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A review of hydrogen-air cloud explosion: the fundamentals, overpressure prediction methods, and influencing factors

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Abstract

Hydrogen is one of the most promising renewable energies that has been observing rapid development over the past years. Recent accidental explosion incidents and the associated damages have demonstrated the importance of hydrogen safety against potential explosions. This article presents a systematic review on hydrogen explosions. Potential explosion scenarios including the existence of impurities and rich-oxygen environment in the production, storage with extreme-high pressure and ultra-low temperature, transportation, and consumption processes are reviewed. Different types of hydrogen-air cloud explosion include expansion and deflagration, detonation, and deflagration-to-detonation transition (DDT). Existing studies on hydrogen explosion covering laboratory and field blasting test, numerical simulation utilizing various computational approaches, and theoretical derivation are reviewed and summarized. CFD modelling is currently one of the main research methods because of its cost effectiveness, though challenges existing in simulation hydrogen-air cloud detonation comparing with testing results. Apart from the properties of hydrogen-air cloud such as concentration, size and heterogeneity, environmental factors such as ignition, ventilation and obstacle are found to strongly influence the loading characteristics of hydrogen-air cloud explosion. Existing prediction approaches for estimating blast loading from hydrogen-air cloud explosion including the TNT equivalent method (TNT-EM), TNO multi-energy method (TNO MEM), and Baker-Strehlow-Tang method (BST) are primarily empirical based. Because of the inherited difference of hydrogen-air cloud from solid explosives and conventional flammable gases, the accuracies of these approaches are still doubtable, which requires further study.
Keywords: hydrogen-air cloud; blast loading; overpressure prediction methods; influencing factors

1 Introduction

The pursuit of clean and renewable energy has become one of the largest challenges for modern society in response to the environmental impact of carbon emissions and the draining of fossil fuels [1-5]. At present, electricity and hydrogen are the two most promising renewable energy sources. Compared with electricity stored through batteries, hydrogen as the fuel has more obvious advantages: firstly, the energy density of hydrogen is much higher, which makes it more suitable for applications in wide and diversified areas such as new energy vehicles, energy storage, power generations as well as domestic and commercial usages. Secondly, the usage of hydrogen is more environmentally friendly than that of electricity, since the latter is stored in heavy metal batteries imposing the risk of heavy metal pollution. Thirdly, the performance of the battery is prone to decay in a low-temperature environment, while hydrogen fuel does not have such problems. Owing to these advantages, more than 50 countries, including the United States, Japan, Germany, France, the United Kingdom, China, and Australia have developed strategic and/or specific goals, tasks, and policy incentives for hydrogen development [6]. Fig. 1 shows some policies of various countries regarding hydrogen development. All these policies show the high potential and strategic significance of hydrogen energy.

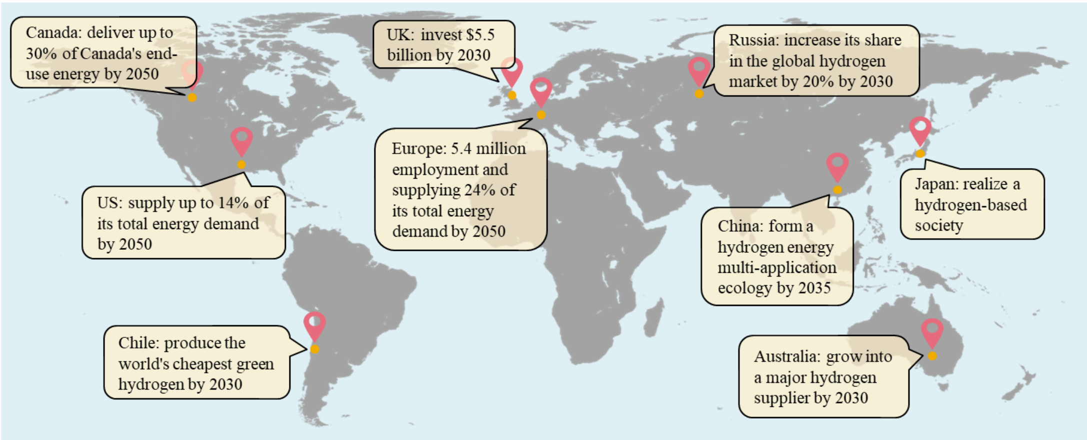

Fig. 1. Hydrogen policies of several countries[7-15]

However, the wide application of hydrogen faces practical challenges. Hydrogen is a highly flammable and explosive chemical. The minimum ignition energy of hydrogen is less than one-tenth that of other hydrocarbon fuels (such as methane), which means hydrogen is extremely easy to be ignited. In 2019 alone, three hydrogen explosion incidents occurred within 20 days around the world [16-18], including a refueling station explosion in Norway, a transport vehicle explosion in the United States, and a hydrogen storage tank explosion in South Korea. To achieve a high energy density and thus improve its cost efficiency, hydrogen is generally stored under extremely high-pressure or low-temperature conditions. Accidental hydrogen explosions thus often lead to severe consequences. For instance, an accidental hydrogen explosion damaged 60 houses in Catawba County in 2020, during which the associated ground shock was felt at nearly 10 miles away [19]. Therefore, for the safe development and wide application of hydrogen, proper study on the risk, consequence, mitigation, and strengthening of hydrogen and related equipment is important for the safety of personnel and properties.

This article reviews existing research related to hydrogen safety focusing on the blast loading of accidental hydrogen explosions. Specifically, this review paper is divided into six sections including this introduction. Section 2 reviews potential scenarios of hydrogen explosions. Section 3 presents the fundamentals of hydrogen explosions and the different types of hydrogen explosions. In Section 4, existing approaches including experimental tests, numerical approaches, and empirical formulae for determining the hydrogen blast loading are presented. In Section 5, influential factors such as hydrogen concentration, size, and heterogeneity, ignition location and intensity, initial temperature and pressure, obstacle and ventilation, water and inert particles, and suppression materials/structures are reviewed. Section 6 concludes this review.

2 Potential Scenarios of Hydrogen Explosion

The risk of hydrogen explosion exists throughout the entire process of production, storage, transportation, and consumption, as shown in Fig. 2.

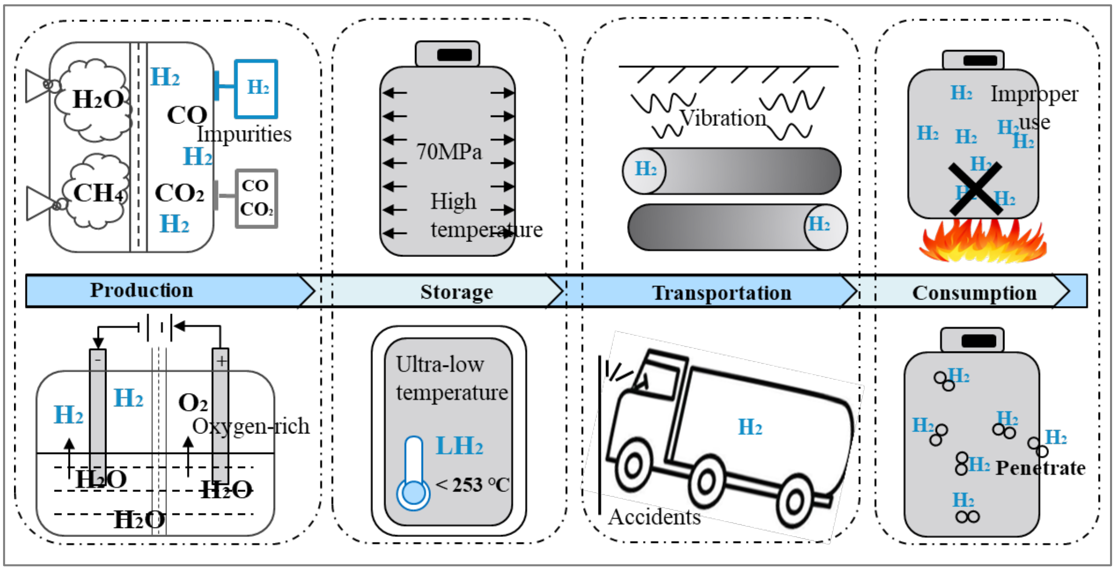

Fig. 2. Potential hydrogen risks in the entire process

2.1 Production

At present, there are two main methods to produce hydrogen, i.e., water electrolysis and reforming. In hydrogen production from electrolytic water, a large amount of oxygen is produced together with hydrogen. Since the density of oxygen is a lot higher than air, it is difficult to diffuse fast enough to the air. Under the action of gravity, it is elementary to form an oxygen-rich environment, which creates one of the most dangerous situations in the industry because all kinds of fuels are prone to severe combustion and explosion. In the process of reforming hydrogen, the safety of hydrogen is usually related to other gases (such as CO, CO_2, and CH_4). Hydrogen production by reforming refers to converting the mixture of fossil fuel and water vapor into hydrogen-rich gas at high temperatures. Taking natural gas (mainly composed of methane) as an example, catalytic reforming is carried out at 3-5atm and about 1000K to generate hydrogen and CO after mixing methane and water vapor. In the subsequent cooling and compression process, all gas impurities except helium are solidified in the hydrogen liquefaction process, resulting in freezing blockage of some system pipelines and explosions.

2.2 Storage

Hydrogen can be stored in the forms of high-pressure gaseous, liquid, and solid hydrogen states. At the current stage, high-pressure gaseous hydrogen storage is the most widely used way since such devices have a simple structure and fast charging and discharging characters which is convenient for hydrogen usage [20]. Since the density of hydrogen is low, to improve the volumetric energy density of hydrogen tanks, the design pressure of gas storage tanks usually reaches 35 MPa or even 70 MPa. Compared with natural gas cylinders (generally 20-25 MPa), high-pressure hydrogen tanks could trigger greater explosion hazards [21].

