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Hydrogen Fireball Consequence Analysis

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A fireball may occur after the catastrophic rupture of a tank containing a flammable substance such as a fuel, if an ignition source is present. The fireball is identified by the combustion of the flammable cloud created after the fuel release and composed by the mixture of the latter and air. In particular, the fuel concentration is higher at the center of the fireball compared with the external layers where the ignition takes place. After its formation, the fireball tends to rise vertically due to the buoyancy of the hot gases involved in the combustion. Moreover, the fireball emits its energy mainly through radiant heat. Hence, the fireball formation may be one of the consequences of both a liquid and a compressed gaseous hydrogen tank explosion. For instance, the fireball is a consequence of a boiling liquid expansion vapor explosion (BLEVE). A BLEVE may occur after the catastrophic rupture of a tank containing a liquid at a temperature higher than its boiling point at atmospheric pressure. The explosion is characterized by the rapid expansion of the liquid and vapor phases due to the depressurization of the vessel.
The aim of this study is to model a liquid hydrogen (LH_2) fireball generated subsequently the BLEVE phenomenon. Different empirical correlations were selected to estimate the fireball dimensions and duration. Moreover, the fireball radiation was estimated by means of a theoretical model. As case study, the fireball generated from the explosion of the LH_2 tank with a volume of 1 m^3, which will be tested during the safe hydrogen fuel handling and use for efficient implementation (SH_2IFT) project, was simulated. The results achieved from the fireball numerical models can be employed to estimate the safety distance from an LH_2 tank and propose appropriate safety barriers. Furthermore, these outputs can aid the writing of critical safety guidelines for hydrogen technologies. Finally, the outcome of this study will be validated with the experimental results during the SH_2IFT project.

1. Introduction

Hydrogen is a highly flammable substance with a very low density at atmospheric conditions (0.0883 kg m^{-3} (NIST, 2019)). For this reason, it is usually stored at high pressures (up to 70 MPa (Kikukawa et al., 2008)). The liquefaction process can increase the hydrogen density (up to 70.9 kg m^{-3}) by cooling the gaseous hydrogen down to its boiling point (20.3 K at atmospheric pressure) (NIST, 2019). Currently, less than 1% of the hydrogen worldwide produced is liquefied (Ausfelder & Bazzanella, 2016). However, the liquid hydrogen (LH_2) production might grow in the forthcoming years as response to the foreseen consumption increase (IEA, 2017). Therefore, LH_2 may be employed in new applications, thus considered as emerging technology from which emerging risks might arise (Jovanović & Badoš, 2013). Boiling Liquid Expanding Vapor Explosion (BLEVE) is a physical explosion, consequence of the catastrophic failure of a vessel which contains a liquefied gas at temperature above its boiling point at atmospheric pressure (Casal et al., 2016). The consequences of a BLEVE are the overpressure of the blast wave, the tank debris thrown away by the explosion and a fireball if the substance contained in the vessel is flammable. This latter can cause damages to the structures in the vicinity of the tank and injuries to the personnel due to the high radiation produced, and it must not be neglected during a risk assessment of a flammable liquefied gas storage vessel (Hemmatian et al., 2017).
In the past, few experiments on LH_2 fireball were conducted. In the 1960s, NASA conducted a series of tests to determine the blast hazards of liquid propellants (including LH_2) as consequence of two disastrous incidents: the Atlas-Centaur rocket failure during the booster phase of its first launch in 1962, and the Saturn-

