temperature for a stoichiometric mixture in air of 2,403 K compared to other fuels. This temperature can be a reason for serious injury at an accident scene, especially at clean laboratory environment where the hydrogen flame is practically invisible. However, hydrogen combustion and hot currents will cause changes in the surroundings that can be used to detect the flame. Although the non-luminous hydrogen flame makes visual detection difficult, there is a strong effect of heat and turbulence on the surrounding atmosphere and raising plume of hot combustion products. These changes are called the *signature of the fire.*

The following section is based on the work performed at Ulster in HySAFER centre [7]. Before discussing radiative heat flux, it is worth noting that a hydrogen flame emits minimal infrared radiation and virtually no visible radiation. Due to the absence of CO_2 radiation bands and the strong absorption by ambient water vapour, the ratio of visible to infrared hydrogen jet flames is 0.88 and the ratio of ultraviolet to infrared flame length is 0.78 [9]. Nevertheless, convective and radiative heat fluxes still remain important and must be assessed for the protection of life, property and the environment.

Effect of radiative heat flux on people, environment and structures is discussed in detail in the Lecture 6 - Harm criteria for people and property.

5.2 Hydrogen jet fires versus jet fires of common fuels

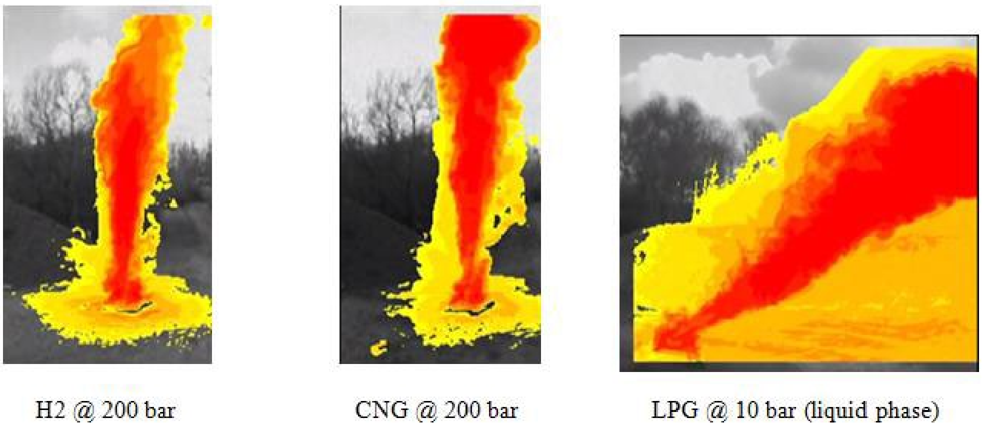
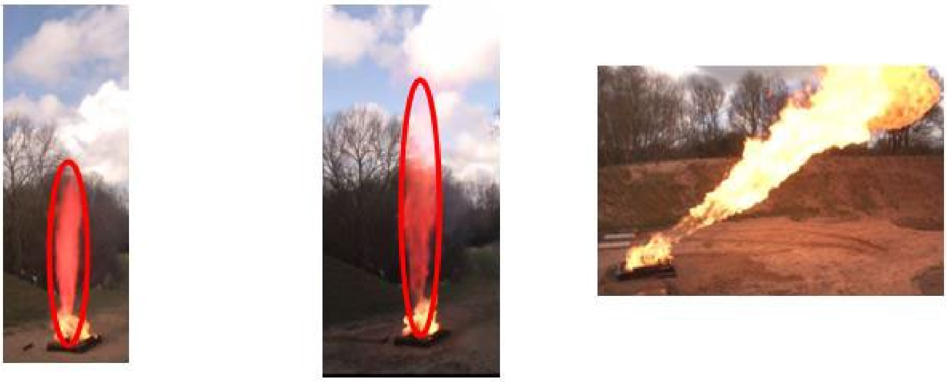


Figure 1. Infrared image of jet fires showing thermal radiation produced by combustion of hydrogen (200 bar), CNG (200 bar) and LPG (10 bar).

As it follows from Figure 1, due to the incomplete combustion, CNG and LPG produce CO_2, CO, soot, and other products, which have higher effect on the radiation compared to hydrogen.

This phenomenon explains why hydrogen combustion is characterised by lower thermal effects than other common fuels, even if the temperature exceeds the one of a CNG flame. Figure 1 shows comparison of thermal radiation produced by hydrogen (200 bar), CNG (200 bar) and LPG (10 bar) – thermal signature of hydrogen jet fire is slightly smaller than that of CNG, and both of them are significantly smaller than thermal radiation from LPG fire.