Liquid hydrogen storage tanks are another popular form of hydrogen transportation, which is more suitable for large-scale, long-distance transportation because of the higher transport efficiency and lower transport costs compared with high-pressure gas hydrogen vessels. Usually, liquid hydrogen is stored in low-temperature compressed liquid form. Although the confining pressure of liquid hydrogen is not large, usually less than 0.7 MPa, the low temperature can embrittle various tank materials causing sudden cracking of the content device. Solid-state hydrogen storage is still in the research stage with very few engineering applications, so it is not discussed in this paper.

2.3 Transportation

Currently, produced hydrogen is primarily transported by delivery trucks and cargo ships using pressure vessels. During transportation, traffic accidents such as vehicle collisions, rear-end collisions, and rollover could lead to tank rupture and thus lead to boiling liquid expanding vapor explosion (BLEVE) which will be covered in detail in Section 4. Pipelines also are used to assist transportation. Structural vibration during transportation is a potential hazard leading to hydrogen leakage and explosion. Hydrogen pipelines in cities are generally buried below or near the road, where passing vehicles cause inevitable vibrations. Such traffic-induced pipeline vibration could result in fatigue forming micro-cracks. Moreover, hydrogen is generally transported in pipelines under high pressure (over 35 MPa), and the hydrogen embrittlement phenomenon could also accelerate the development of micro-cracks. Hydrogen leaked from micro-cracks of buried pipelines can easily accumulate and form hydrogen-air clouds. Weak electrostatic sparks can cause ignition or detonation when the hydrogen concentration reaches a certain ratio. The explosion of a hydrogen cloud will heat up the pipeline rapidly, making the internal hydrogen expand and triggering the consequent explosions.

2.4 Consumption

During the consumption phase, the electrostatic spark and open fire could result in an explosion of leaked hydrogen [22]. A unique phenomenon - hydrogen embrittlement, where hydrogen containers adsorb hydrogen under high pressure causing small cracks in the interior, will accelerate equipment failure and hydrogen leakage [23]. Moreover, permeation in terminal applications requires special attention. The hydrogen molecule is small, and the diffusion coefficient is high, especially easy to penetrate outward. As one of the high potential hydrogen consumption media, hydrogen-fueled vehicles could be widely used. The hydrogen tank pressure for vehicle is over 35MPa, which could further intensify hydrogen penetration [21].

As a consequence, leakage of hydrogen is more likely than conventional flammable gas which may result in explosions.

3 Fundamentals of Hydrogen Explosion

3.1 Ignition (basic combustion and explosion properties)

As an active combustible chemical, hydrogen has a high risk of deflagration and detonation. Post-event investigations identified that 20% of losses in hydrogen accidents are caused by fire, while over 75% of the total losses are accounted for by explosion [24, 25]. There are three basic conditions to be met for hydrogen combustion: 1) suitable concentration of hydrogen; 2) suitable concentration of oxidizer; 3) ignition source with sufficient energy.

Hydrogen has a wider range of flammable concentrations than most hydrocarbons. Table 1 lists the flammability limits of hydrogen under ambient conditions [26], where the flammability limit of a hydrogen-air cloud is about 4%~75%. Moreover, the range of flammability limit is greater when the flame of hydrogen propagates upward than that downward. Factors such as temperature, pressure, the presence or absence of diluent, and the shape of the structure could all affect the flammability limits of hydrogen [27, 28]. Table 2 summarizes the flammability range of hydrogen by different existing design standards [27]. To trigger a hydrogen-air cloud explosion, the concentration of hydrogen in the air needs to be within a narrower hydrogen concentration limit. Existing studies on the detonation limit of hydrogen vary substantially. ISO recommends the detonation range for hydrogen-air clouds to be 18% ~ 58% [29], while some studies showed that a minimum of 12.5% of hydrogen concentration ratio could lead to the transition to detonation [30]. Some researchers thus conservatively recommended that the hydrogen-air cloud explosion can be triggered when the hydrogen concentration is between 11% and 70% [31, 32]. With the increase of hydrogen concentration, the resulted peak overpressure will initially increase and then decrease. The maximum overpressure would be obtained when the equivalence ratio (hydrogen to oxygen ratio divided by stoichiometry) is about 1.6 in the hydrogen explosion without the obstacle [33, 34] and 0.9 to 1.3 with obstacles [35].

Minimum ignition energy refers to the minimum energy that can cause gas combustion [36], which is usually determined by an electric spark test [37]. Only when the ignition energy is larger than the minimum ignition energy hydrogen can be ignited. The minimum ignition energy of hydrogen in air is very small, which is nearly a quantitative product smaller than that of normal hydrocarbon fuels (at 101.3kPa and ambient temperature, the minimum ignition energy of hydrogen is less than 0.02 mJ, while methane is about 0.28 mJ) [38, 39]. Therefore, hydrogen can be ignited by the presence of any weak ignition source (electric spark, hot surface, open flame, etc.) or even the energy released by static electricity in the human body (up to 8.33 mJ) [40]. Mitigation of hydrogen explosion in the event of leakage by eliminating ignition sources is thus very challenging. In addition, because of the very small ignition energy, when hydrogen is released at high pressure, the strong shock wave generated by high-pressure hydrogen jet can cause hydrogen to be ignited spontaneously. Zhou et al. [41] reviewed the self-ignition phenomenon of high-pressure hydrogen discharge. Fig. 3 shows the schematic view of self-ignition inside the tube [38, 42]. The minimum ignition energy required by the hydrogen-air cloud is influenced by ambient temperature which decreases as the temperature increases [43, 44].

Table 1 Flammability limits (1 atm) [26]

Conditions		**Hydrogen Content (vol %)**			
		Upper propagation		Downward propagation	
		Lower limit	Upper limit	Lower limit	Upper limit
Hydrogen in air	Spherical Vessels	4.1	74.8	8.9	74.5
	Tubes	4.6	75.5	—	—
Hydrogen in oxygen		4.1	94.0	4.1	92.0
Hydrogen plus inert gas mixture	H_2+N_2+21 vol % O_2	7.7	75.7	8.7	75.7
	H_2+CO_2+21 vol % O_2	5.3	69.8	13.1	69.8
	H_2+He+21 vol % O_2	4.2	74.6	9.0	74.6

Table 2 Hydrogen flammability limits with different ignition conditions [27]

	LFL	UFL	Ignition vessel	Ignition source
DIN 51649	3.8%	75.8%	Vertical glass tube (60mm diameter by 300mm height)	High voltage spark, duration 0.5s (app.5 J)
EN 1839(T)	3.6%	76.6%	Vertical glass tube (80mm diameter by 300mm height)	High voltage spark, duration 0.2s(app.2 J)
EN 1839(B)	4.2%	77.0%	Closed spherical steel vessel, (volume 14 dm^3)	Fusing(exploding) wire (10J-20J)
ASTM E 681	3.75%	75.1%	Glass flask (volume 5 dm^3)	High voltage spark, duration 0.4s(app.4 J)

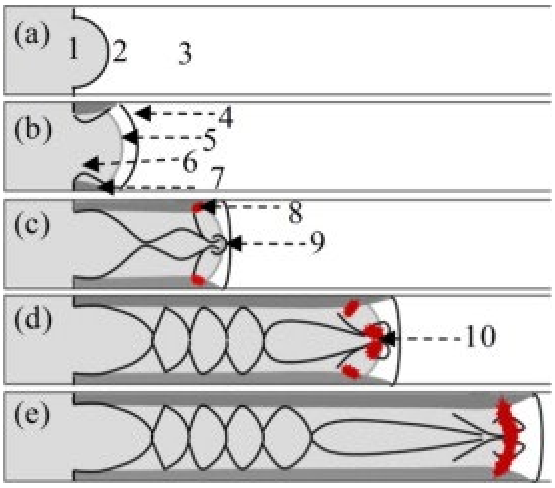

Fig. 3. Schematic of spontaneous ignition inside the tube [42], (a) configuration before rupture; (b) initial shock formation; (c) generation of vortex ring and reaction in the core and boundary layer region due to shock–shock/shock–boundary layer interaction, respectively; (d) reaction in the core region; (e) merge of two reaction regions. (1) High-pressure hydrogen, (2) rupture disk, (3) ambient air, (4) multi-dimensional incident shock, (5) contact surface, (6) reflected shock, (7) boundary layer of hot air due to shock, (8) reaction in the boundary layer region, (9) vortex ring, (10) reaction in the core region.

3.2 Types of hydrogen explosion

According to the flame combustion speed and the mixing condition of hydrogen with air, Hydrogen explosion can be categorized into expansion deflagration, mixture deflagration, detonation, and deflagration-to-detonation (DDT). When hydrogen leaks on a small scale and is ignited with a low ignition energy before it is fully mixed with air, jet flame or fireball will be produced. When hydrogen leaks violently from the high-pressure gaseous or liquid hydrogen storage tanks, deflagration will be produced with large fireballs producing significant overpressure. If the leaked hydrogen is not ignited immediately but fully mixed with air to form a combustible hydrogen-air cloud. Once ignited, deflagration will be produced, which may grow into detonation deflagration.

3.2.1 Hydrogen expansion and deflagration

Hydrogen expansion and deflagration could occur on a cracked and heated hydrogen container, where hydrogen expands rapidly and generates a jet fire or a fireball, producing sharply rising overpressure inside the container that breaks through the container wall. Table 3 summarizes recent studies on hydrogen expansion and deflagration, in which gaseous and liquid hydrogen are investigated through experimental, numerical, and analytical approaches. For engineering applications of hydrogen expansion and deflagration, pressure vessel burst (PVB) and boiling liquid expanding vapor explosion (BLEVE) are the two common categories which result in most catastrophic consequences.