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IV explosion at the beginning of its firing test in 1964 (Gayle, 1964). In these tests, LH_2 fireballs were generated after the explosion of several vessels which contained different amounts of propellant, i.e. fuel (LH_2) and oxidizer (liquid oxygen, LOX) with a 1:5 ratio, in the range of 200 ÷ 100,000 lb (~91 ÷ 45,359 kg) (Gayle & Bransford, 1965). LH_2 fireballs were obtained also during the research programme conducted by BMW, car manufacture, in the period 1992-1996 (Pehr, 1996). BLEVE explosions were triggered by means of cutting charges installed on the LH_2 tanks designed for the hydrogen powered cars. The LH_2 tank mass content varied from 1.8 to 5.4 kg during the experiments. In 2005, a hydrogen fireball were achieved from a pressurized vessel during the fire exposure test conducted by Zalosh & Weyandt (2005). In that case, the composite tank with a volume of 72.4 L was filled with 1.64 kg of hydrogen at 34.3 MPa, engulfed in a propane fire. A thorough qualitative risk analysis was conducted in the European project Integrated design for demonstration of efficient liquefaction of hydrogen (IDEALHY) (Lowesmith & Hankinson, 2013). BLEVE explosion was considered as consequence of the loss of containment of a storage vessel provoked by an external fire. The fireballs generated after the explosion of tanks with different hydrogen mass contents (3 ÷ 700 t) were simulated by means of theoretical and empirical models. As result of this analysis, the most severe consequence for both the transportation and liquefaction applications was a BLEVE of a road tanker and of a storage tank respectively. Currently, the consequences of handling and use of large amount of hydrogen are investigated in the Safe Hydrogen fuel handling and Use for Efficient Implementation (SH_2IFT) project (Sintef, 2019). BLEVE is one of the two physical explosions analyzed in this project. Both experimental tests and modelling activity will be carried out within the project. The aim of this study is to conduct a preliminary consequence analysis of the hydrogen fireball generated after the BLEVE of an LH_2 tank as part of the SH_2IFT project. Theoretical models and empirical correlations are employed in this investigation. The idea is to estimate the consequences of the BMW bursting tests previously described, in order to validate the models for LH_2. Furthermore, a sort of blind simulation is performed by providing the fireball parameters expected after the explosion of the LH_2 vessels during the SH_2IFT experimental tests. The methodology adopted in this study is described in Sec. 2, while the results and the discussion are reported in Sec. 3 and 4 respectively.

2. Methodology

One of the most critical and arduous challenges of a fireball consequence analysis is the determination of the fuel amount which participates in the fireball formation. In this study, it was assumed that the whole tank content is burnt in the fireball in order to assess the worst-case scenario. The fireball diameter, duration and height, depicted in Figure 1, were estimated together with the radiative heat flux emitted toward a target to determine the safety distance from the vessel. In the following, the selected methodology is described in detail.

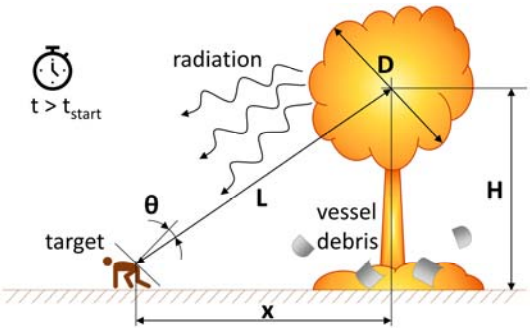

Figure 1: fireball parameters considered during a consequence analysis: diameter D, duration t, height of the fireball center H, horizontal distance from the release to the target x, distance from the fireball center to the target L, and angle between the target surface normal and the fireball axis θ.

2.1 Diameter

Different correlations to estimate the LH_2/LOX fireball diameter were proposed as result of the blast hazards tests of liquid propellant conducted by NASA (Gayle & Bransford, 1965), (High, 1968). In this study, Eq(1) proposed by Hord (1972) was used to estimate the fireball diameter:

$$D \approx 7.93 \cdot {W_f}^{1/3} \quad (1)$$

where D is the maximum fireball diameter in m and W_f is the fuel mass in kg.

2.2 Duration

The fireball dynamic, thus its duration, depends on the release momentum which derives from the flash evaporation of liquefied gases during a BLEVE. Therefore, Beyler (2016) categorized the fireballs in momentum- and buoyancy-dominated. The correlations proposed by Gayle & Bransford (1965) and High (1968) for liquid propellant fireballs, are similar to the momentum-dominated fireball formula (Eq(2)) proposed by CCPS (2010):

$$t = 0.45 \cdot m^{1/3} \tag{2}$$

where *m* is the fuel mass in kg. The duration correlation for buoyancy-dominated fireball is reported in Eq(3):

$$t = 2.6 \cdot m^{1/6} \tag{3}$$

where *m* is again the fuel mass in kg. CCPS (2010) suggested to use Eq(2) for fuel masses lighter than 30,000 kg, and Eq(3) otherwise. In this analysis a comparison between both equations was conducted.