Equivalent Ø: 3,1 mm
H2 length flame: 5,5 m

Equivalent Ø: 3,1 mm
CNG length flame: 8 m

LPG length flame

Figure 2. Comparison of the flame lengths for jet fires of hydrogen (orifice diameter 3.1 mm), CNG (orifice diameter 3.1 mm), and LPG.

6. Fire of FC vehicles

Fuel Cell Vehicles (FCVs) are one of the main fast developing applications of FCH technologies. Similar to a battery-electric car, a fuel cell car does not have the internal combustion engine. Fuel cells convert the energy stored in chemical form directly into electrical energy that powers the cars. Worldwide, several thousand FCV have been established, and small fleets of fuel cell cars are being used especially by companies and government agencies but also private persons. These include released serial models from Hyundai (iX35 fuel cell and NEXO) and Toyota Mirai I and II models. More than a thousand cars running in Germany with a hundred refilling stations in operation! Also, some fire brigade cars are already fuel cell vehicles.

As an example, according to fire statistics in Great Britain [10], in the UK, 28,800 road vehicle fires were registered in 2011-2012. For comparison, in USA 172,500 automobile fires occurred in the same period. Different types of vehicles were affected: motor cars, heavy goods vehicles, light goods vehicles, public transport vehicles etc. The majority (65 %) of fires occurred in cars, 10 % were in vans, 4 % were in lorries and 2 % in buses or minibuses [10]. Fire causes can be accidental, deliberate, or unknown. The majority of deliberate fires (43%) involved road vehicles: 13,900 fires. The number of fatalities in road vehicle fires in 2011-12 was 37 [10].

During period from 2000 to 2006, 20 catastrophic CNG tank failures were documented, 11 of them have been attributed to vehicle fires [11]. Of these 11 incidents, the evidence suggests that the majority of the PRDs failed to activate (in case of a localized fire). "Testing has shown that all fuel tanks (both CNG and hydrogen) regardless of working pressure are highly susceptible to rapid degradation due to localized fires" [11]. This means that catastrophic failure cannot be ruled out of the risk assessment [10].

Hazards and associated risks for FCVs should be proven and interpreted in a professional way, with the full comprehension of consequences by all stakeholders, starting from FC system designers through regulators to users. The first comparison of the "severity" of a hydrogen and gasoline (petrol) fuel leaks and ignitions was performed by Swain [13]. Figure 3 shows the snapshots of hydrogen jet fire and gasoline fire at 3 s (left) and 60 s (right) after a car fire initiation. It should be noted that these early images do NOT reflect more recent angled and smaller diameter TPRD design.

Figure 3. Hydrogen jet fire and gasoline fire: 3 s (left) and 60 s (right) after a car fire initiation [13].

Acknowledgement

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References

1. Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II. Available from: www.bookboon.com, free download e-book.
2. Cheng, TS, Chiou, CR (1998). Experimental investigation of the characteristics of turbulent hydrogen jet flames. Combustion Science and Technology. Col. 136, p. 81-84.
3. Dorofeev, SB (2009). Evaluation of hydrogen explosion hazards: phenomenology and potential flame acceleration and DDT. 4th European Summer School on Hydrogen Safety.
4. Birch, AD, Brown, MG, Dodson, MG, Swaffield, F (1984). The structure and concentration decay of high pressure jets of natural gas. Combustion Science and Technology. Vol. 36, p. 249-261.
5. NFPA (2009). Compressed Natural Gas (CNG) Vehicular Fuel Systems Code, 52.

6. LaChance, J, Tchouvelev, A and Engebo, A (2011). Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. Vol. 36 p. 2381-2388.
7. Saffers, JB (2010). Principles of hydrogen safety engineering. PhD thesis. University of Ulster.
8. Schefer, RW, Houf, WG, Bourne, B and Colton, J (2006). Spatial and radiative properties of an open-flame hydrogen plume. International Journal of Hydrogen Energy. Vol. 31, pp. 1332-1340.
9. Houf, WG and Schefer, RW (2007). Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen. International Journal of Hydrogen Energy. Vol. 32, pp. 136-151.
10. Case for safety. Relative frequency of failure modes. Available from: http://h2safe.net/case_safety.html [accessed on 25.11.20].
11. Fire statistics, Great Britain, 2011-2012. Department of Communities and Local Government.
12. Gambone, LR and Wong, JY (2007). Fire protection strategy for compressed hydrogen-powered vehicles. 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007.
13. Swain, MR (2001). Fuel leak simulation. Proceedings of the 2001 DOE Hydrogen Program Review. Available from: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf [Accessed 25.11.20].