Table 3 Recent research for hydrogen expansion and deflagration

Category	Year	Method	Objective	Scenario	Reference
Gaseous	2022	Experiment	Detailed data on the tank wall temperature and inner pressure	High-pressure tank under fire exposure	Li et al.[45]
	2022	Analytical	Establish thermal radiation models to predict the radiant heat flux field	Jet flame to ruptured tank surface	Wu et al. [46]
	2021	Modelling	Underly blast wave and fireball dynamics	High-pressure hydrogen tank rupture in a fire	Molkov et al.[47]
	2021	Modelling	Study the performance of the storage tank rapture	Hydrogen tank with TPRD in fire	Molkov et al.[48]
	2020	Calculating	Develop hazard distance nomograms	Stationary and onboard ruptures in fire	Kashkarov et al.[49]
	2020	Modelling	Present a universal correlation for blast wave decay	Hydrogen tank rupture in a tunnel fire	Molkov and Dery[50]
	2018	Experiment	Two catastrophic explosion accidents caused by TPRD failure	Accidental tank rupture during fire	Shen et al.[51]
	2017	Modelling	Interaction between the blast wave propagation and combustion process	Hydrogen tank rupture due to fire	Kim et al.[52]
	2015	Experiment	Investigate unsteady high-pressure hydrogen release	Vessel rupture	Mironov et al.[53]
	2014	Experiment	Investigate self-ignition behavior of highly transient jets	Hydrogen jet ignition and explosion	Kessler et al.[54]
Liquid	2022	Modelling	Extent initial conditions influence the blast wave	Storage vessel rupture	Ustolin et al.[55]
	2021	Experiment	Measure the visible flame length and heat-flux characteristics from high-aspect ratio nozzles	Leakage at hydrogen fueling stations	Hecht and Chowdhury [56]
	2020	Experiment	Measure the blast pressure at the ignition and the flame length	Hydrogen leakage from nozzle	Kobayashi et al. [57]
	2020	Analytical and modelling	Results of overpressure, fragments projection and eventually a fireball	Catastrophic tank rupture	Ustolin et al. [58]
	2019	Analytical	Compare fire and explosion hazards of various alternative fuel	Vehicles in tunnels	Li [59]
	2017	Experiment	Study the dispersion and thermo-physical properties	Under-expanded cryogenic jets	Panda and Hecht [60]
	2017	Modelling	Coupled response between the pressure and the unstable boiling	Storage and transportation	Ren et al. [61]
	2014	Experiment	Flammability limits, flame speeds and radiative heat levels	Ignition of spill of LH2	Hall et al. [62]
	2013	Modelling	Comprehensive investigation for hazards	Vehicles	Li et al. [63]
	2012	Modelling	The subsequent consequences	Accidental release from liquid storage	Li et al.[64]
	2012	Experiment	provide novel data on cryogenic sonic hydrogen jets	Under steady-state sonic release	Friedrich et al. [65]

<u>Pressure vessel burst (PVB)</u>

Hydrogen deflagration could happen to a high-pressure gas tank when a burst occurs to the pressure vessel resulting in hydrogen leakage and being ignited. In practice, malfunction of safety pressure relief device, container internal pressure increases due to external heat sources (such as a fire in adjacent areas), and tank failure due to combined action of hydrogen embrittlement and material damage (such as a strong collision in traffic accidents), etc. could all lead to PVB of hydrogen. If the crack is very small, it may only generate a jet fire; otherwise, it would produce a fireball resulting in hydrogen deflagration. Table 3 tabulates existing studies investigating the behavior of hydrogen PVB. For example, Shen et al. [51] carried out a field test to study the failure process of a 35MPa hydrogen storage tank subjected to fire when its thermally activated pressure relief device failed. As shown in Fig. 4, when the pressure tank bursts in the fire, a huge fireball was formed. However, there was only partial flame developed before the rupture of the tank. Some researchers also numerically simulated PVB of hydrogen using CFD tools [47, 48]. Till now, there is rarely any study on the combination of hydrogen PVB and structure damage yet. Existing studies on PVB for hydrogen is also very limited while this is very related to the storage, transportation and utilization of hydrogen in practice. Therefore, more researches are expected.

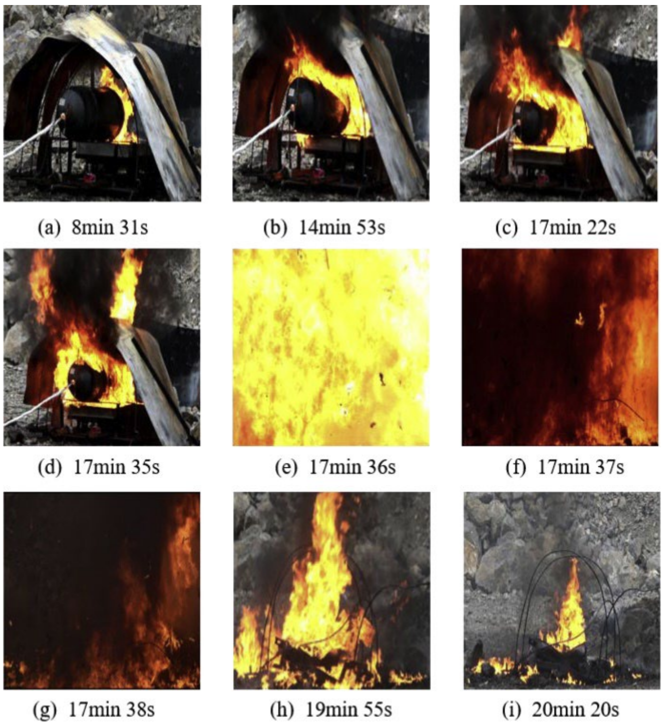

Fig. 4. The failure process of a high-pressure storage tank [51], (a-d) the fire extends before tank rupture; (e-g) tank rupture and fireball generation; (h-i) the fire disappears with hydrogen exhausted.

Boiling liquid expanding vapor explosion (BLEVE)

BLEVE may occur when a liquid hydrogen container ruptures. BLEVE of hydrogen storage tank could occur when a liquid hydrogen container collides, or hydrogen overflows into the vacuum layer when the internal wall of a storage tank fails under fatigue. Because of the damage to the insulation layer, the temperature in the tank rises suddenly and the liquid hydrogen in the container will be overheated. When the overheat limit is reached, the liquid begins to boil and evaporate rapidly, causing the internal pressure to rise rapidly until the container ruptures. When a large crack or fracture occurs in the container, the spontaneous combustion of hydrogen leakage further heats the liquid hydrogen in the container. The rapid vaporization of liquid hydrogen further increases the pressure in the container causing a physical explosion. At the same time, a large fireball is generated which forms strong thermal radiation. At the ambient condition, the density of coexisting gas-liquid hydrogen (20.37 K) is larger than that of air. Leaked hydrogen will slide close to the ground instead of diffusing upward, which will absorb heat continuously and gradually mixes with air to form a hydrogen-air cloud [66], as shown in Fig. 5. Experimental and numerical study of hydrogen BLEVE is relatively limited. For example, Pehr from BMW conducted BLEVE blast tests for liquefied hydrogen tank systems to assess the safety and acceptance of hydrogen tank systems for passenger vehicles [67]. Ustolin et al. [58] conducted CFD simulations to model Pehr's test, where a similar trend of blast overpressure was obtained. Till now, there is still a lack of systematic study of hydrogen BLEVE and its impact on structures.

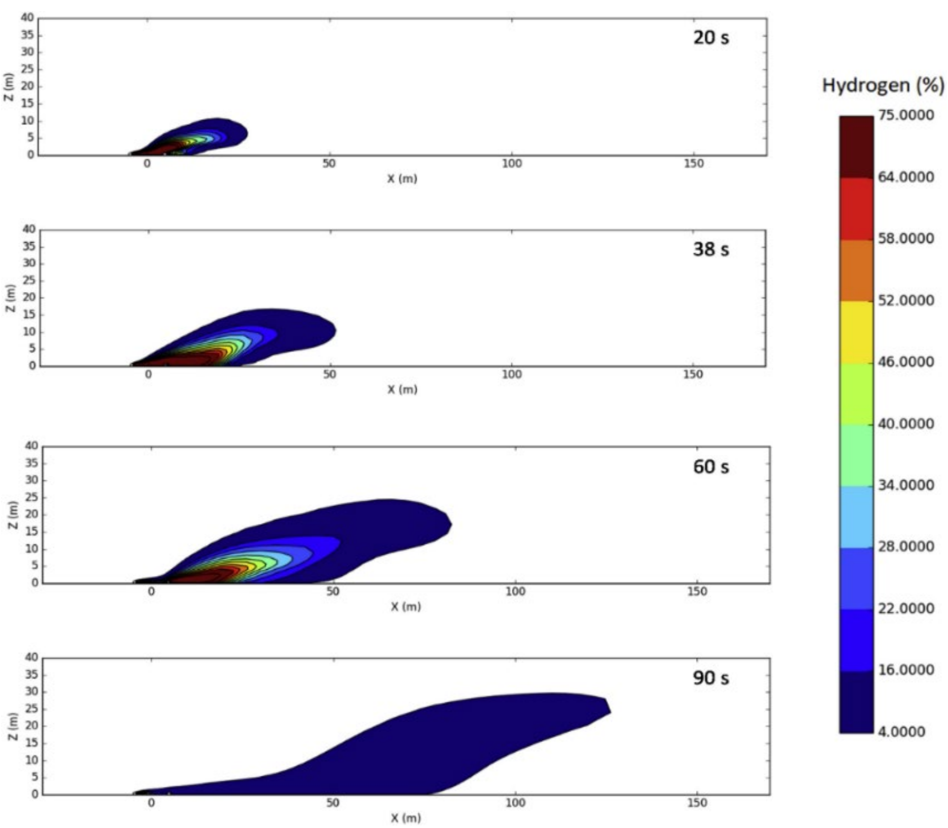

Fig. 5. Development of the flammable hydrogen gas cloud after spill [66]

3.2.2 *Hydrogen-air cloud deflagration*

Hydrogen-air cloud deflagrations are the most common form of hydrogen explosions. When hydrogen is fully mixed with air forming a large volume of the gas cloud, vapor cloud explosion (VCE) will occur when ignited if the flammable or explosion limit is reached. Table 4 summarizes existing studies on hydrogen-air cloud deflagration. Hydrogen-air cloud deflagration is the best-studied type of hydrogen explosion. There is ample existing literature ranging from flame propagation mechanisms of unstable flame acceleration to influencing factors to different scenarios. Compared with other VCE (such as methane), existing studies showed that an unconfined hydrogen-air cloud could produce considerable overpressure [68, 69]. Fig. 6 shows high-speed camera images of a 30% hydrogen-air cloud deflagration process in the unconfined condition [70], which generates a considerable fireball. Compared with the unconfined conditions, confined hydrogen-air clouds could produce much higher blast overpressure which therefore is more dangerous. Pitts et al. [71] performed hydrogen deflagrations tests in a conventional confined garage (6.1m×6.1m×3.05m) with a hydrogen concentration of 29.3%. It can be seen from Fig. 7 that the garage structure was totally written off. It therefore demonstrates that proper structure protection is needed against potential hydrogen-air cloud deflagration. More thorough study is expected to predict blast loading of hydrogen VCE and to develop effective and efficient mitigation and structural protection approaches.