2.3 Height of the fireball center

The fireball raise height depends on the fireball type (momentum- or buoyancy-dominated) as demonstrated by Fay & Lewis (1977). In this analysis, the equation proposed by van den Bosch & Weterings (2005) (Eq(4)) was selected to calculate the maximum height of the center of the fireball.

$$H = D_{max} \tag{4}$$

where D_{max} is the maximum fireball diameter in m, estimated with Eq(1).

2.4 Radiative heat flux and thermal dose

The solid flame model, employed in this study, is widely used to estimate the incident radiation per unit area and unit time from a fireball (CCPS, 2010). The model approximates the fire geometry with a basic geometrical shape (e.g. sphere). Furthermore, the whole thermal radiation is assumed as diffused from the shape surface. Therefore, the incident radiation from the fireball is estimated with Eq(5):

$$q = \tau \cdot F \cdot E \tag{5}$$

where τ is the atmospheric attenuation (transmissivity), *F* is the view factor, and *E* is the surface emissive power (SEP) in W m^{-2}. This latter is the radiative heat flux which is emitted from the fireball surface per unit time and is usually measured during experimental tests by means of pyrometers. It can be theoretically estimated with the Stefan-Boltzmann's law (Eq(6)) as performed in this study.

$$E = \varepsilon \cdot \sigma \cdot T^4 \tag{6}$$

where ε is the emissivity, σ is the Stefan-Boltzmann constant equal to 5.67 × 10^{-8} W m^{-2} K^{-4}, and *T* is the flame temperature in K. In this analysis, the maximum theoretical SEP value was determined by assuming that the flame is a black body ($\varepsilon = 1$) and its temperature is close to the stochiometric combustion temperature (2318 K for hydrogen in air (Pehr, 1996)). The view factor in Eq(5) correlates the radiation received by the receptor and the SEP emitted by the fireball surface. Assuming a spherical fireball, the view factor is calculated with Eq(7) when the distance from the release point to the target, *x*, is longer than the fireball radius (*D/2*), (Beyler, 2016):

$$F = \left(\frac{R}{L}\right)^2 \cos\theta \tag{7}$$

where *R* is the fireball radius in m, *L* is the distance from the fireball center to the target in m and θ is the angle between the target surface normal and the fireball axis in degree (Figure 1). In this study, the value of this angle was zero to provide the most conservative estimation. The incident radiation is attenuated by the atmospheric transmissivity (τ_a) which is function of the atmospheric air temperature, path length (between the fireball and the target) and chemical species present in air (primarily water vapor, i.e. humidity). Eq(8), proposed by van den Bosch & Weterings (2005), was selected in this analysis.

$$\tau_a = 2.02 \cdot (p_w \cdot (L - R))^{-0.09} = 2.02 \cdot (RH \cdot p_w^0 \cdot (L - R))^{-0.09} \tag{8}$$

where p_w is the partial pressure of vapor water in air in Pa, *L* is again the distance between the fireball center and the target in m, *R* is the fireball radius in m, *RH* is the relative humidity (70% in this analysis), and p_w^0 is the partial pressure of saturated vapor water (1705 Pa at 15°C (van den Bosch & Weterings, 2005)). Burn injuries depends on the duration of exposure to the radiative het flux, i.e. the thermal dose which is estimated with Eq(9):

$$Thermal\ dose = q^{4/3} \cdot t \quad (9)$$

where q is the incident radiation in kW m^{-2} and t is the duration of exposure (fireball duration) in s. The relationship between burn level and thermal dose from infrared radiation are published in (Rew, 1997). The maximum tolerable thermal dose which does not provoke any injury is 80 $kW^{4/3}$ $m^{-2/3}$ s. The safety distance from the tank for personnel during the explosion is the distance value between the release point and the target (x) for which this thermal dose threshold is attained. In this study, the safety distance is only based on the thermal contribution neglecting the overpressure from the blast wave. Finally, the described theoretical models and empirical correlations were validated with the outcomes of the BMW tests and an estimation of the fireball generated during the forthcoming SH_2IFT LH_2 BLEVE tests was provided.