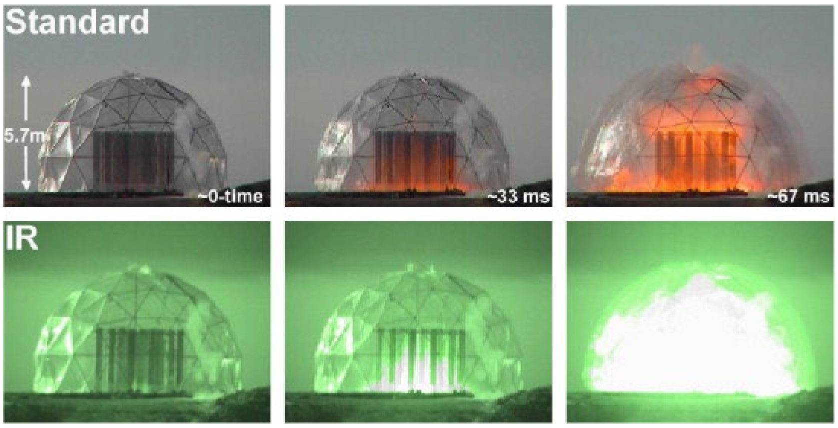

Fig. 6 High-speed camera images of a 30% hydrogen explosion test [70]

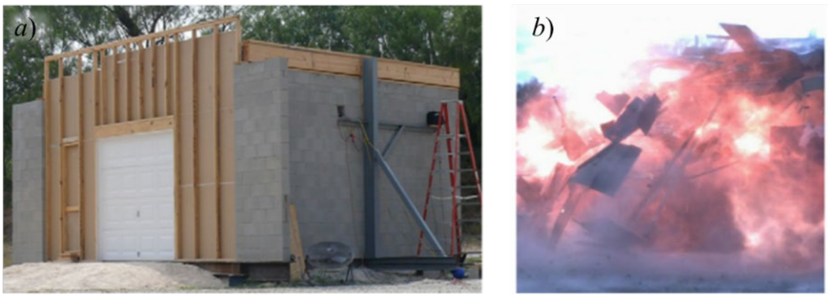

Fig. 7 Hydrogen deflagrations in a garage: a) before the explosion; b) during the test [71]

Table 4 Summary of research on hydrogen-air cloud deflagration

Category	Year	Method	Objective	Scenario	Reference
Propagation mechanism	2022	Modeling	Dynamics of premixed flames propagating	Planar ignition in a closed tube	Shen et al. [72]
	2021	Experiment	Oscillation of flame propagation in duct	Open end to the closed end	Yu et al. [73]
	2021	Experiment	Premixed flame with various hydrogen volume fractions	In duct with both ends open	Yang et al. [74]
	2021	Modeling	Effects on the flame propagation characteristics	In pipes with different contractions/expansion angles	Song et al. [75]

	2022	Experiment	Propagation behavior of shape change in the flaring rate pipe	Different hydrogen doping ratios	Dong et al. [76]
Influence factors	2022	Experiment	Hydrogen-air vented deflagration in a smooth rectangular tube	Various vent areas for different hydrogen concentration	Wang et al. [77]
	2022	Experiment	Effect of blockage ratio of obstacle on vented hydrogen-air explosion	Obstructed rectangular tube	Wang et al. [78]
	2021	Experiment	Flame propagation structure and overpressure wave	Different hydrogen volume fractions and ignition positions	Yao et al. [79]
	2021	Experiment and modeling	Effect of aspect ratio for flame propagation	Closed rectangular channels	Shen et al. [80]
	2021	Experiment	Effect of metal wire mesh for flame quenching behaviors	Hydrogen/air volume ratio is 2:3	Jin et al. [81]
Different scenario	2021	Modeling	Conditional probability of damage	Hydrogen explosion in a mine tunnel	Skob et al. [82]
	2018	Experiment	Behavior of hydrogen jet releases and explosion	Confined or congested area	Shirvill et al. [83]
	2019	Modeling	Leakage and explosion of station	Hydrogen refueling station	Liang et al. [84]
	2021	Modeling	Ignition and failure mechanisms of hydrogen explosion accident	Fukushima Daiichi Nuclear Power Plant Unit 1	Fujisawa et al. [85]
	2021	Experiment	Behavior in various hydrogen volume ratio at different ignition positions	Tank with lean hydrogen-air mixture	Hu and Zhai [86]

3.2.3 Hydrogen-air cloud detonation

The hydrogen-air cloud can be detonated and produce a much higher blast loading [87, 88]. Different from deflagration, detonation is essentially the adiabatic compression of the leading shock wave, which makes the combustible mixture ignite with a faster heat release rate [89]. The detonation reaction time is much lower than the chemical reaction time of deflagration, and the overpressure produced by hydrogen-air cloud detonation is much higher than that produced by deflagration. Considerable studies have been conducted over the past few years on hydrogen-air cloud detonation [90-93], where the detonation mechanism, blast wave propagation [88, 94-97], and explosion mitigation [98-101] were studied. To facilitate the comparison of the blast overpressure data between hydrogen detonation and deflagration, Groethe et al. [70] conducted field detonation tests. C-4 high explosive was used to detonate a

30% concentration hydrogen-air cloud. Fig. 8 shows the high-speed images of the tests, from which the flame speed during detonation reached about 1980 m/s. With the same hydrogen concentration ratio, the peak overpressure of detonation was found to be about 5 times that of hydrogen deflagration.

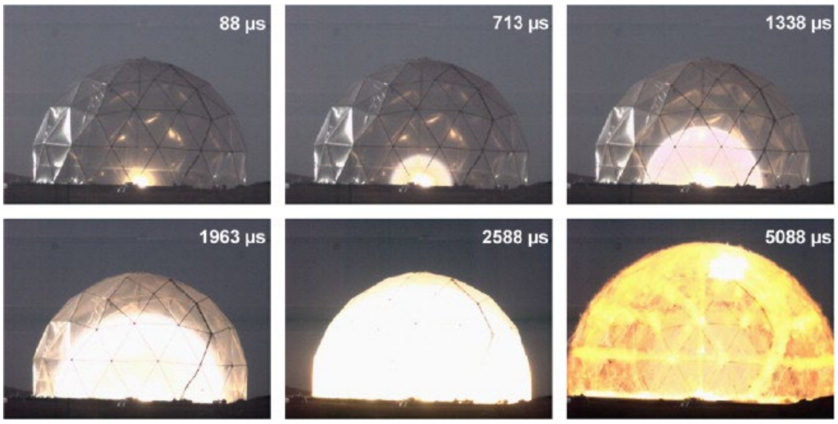

Fig. 8 High-speed images of hydrogen air cloud detonation test [70]

3.2.4 Deflagration-to-detonation transition (DDT)

Deflagration of the hydrogen-air cloud could transit into detonation [102-105]. Being different from direct detonation that requires a strong ignition source, DDT usually starts with a normal fire. In a confined space or blocked environment, the combustion speed will accelerate to deflagration with the acceleration of time and distance due to the turbulent mixing of unburned hydrogen and air near the obstacle. With further flame acceleration, deflagration could transit to detonation, resulting in degassing to detonation transition. With further acceleration, the deflagration could transit to a detonation, producing a deflagration-to-detonation transition. A representative research program of DDT tests for hydrogen-air mixtures was reported by Sherman et al. [106]. Fig. 9 shows the relationship between the flame speed and the distance from the ignition for various hydrogen-air mixtures in a tunnel [106, 107]. It can be observed that the flame velocity increases with distance from the ignition point. With a high concentration of hydrogen and obstacles, DDT could be triggered in the hydrogen-air mixtures [107]. Recently, researchers show an increased interest in DDT, especially in the inhomogeneous hydrogen-air mixture. A summary of existing studies on DDT of hydrogen is listed in Table 5. Existing study on the mechanism of DDT is still very limited due to the difficulty of testing preparation and available numerical approach.

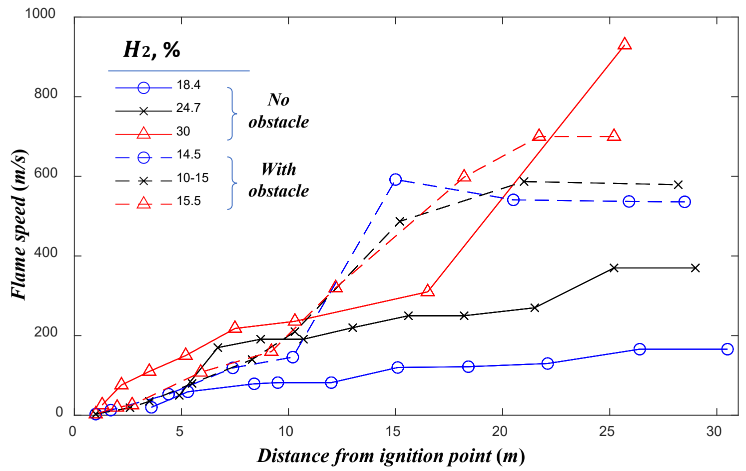

Fig. 9. Relationship between the planar flame speed and the distance from the ignition point [106, 107]

Table 5 Recent research for DDT of hydrogen

Category	Year	Method	Objective	Scenario	Reference
Propagation mechanism	2022	Theoretics and modeling	Revisit and explain the phenomenon	Sudden FA and subsequent DDT	Bykov et al. [108]
	2022	Theoretics and modeling	Use chemical-diffusive model to predict FA, DDT and detonation	Premixed flames in channels with obstacles	Lu et al. [109]
	2021	Modeling	Simulate DDT process and analyze the flow field	An obstacle tube	Tang et al. [110]
	2021	Theoretics	Develop a hybrid pressure-density-based solver	Deflagration, FA, DDT and detonation	Wieland et al. [111]
	2019	Theoretics	Predict DDT based on oxygen concentration	In the presence of inerting diluents	Zhang et al. [112]
	2019	Theoretics	Develop a new technique to track the flame position along the tube	Discern possible FA or DDT scenarios	Scarpa et al. [113]
	2018	Theoretics and modeling	Evolve a unified numerical framework based on OpenFOAM	Deflagration to Detonation Transition	Karanam et al. [114]
	2017	Theoretics	Verify the capability of developed numerical model	FA and DDT with concentration gradients	Wang and Wen[115]
	2015	Theoretics	Verify computationally efficient CFD simulation	Explosions (including DDT)	Hasslberger et al. [116]
	2012	Experiment	Investigate the mechanism of DDT	Different pitch and height of the repeated obstacles	Obara et al. [117]
Influence factors	2022	Modeling	Investigate the DDT phenomenon by solving fully compressible reactive flow	Tube with sudden cross-section expansion	Jia et al. [118]
	2021	Experiment	Compare the explosion behaviors with different oxidizer	In a closed cylindrical vessel (7.3 L)	Wang et al. [119]
	2021	Experiment	Investigate the influence of the number, spacing, and blockage ratio of obstacle rods	DDT in a tube with straight-shaped rods	Seki et al. [120]
	2021	Modeling	Investigate the effect of obstacle spacing and mixture concentration	In a homogeneous and inhomogeneous hydrogen-air mixture	Saeid et al. [104]

	2020	Modeling	Examine the effect of obstacle shape	On the FA and DDT	Xiao et al. [121]
	2020	Experiment	Examine the effect of orifice geometries	On the detonation transmission	Sun et al. [122]
	2020	Experiment	Explore the influences of mesh aluminium alloys and spherical non-metallic materials	A 2 m-long cylindrical tube	Song et al. [123]
	2020	Experiment	Investigate the blockage ratio and obstacle spacing	Flame propagation in stoichiometric H_2/O_2	Ahumada et al. [124]
	2019	Experiment	Investigate the influence of the unburnt gas initial pressure	Flame propagation	Scarpa et al. [125]
	2019	Experiment	Study the effect of thin layer geometry	A rectangular chamber	Kuznetsov et al. [126]

4 Analysis Methods for Hydrogen Explosion

To understand blast loading generated by hydrogen explosion, existing studies employ experimental tests, CFD modelling, and empirical methods. In this section, available studies of hydrogen explosion are reviewed and summarized.

4.1 Experimental testing

Experimental tests are the most direct methods of investigating hydrogen explosions. Available experimental studies in open literatures are summarized and categorized into field experiments and laboratory tests. Fig. 10 shows selected experiments of hydrogen explosion tests. Small-scale laboratory explosion tests are usually conducted to study the mechanism and to explore the influencing factors and corresponding relationships for hydrogen explosion, while scaled or full-scale field blast tests are also performed to verify the findings and to obtain more realistic data due to the size effect [127].

In a blast incident, the overpressure of the blast wave generated by hydrogen explosion can cause severe damage to structures, which therefore is the primary interest for structural engineers in analysis and design of structures against hydrogen explosions. Table 6 summarizes the existing studies of hydrogen explosions, where the tests are categorized according to explosion type, i.e., expansion and deflagration (including tank rupture and jet release), deflagration, and detonation. It could be found in Table 6 that the intensity of different hydrogen explosion overpressures varies by several orders of magnitude, ranging from several kPa of expansion deflagration to several MPa of detonation. Fig. 11 shows the typical blast overpressure time histories of hydrogen explosion. For hydrogen storage tank rupture, a maximum blast is produced in the tank due to the intensive expansion of the leaked hydrogen, which then decays rapidly and exponentially with the distance and the time. Zalosh [128] conducted field blast test on scaled hydrogen storage tank with a confining pressure of 35MPa subjected to fire burning. PVB occurred which led to hydrogen deflagration. Typical triangle shape blast overpressure time history was recorded at various stand-off distances from the tank. A peak blast overpressure of 300 kPa was recorded at 1.9m stand-off distance, which reduced to 41 kPa at 6.5m. The blast overpressure also decayed quickly to ambient in about 5ms. For jet release of hydrogen explosion, the magnitude of the overpressure is closely related to the initial inner pressure of the tank, where in the blast overpressure time histories multiple peaks are normally recorded since the position of the deflagration centroid would move over time. Mogi et al. [129] performed hydrogen jet release test on an 18.8 MPa hydrogen tank with a 10 mm pinhole nozzle. The jet hydrogen self-ignited when hydrogen was released at high pressure, and a fireball was formed. As shown in Fig. 11b, the peak overpressure consists of two parts, i.e., the shock wave from the gas discharge and the pressure wave of deflagration, which decays from 40 kPa (near the nozzle exit) to 7 kPa at 1.5 m. As the internal pressure of the hydrogen tank increased to 40MPa, the peak blast overpressure increased to 103 kPa at a distance of 0.5 m [83]. The overpressure then decayed to ambient as hydrogen burned out. It is also to note that hydrogen-air cloud deflagration would also generate a considerable negative overpressure since 2 hydrogen molecules and 1 oxygen molecule only form 1 water molecule. Therefore, when designing specific structures such as laminated glass that are sensitive to negative blast pressure, special attention should be paid against hydrogen-air cloud explosion. Compared with hydrogen-air cloud deflagration which normally generates peak blast overpressure of 1-100kPa, hydrogen-air cloud detonation is much more dangerous, which could lead to peak blast overpressures of MPa range in the confined condition although the duration compared with deflagration is much shorter. For example, Mueschke et al. [133] detonated 29.5% hydrogen-air mixture in a 2.83m^3 space with C-4. As shown in Fig. 11d, typical triangle shape blast overpressure time history was recorded at various positions, where a peak overpressure of 5.4MPa and a positive overpressure duration of 1ms was measured.

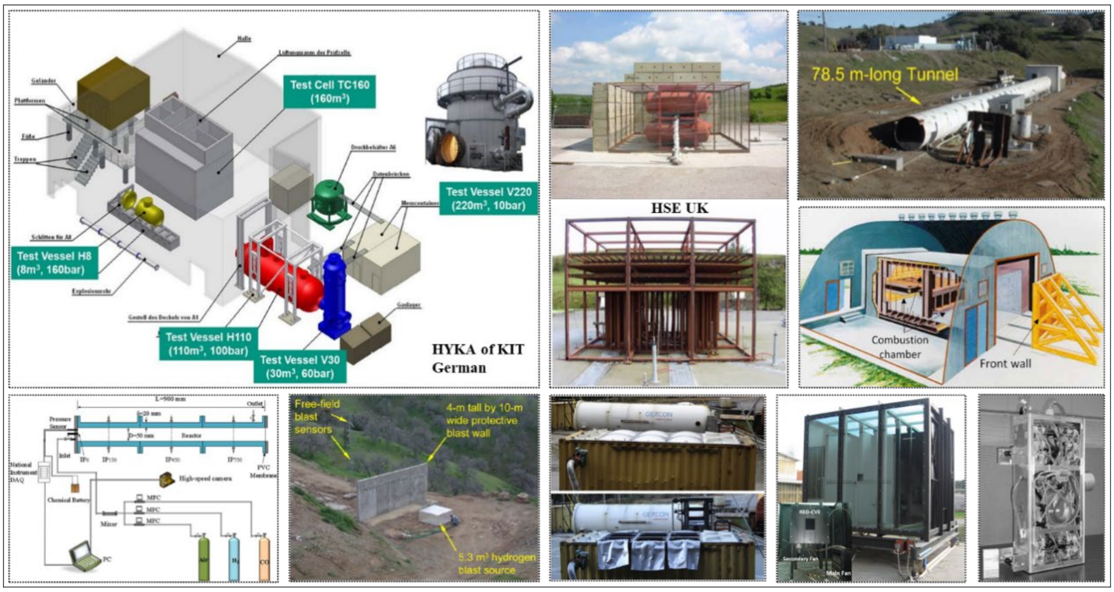

Fig. 10 Selected experimental studies on hydrogen explosion [70, 83, 130-136]

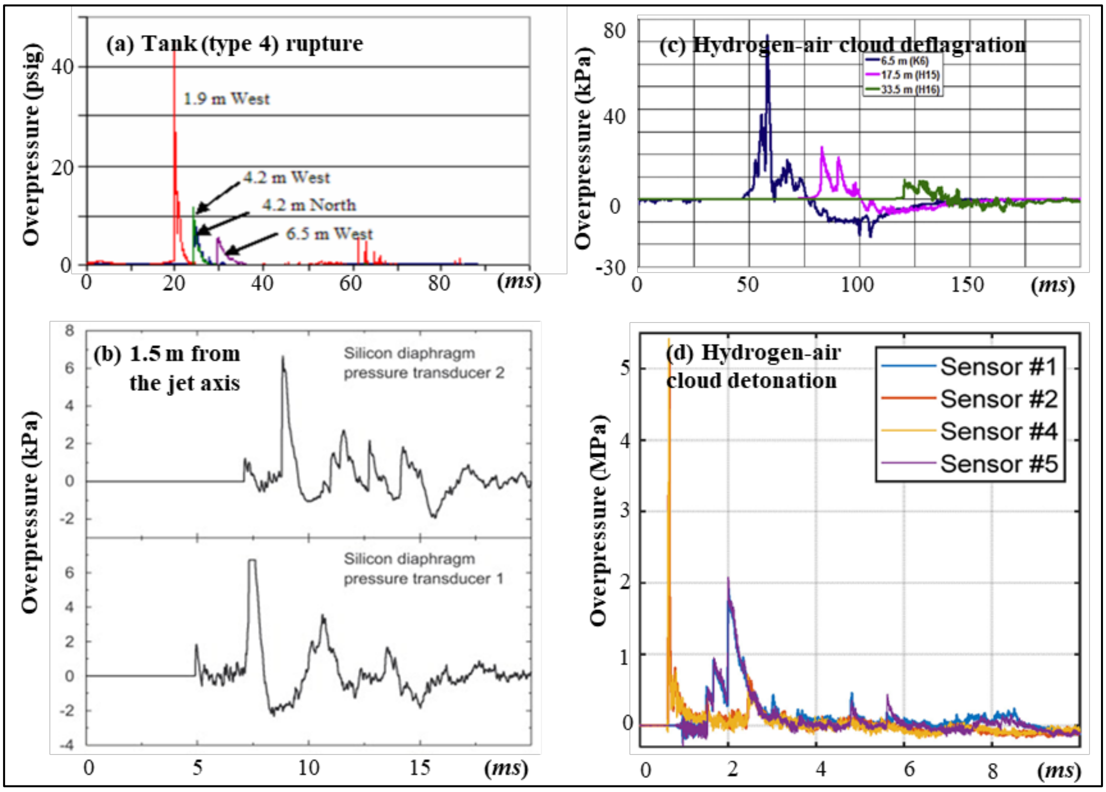

Fig. 11 Typical overpressure time histories [83, 128, 129, 137]: (a) tank rupture; (b) jet release; (c)hydrogen-air cloud deflagration; (d) hydrogen-air cloud detonation.