3. Results

A total of 10 single walled LH_2 tanks, insulated with a layer of foam, were destroyed by means of cutting charges during the BMW bursting tests. The LH_2 mass content in the vessels varied from 1.8 to 5.4 kg. Despite these tanks were equipped with temperature, pressure and LH_2 level sensors, the fireball results are not correlated with these parameters. Pehr (1996) reported a maximum fireball diameter of 20 m, height of the fireball center between 16 and 20 m, and 4 s as longest duration between the fireball ignition and extinction. Moreover, a radiation spectroscopy was carried out during the tests highlighting ultraviolet (from OH-radicals and H_2O molecules), infrared and visible radiations (from solid particles). However, the radiative flux emitted from the fireball at a certain distance was not provided in (Pehr, 1996). Similar results were obtained by applying the methodology previously described in Sec. 2. The highest hydrogen mass (5.4 kg) was adopted to calculate the most conservative case. A maximum diameter and height of the fireball center of 13.9 m were estimated for a total duration of 0.8 s (with momentum-dominated fireball equation) and 3.4 s (with buoyancy-dominated fireball equation). The safety distance from the tank to the target (personnel) was 77.8 m. The maximum error values between the estimations and the test results were 30.5% in the case of the maximum diameter and height of the fireball center and 80% for the fireball duration.

During the SH_2IFT project, three double walled LH_2 tanks with a volume of 1 m^3 filled at 50% will be engulfed in a propane fire until the tank failure will cause a BLEVE. Considering the LH_2 density (70.9 kg m^{-3}) initially stored at 1 bar at a temperature close to the boiling point (20.3 K), the hydrogen mass content in the tank will be 35.5 kg (NIST, 2019). This mass was used in the blind simulation of the fireball, consequence of an LH_2 BLEVE. According to this evaluation, the fireball will last from 1.5 to 4.7 s expanding to a maximum diameter and height of 25.9 m. The thermal dose of 80 $kW^{4/3}$ $m^{-2/3}$ s for a target exposed to the fireball is expected at 159.1 m, thus this is the safety distance from the LH_2 tank. In Table 1, the results of this analysis are reported for comparison.

Table 1: Comparison between the experimental data from the BMW bursting tests (Pehr, 1996) and the empirical model outcomes for the BMW and SH_2IFT LH_2 BLEVE tests.

Fireball parameters and safety distance	BMW tests	BMW tests estimation	Error (%)	SH_2IFT BLEVE tests blind simulation
LH_2 mass (kg)	1.8 ÷ 5.4	5.4	---	35.5
Max. diameter (m)	20.0	13.9	30.5	25.9
Duration (s)	4.0	0.8 ÷ 3.4	80.0 ÷ 15.0	1.5 ÷ 4.7
Height (m)	16.0 ÷ 20.0	13.9	13.1 ÷ 30.5	25.9
Safety distance (thermal dose = 80 $kW^{4/3}$ $m^{-2/3}$ s) (m)	---	77.8	---	159.1

4. Discussion

According to (Gayle & Bransford, 1965), the fireballs generated by propellant explosions after rocket failures have a diameter similar to those for high explosives, while the duration for the propellants is appreciably longer. Furthermore, the authors observed that the diameter depends on the cube root of the propellant weight and it varies inversely with the cube root of the atmospheric pressure. Pehr (1996) noticed that the diameter was influenced by the tank pressure as well. However, both the atmospheric pressure and the tank pressure prior the explosion are not included in any correlation. In (Gayle & Bransford, 1965), a standard error of 30% was estimated for the data scatter with the fitting curve. This was also noted in this study, where the maximum diameter of the BMW tests was underestimated of about 30% by using the (Hord, 1972) equation. Moreover, Zalosh & Weyandt (2005) estimated with the same correlation a fireball diameter value 19% higher than the experimental results for the hydrogen pressurized tank. According to these observations, the diameter estimated in the blind simulation of the SH_2IFT tests might vary by ± 30% in the range of 18.1 ÷ 33.7 m. Even though these results may be within the error interval estimated by Gayle & Bransford (1965), an underestimation is not acceptable when a risk assessment is performed, and the most severe consequences are sought. During the NASA test series, it was difficult to estimate the exact fireball duration probably due to the variation in photography techniques (Gayle & Bransford, 1965). For this reason, the data scatter provided a standard error of 84%. The authors proposed to estimate the fireball duration with the same correlation for all types of liquid propellant tested This equation is similar to the momentum-dominated fireball formula described in Sec. 2. In this study, the duration calculation gave a similar error (80%) using this approach, while adopting the buoyancy-dominated fireball equation, the error was reduced to 15%. This latter equation gave a more accurate evaluation of the fireball duration also in (Zalosh & Weyandt, 2005). According to CCPS (2010), the momentum-dominated fireball equation should provide a more precise time estimation for small amount of fuel (< 30,000 kg). The results of this analysis are not in agreement with this theory, and again an underestimation was provided by these correlations.