Table 6 Summary of experimental studies on hydrogen explosions

Category	Scenario	P_{max}	Reference
Hydrogen expansion	Hydrogen tank (35 MPa, type 4) during fire	300 kPa (1.9 m) and 41 kPa (6.5 m)	Zalosh [128]

deflagration	Hydrogen tank (35 MPa, type 3) during fire	140 kPa (1.2 m) and 30 kPa (4.8 m)	Zalosh [128]
	Jet releases from a hydrogen tank (40 MPa)	103 kPa (0.5 m)	Shirvill et al. [83]
	Jet release from an 18.8 MPa hydrogen tank with a 10 mm pinhole nozzle	40 kPa (near the nozzle exit) and 7 kPa (1.5 m)	Mogi et al.[129]
	Jet release from a cryogenic pressurized hydrogen with a 0.7 mm pinhole nozzle	>3 kPa (1 m)	Kobayashi et al. [57]
Hydrogen-air cloud deflagration	300 m^3 dome frame with obstacle (30%)	17 kPa (15.6 m)	Groethe et al. [70]
	In a 78.5-m-long tunnel (30%)	150 kPa (near the tunnel end)	Groethe et al. [70]
	In a garage (29.3%)	60 kPa (Inter garage)	Pitts et al.[71]
	Repeated pipe congestion in 3 ×3× 2 m^3 metal framework (28.9-34%)	86 kPa-123 kPa	Shirvill et al. [132]
	Premixed 5.4 ×6.0 ×2.5 m^3 hydrogen-air clouds (31.5%) with 2 walls	140 kPa (centerline) and 19.5 kPa (17.5 m)	Shirvill et al. [83]
	Hydrogen leaks through a break in piping and blows down to atmosphere (40 MPa)	20.4 kPa (3.9 m)	Takeno et al. [138]
	Gexcon conducted 66 vented hydrogen deflagration experiments in 20-foot shipping containers	< 67. 7 kPa	Skjold et al. [139]
	In a 57 m^3 chamber with a 0.55m^2 vent and initial turbulence (9%, mixing fans with 1,000 rpm)	35 kPa	Liang et al. [140]
Hydrogen-air cloud detonation	In the 4×4×1800 mm^3 channel (66%)	2.95 MPa (end of DDT)	Bykov et al. [108]
	300 m^3 dome frame with obstacle in a unconfined condition (30%)	90 kPa (15.6 m)	Groethe et al. [70]
	Detonation tests at the RUT facility in Russia	>2.5 MPa	Zbikowski et al. [141]
	Premixture in a 2.83m^3 test fixture (29.5%, 0.865 kg TNT equiv.)	5.4 MPa	Mueschke et al. [137]
	hydrogen-air mixture was fixed as 29.6% with 1500 mJ ignition energy in the tube	About 2.0 MPa	Rao et al. [101]

4.2 Numerical modeling

Numerical modeling approach has also been employed to simulate hydrogen explosion considering its cost-effectiveness compared to the experimental method. Computational fluid dynamic (CFD) modeling was performed by various researchers to help in understanding the mechanisms and explaining the observed phenomena of hydrogen explosion, and to obtain a comprehensive understanding on the diffusion of hydrogen clouds [63, 142-144], development of flames and explosions [55, 75, 145, 146], and interaction of different factors in various scenarios [63, 82, 147, 148]. Some popularly used CFD modeling software, including FLACS, OpenFOAM, and ANSYS-Fluent, are commonly employed for the simulation of hydrogen explosions. These numerical approaches and their accuracies are reviewed herein.

4.2.1 FLACS

Based on a large number of testing and theoretical derivation, GexCon developed a special module in FLACS-CFD to simulate hydrogen explosion [149]. As a popular industry software to model flammable gas dispersion and explosion, FLACS has a user-friendly interface and pre- and post-processing tools. The accuracy of FLACS in modeling hydrogen was verified by different researchers [144, 150]. Vyazmina and Jallais [151] chose existing hydrogen explosion experiments with various configurations to evaluate the accuracy of FLACS modeling. It was found that FLACS is not suitable for small scale (1<m^3) deflagrations with small vert areas because FLACS would overestimate the blast overpressure and experience mesh convergence issues, as shown in Fig. 12. The manual of FLACS recommends using a grid size larger than 2 cm in the explosion simulations. More validation and verification are still needed to further examine the accuracy and suitability of FLACS in hydrogen explosion modeling. Most important of all, as an industrial software package, FLACS could not be easily modified by researchers to improve the modeling accuracy, and the current version of FLACS is only available for modeling hydrogen deflagration but not hydrogen detonation.

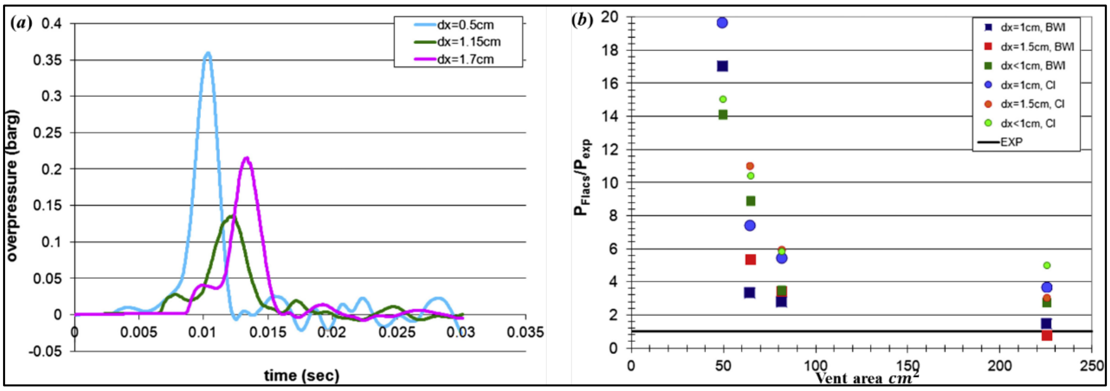

Fig. 12 Numerical simulation of FLACS [151]: (a) deflagrations in the small scale combustion chambers; (b) deflagrations with small vent areas.

4.2.2 OpenFOAM

Open-Source Field Operation and Manipulation (OpenFOAM) is another popular numerical software capable of hydrogen explosions. Compared with FLACS, OpenFOAM is less user-friendly with no user interface. Thus, pre- and post- processing become complex and tedious. HySEA used the OpenFOAM framework to simulate the vented inhomogeneous hydrogen deflagrations in a 20-foot ISO container and evaluated the modeling accuracies [139]. It was found that the predicted blast overpressure was lower than the test measured overpressure. However, compared to FLACS, OpenFOAM as an open-source software is more flexible and extensible that researchers can modify the solver, boundary conditions, initial conditions, and turbulence model for hydrogen explosion predictions in various scenarios. As a result, it is common for researchers to use OpenFOAM to study the DDT [103, 108-110] and the direct detonation of hydrogen-air clouds [152-154].

4.2.3 ANSYS

ANSYS is one of the most powerful computational fluid dynamics (CFD) software, which integrates various products, such as CFX and Fluent that can provide simulations for hydrogen explosions [143, 155, 156]. Tolias et al. [155] used different CFD models to simulate 18% hydrogen deflagrations carried out by FM Global in a vented enclosure and assessed the reliability of these CFD models. Compared with the conservative results by FLACS, CFX and Fluent can get more accurate predictions of peak blast overpressure [155]. After reaching the peak blast overpressure, the predicted overpressure by CFX and Fluent would decrease to about ambient, then rise to a small value and maintain for a period, which is inconsistent with available experimental results. Besides, the accuracy of CFX results is very sensitive on the grid/mesh size and the initial turbulence conditions [155], which should therefore be properly verified before applying for numerical modelling.

4.2.4 Accuracy and improvement

Overall, deviation exists between numerical simulation results and experimental data, which indicates that there still needs a significant improvement for CFD modeling tools toward more accurate modeling of blast loading generated by hydrogen explosions. Some continuing improvements have been ongoing. For example, Gexcon [146] modified FLACS to decrease the diffusivity towards a more pronounced concentrate gradient of the hydrogen. Karanam et al. [114] evolved the unified numerical framework based on OpenFOAM for hydrogen explosion prediction, which enables modelling of DDT for hydrogen explosion.

4.3 Empirical formulae and theoretical method

Empirical formulae derived from best-fitting experimental data have been applied for prediction of hydrogen explosion overpressures, while theoretical derivation and design guides for combustible gas and explosive have also been migrated and used for hydrogen explosions overpressure predictions. In engineering applications, there are three traditional approaches commonly used to predict blast loading of VCE, including the TNT equivalent method (TNT-EM), TNO multi-energy method (TNO MEM), and Baker-Strehlow-Tang method (BST). TNT-EM converts the released energy of the explosive to the charge energy of TNT in an explosion. TNO MEM considers the power of vapor cloud explosion depending on the boundary conditions, which assumes the unconstrained part of the vapor cloud has little contribution to the blasting intensity. The BST method considers the different flame speeds of different explosives or VCEs, but it is generally similar to the TNO MEM. Both provide a family of curves that are used to select dimensionless parameters, which are then unscaled to determine the actual overpressures [157]. More details about these three methods can be found in [69, 137, 158].

The accuracies of these methods in predicting the blast loading of hydrogen explosion were evaluated by comparing the prediction results with available testing data on hydrogen-air cloud explosions [69, 137]. Fig. 13 compares the peak overpressures and impulses of the test measurements with the predictions of these three approaches in stoichiometric hydrogen-air cloud (29.5% hydrogen concentration) deflagration in a 0.283m^3 confined chamber that is detonated using 6g C-4 [137]. It can be found that the prediction accuracies of these three methods are poor, although these methods can obtain the rough order of magnitude of the blast overpressure. Relatively, TNO MEM performed better than TNT-EN and BST, especially in predicting the peak overpressures, while the TNT-EM method gave the worst prediction. There are several reasons for the large variations: firstly, these traditional methods are designed for a symmetrical barrier-free environment, which differs from the particular scenario with hydrogen explosions in confined space. Secondly, hydrogen is more active than traditional combustible gas, which releases more energy and thus produces higher blast overpressure and impulse. Thirdly, the model parameters of TNO MEM and BST for hydrocarbon fuels may not be suitable for hydrogen. Mukhim et al. [69] also compared the prediction result of the TNO MEM and BST model with experimental data of unconfined hydrogen-air cloud explosions. As shown in Fig. 14a), experimental data scattered between curve 1 and 10 in lieu of around curve 1 with the testing condition following TNO instruction (Fig.14.a). Similarly, as illustrated in Fig. 14b, the prediction of the BST model also could not give a proper estimation, where existing testing data scatter between Mach number 0.5 and 0.0742 instead of 0.0742 following BST instruction (Fig.14.b) for the open-air explosion without confinement. Overall, these conventional methods could not accurately predict blast loading of hydrogen-air cloud explosions. Some improvements could be made with suitable model parameters to apply these traditional methods for hydrogen-air cloud explosion, which nevertheless do not exist yet.

Recently, some scholars also proposed some empirical formulae for hydrogen explosions. For the high-pressure hydrogen gas storage tank, Kashkarov and Molkov with their colleagues [49, 159] developed predictive models to assess the deterministic hazard distances for tank rupture and hydrogen deflagration. Ustolin et al. [58] proposed an approach to predict the blast overpressure of hydrogen BLEVE. In terms of hydrogen-air cloud explosion in unconfined conditions, Mukhim et al. [69] developed a method to assess the overpressures for a given concentration and volume. Jallais et al. [160] presented a simplified method based on their CFD simulations to determine the blast loading of hydrogen jet. Challenges exist in predicting the blast loading of vented hydrogen-air cloud explosions because of the complexity introduced by ventilation dimension, shape, and activation pressure. Mokhtar et al. [161] used four empirical equations for gas venting and found none of them was able to provide a reliable prediction of the blast overpressure of hydrogen-air explosion. Sinha and Wen [162] also proposed an empirical model which nevertheless is applicable to only limited conditions, such as no presence of obstacles. Overall, there is still a gap between the current experimental data and the simplified empirical methods for accurate prediction of blast loading from hydrogen explosions.

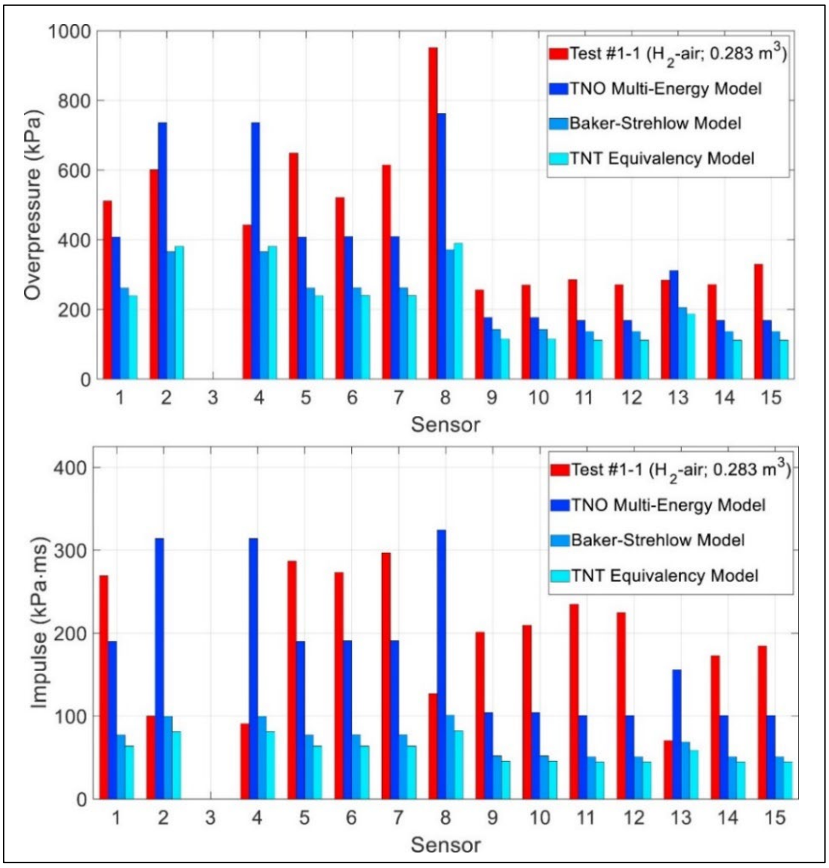

Fig. 13. Peak overpressure and impulse of hydrogen explosions and traditional models [137]

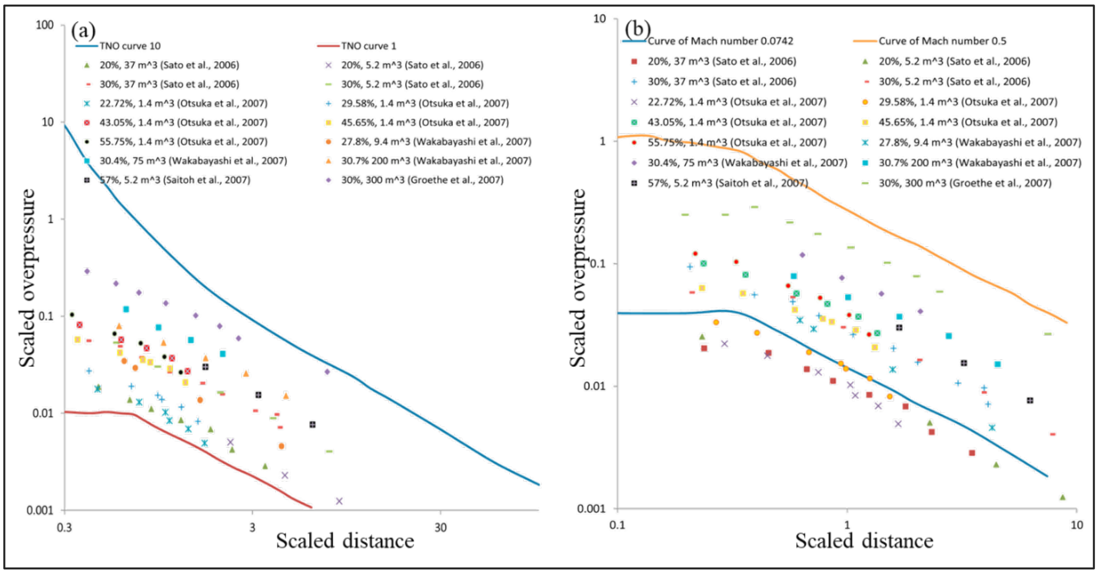

Fig. 14. Experimental data scatterplot [69]: (a) with TNO MEM; (b) with BST model.

4.4 Other methods

Apart from the above methods, there are some phenomenological models (such as SCOPE and PHAST) and artificial intelligence models, which have been introduced for prediction of blast loading from the hydrogen explosions [163-165]. The phenomenological model falls between the empirical formulae and the CFD modeling approaches, which represents the critical explosion physics and is developed based on the empirical models. Artificial intelligence models for overpressure prediction are a recent trend due to the fast development of artificial intelligence, which could help to derive more accurate predictions provided enough reliable data is available to train the algorithm. Besides, there are also some other attempts. For example, Du et al. [166] used smoothed particle hydrodynamics method to model hydrogen explosions. Silvestrini et al. [167] proposed an Energy Concentration Concept (ECF) to evaluate the blast overpressure of hydrogen explosions. The suitability and accuracy of these various approaches still require further and more systematic validation and verification.

5 Influencing Factors of Hydrogen Explosion

As mentioned above, blast loading of hydrogen explosions can be influenced by various factors. In this section, the influences of these factors, including hydrogen-air cloud size and heterogeneity, ignition energy and location, ambient temperature and pressure, obstacle, ventilation, water and inert particles, and explosion suppression materials/structures, on the characteristic of hydrogen explosions and the accuracy of the blast overpressure estimation are reviewed and summarized.

5.1 Hydrogen-air cloud size and heterogeneity

The size of a hydrogen-air cloud plays a crucial role in the produced blast loading. If the volume of the cloud is small, there is not enough hydrogen to support the turbulent acceleration of the flame, only combustion or even extinction will occur; while if the volume of the cloud is large enough, DDT may occur after being ignited. As shown in Fig. 7, the flame speed of the premixed hydrogen-air clouds increases with the increase of the flame spread distance. The overpressure generated during a deflagration process also would increase with the flame speed [35, 168]. In the pipeline where detonation can propagate, the combustion supporting distance from deflagration to detonation (DDT) is usually 100 times the diameter of the pipeline. As a result, the radial difference of existing studies on the detonation limit is probably because of the scale and size of the experimental device used. The larger the size of the experimental device, the more violent the explosion results, and the larger the detonation limit width [31]. Therefore, the size of a hydrogen-air cloud is of significance for detonation limit and hydrogen explosion results.