The lift-off velocity of the fireball is nearly independent of the propellant weight (High, 1968) and it was not assessed in this study since the available test results are not sufficiently detailed. The maximum height of the fireball center was estimated with the equation proposed by van den Bosch & Weterings (2005) since it provides the most conservative estimation. Bader et al. (1971) developed a model to estimate the minimum propellant weight for the fireball to liftoff. If the propellant mass is lower than this critical value, the fireball will not form, and the propellant will burn on the ground as residual fires. This model was validated with the results of the Pyro test series (Willoughby et al., 1968) where explosion of a propellant weight (1:5 fuel-oxidizer ratio) lower than 200 lb (90.7 kg, equivalent to 15.1 kg of LH_2) did not lift-off. During the BMW tests the fireballs rose up to a height between 16 and 20 m when the hydrogen mass content in the LH_2 vessel prior the explosion was between 1.8 and 5.4 kg. The model developed by Bader et al. (1971) should be tuned according to these results. A fireball generated by the explosion of an LH_2 vessel emits ultraviolet, infrared and visible radiations (Pehr, 1996). The hydrogen fireball seems to have a high luminosity (Zalosh & Weyandt, 2005), while the hydrogen flame is well-known to have a low visibility compared with the other hydrocarbons (Schefer et al., 2009). One reason for this can be the participation of the tank material in the combustion (polyethylene products and carbon fiber fragments) or other fuels burnt externally to the vessel (propane) (Zalosh & Weyandt, 2005). Furthermore, very high temperatures were locally measured in the hydrogen fireball both during the BMW and NASA tests. The highest temperature was close to the stoichiometric combustion temperature of hydrogen in air (2318 K) (Pehr, 1996). This affects the surface emissive power estimated with the Stefan Boltzmann's law, and hence the incident radiation and thermal dose. The SEP can be estimated with the method prosed by (van den Bosch & Weterings, 2005) in which the fuel mass and the heat of combustion of the flammable substance are considered. In this case, this method presents a less conservative estimation compared with the Stefan-Boltzmann's law. According to CCPS (2010), the SEP is influenced by the fuel mass and the pressure of the vessel prior the release. This latter parameter is usually not considered in the theoretical models. Pehr, (1996) stated that was not possible to develop a thermal radiation model close to the hydrogen fireball since the particles distribution, gas concentration and fireball temperature were unknown due to the rapid fireball expansion. Moreover, Prugh (1994) developed a model for hydrocarbons fireball thermal radiation without including hydrogen in the discussion because its flame temperature is very high and its emissivity is very low. The thermal dose criterion was employed to assess the safety distance from the LH_2 vessel during an explosion. The results achieved are very conservative since the lower threshold of the range (80 ÷ 130 $kW^{4/3}$ $m^{-2/3}$ s) suggested by Rew (1997) was adopted in this analysis.

These observations should lead to future studies on the hydrogen fireball consequences either by improving and tuning the existing theoretical models or by exploiting the CFD tools for a more accurate and thorough assessment of all the fireball parameters. Multiphysics analysis could provide a wide overview on how the parameters influence the fireball consequences. For instance, a structural analysis may determine if the vessel type (single or double walled) affect the explosion consequences such as the blast wave overpressure and the fireball characteristics. The experimental data available in the literature are not sufficient to validate the developed models. A broader amount of data is required to comprehend the complex physical phenomena involved in the combustion of hydrogen as consequence of a BLEVE, and the SH_2IFT project will partially fill this knowledge dearth.

5. Conclusions

A consequence analysis on hydrogen fireball generated after an LH_2 BLEVE explosion was conducted. In particular, the fireball dimensions, duration and radiation were estimated by means of empirical and theoretical models. The evaluation of the radiation at different distances allowed the determination of the safety distance from an LH_2 tank. The safety distance is a fundamental parameter for the selection of appropriate safety barriers and in the writing of safety guidelines. In this analysis, the BMW bursting tests were simulated obtaining an underestimation of the fireball diameter and duration. Furthermore, a sort of blind simulation of the SH_2IFT LH_2 BLEVE tests was carried out. The results of the SH_2IFT project will be used to validate the results of this analysis and fulfill part of the knowledge gap in hydrogen fireball.

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