Except for cloud size, heterogeneity of hydrogen in the air cloud could also influence the blast loading. The molar mass of hydrogen is very easy to float up since it is much lighter than air. As a result, even if the overall hydrogen concentration in a confined space is below the lower limit of flammability, explosives may still be triggered at the top of the space due to local hydrogen accumulation. Most existing studies would mix the hydrogen-air cloud thoroughly to achieve a homogenous distribution of hydrogen before it is ignited, while some studies give contradicted conclusions about the influence of inhomogeneity on hydrogen explosion. Some researchers believed that the inhomogeneity would help to reduce flame propagation velocity thus mitigating the blast effect [169], while others argued that the concentration gradients could increase the flame acceleration and thus more likely to form DDT [152]. Considering the low density of hydrogen which tends to form inhomogeneous air clouds, more studies are needed to better understand the influence of hydrogen heterogeneity in air clouds to blast loading characteristics.

5.2 Ignition intensity and location

Influences of ignition intensity and location on hydrogen explosions have been investigated. The intensity of the ignition source directly determines the type of hydrogen explosion (expansion and deflagration, detonation, or DDT). It dates back to 1960-1982 when the US Air Force and NASA conducted a series of experimental and modeling studies on hydrogen leakage and explosion [107, 170], which found that direct detonation of hydrogen requires strong ignition sources including high explosives, jet flame, and high voltage capacitor shorts, while weak ignition sources, such as hot surface or spark, can only produce fire and deflagration [107]. Besides, these experiments also showed that the blast overpressure of hydrogen explosion will increase with the ignition energy [171, 172]. Because higher ignition energy means more heat is released, it leads to a larger high-temperature ignition core and a longer heating time. When the ignition energy gradually increases, the flame growth process will be affected, which usually produces from a laminar fire to deflagration and even to detonation. In common engineering applications of hydrogen as renewable energy, a weak ignition source is generally considered as the most likely source for hydrogen explosion accidents. Nevertheless, it should be emphasized that a weak ignition source which generates deflagration also could end up with hydrogen deflagration transforming into detonation if the hydrogen cloud size is sufficiently large.

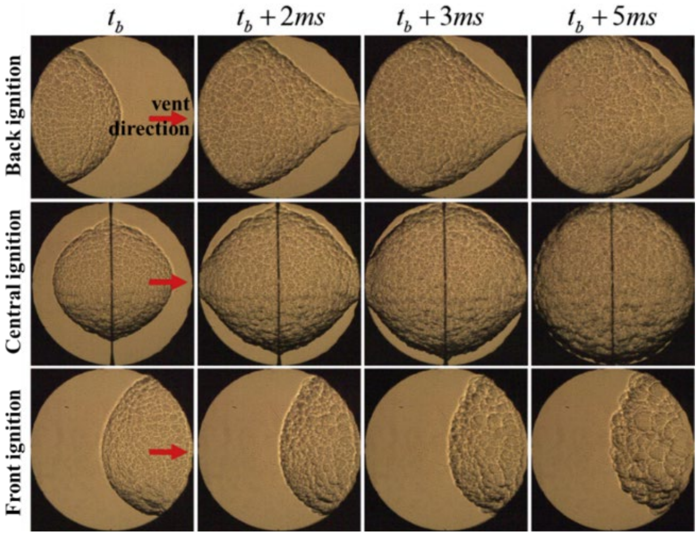

Fig. 15. Schlieren images of the flame propagating with different ignition position [173]

Ignition location would strongly affect the peak overpressure of hydrogen explosions. For the front ignition of hydrogen-air clouds in a confined space, consistent experimental results were reported by different researchers [173-176]. In general, a front ignition always produces the minimum peak blast overpressure, because the flame propagates in the opposite direction to the venting and slows down, resulting in a minimum flame velocity and a minimum blast overpressure. Compared to front ignition, when the hydrogen-air cloud is subjected to central or back ignition, the flame propagation speed would accelerate due to the surface gas flow and generates a higher blast overpressure, as shown in Fig. 15 [173]. However, there is no consensus on whether central ignition or back ignition would produce a large internal overpressure. Some tests showed that a central ignition produces the maximum internal peak overpressure because the flame would have the largest flame area [173, 174]; while others reported a back ignition generates the maximum internal peak overpressure because there is a longer distance for the flame to accelerate [175, 176]. A possible reason for the different experimental results is the different vessel sizes and shapes used in the experiments. In addition, for a tubular container with a closing end and an opening end, the overpressure of the closing end would become more intense as the ignition position moves to the opening end [79, 135].

5.3 Ambient temperature and pressure

Ambient pressure and temperature are found to be important parameters that affect the blast loading of hydrogen-air cloud explosions. The increase of the initial pressure can significantly increase the hydrogen explosion overpressure. Under adiabatic isovolumetric conditions, the blast overpressure is approximately proportional to the initial pressure [125, 177], as shown in Fig. 16a). This is because with the rise of initial pressure in the isothermal constant volume conditions, the hydrogen would be compressed and the density of hydrogen in the same volume would increase. Since blast overpressure is strongly dependent on hydrogen density, a higher initial ambient pressure would thus lead to the rise of blast overpressure. Nevertheless, as discussed in section 3.1, the peak overpressure will decrease as the hydrogen concentration ratio continues to increase after the "optimized" ratio. Therefore, a very high ambient pressure may lead to reduced peak blast overpressure, which however is not proven yet. Moreover, as the initial pressure increases the turbulent flame propagation velocity would decrease, which is attributed to the interaction of the reflected shock wave with the flame [125, 178].

Adverse effect is reported about the influence of initial temperature on the blast overpressure of hydrogen explosions. As shown in Fig. 16b), under the same initial pressure, an increase in the initial temperature leads to the decrease of blast overpressure [177]. This is because as the ambient temperature increases, hydrogen will expand resulting in reduced hydrogen density and thus a lower blast overpressure. The increase in ambient temperature could increase the flame propagation speed, which leads to a faster blast pressure rise. This is beneficial for the flame propagation speed, which leads to a faster pressure rise. Similar effects of ambient pressure and temperature are also found on other combustible gas such as hydrogen-enriched natural gas and propane [179, 180].

Moreover, ambient pressure and temperature also would affect the flammability limits of hydrogen, which can even determine whether explosions would occur or not. The wider range of flammability limits means that the hydrogen-air cloud is becoming more active and prone to explosion. As shown in Table 7, for a low-pressure environment, the range of flammability limits of hydrogen-air cloud would reduce as ambient pressure reduce significantly. For a high-pressure environment (in Table 8), as ambient pressure increases, the lower limit of flammability would increase slightly, while the upper limit would fluctuate around 73%. Schroder and Holtappels [27] studied the influence of ambient temperature and found that under elevated temperature the lower limit of hydrogen-air cloud flammability reduces from 3.9% at 20°C to 1.5% at 400°C, while the upper limit increases from 75.2% to 87.6%. Therefore, ambient temperature and pressure could both influence the flammability limit and blast loading of hydrogen-air cloud explosions. However, since these studies were all in a controlled laboratory environment and on a small scale, their influence on large scale engineering applications requires further validation. Since ambient temperature and pressure would not fluctuate substantially, their influences also need further quantitation.

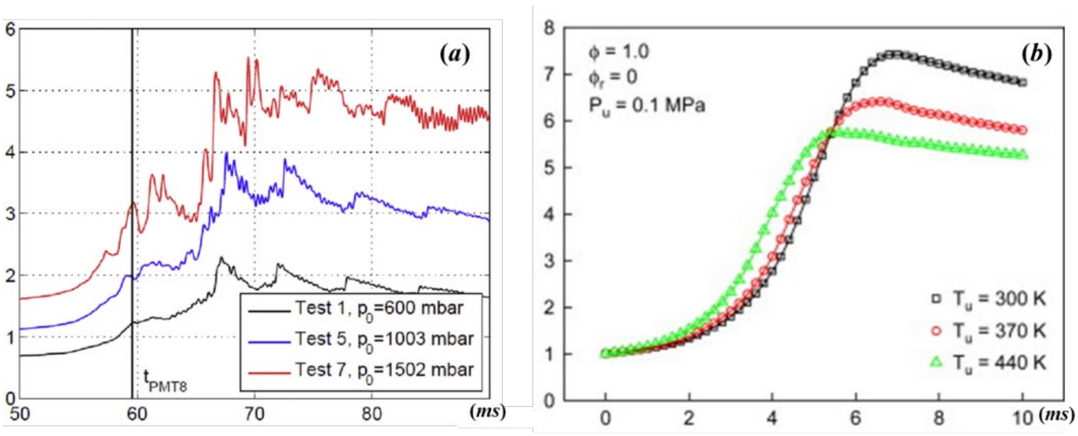

Fig. 16. Blast pressure (bar) time histories [125, 177]: (a) with different pressures; (b) with different temperatures.

Table 7 Influence of low pressure on the flammability limits of hydrogen-air mixture (vol %) [26]

Pressure kPa	2.5 cm Tube		2L Sphere	
	Lower limit	Upper limit	Lower limit	Upper limit
20	4	56	5	52
10	10	42	11	35
7	15	33	16	27

Table 8 Flammability limits of hydrogen-air mixture with different pressure and temperature (vol %) [27]

Conditions: 20 °C			**Conditions:** 1 atm		
Pressure (bar)	Lower limit	Upper limit	**Temperature** °C	Lower limit	Upper limit
1	4.3	76.5	20	3.9	75.2
5	4.4	73.1	100	3.4	77.6
10	4.7	72.1	200	2.9	81.3
20	4.9	71.1	300	2.1	83.9
30	5.1	71.7	400	1.5	87.6
40	5.3	73.3	-	-	-
50	5.6	73.8	-	-	-
100	5.6	73.4	-	-	-
150	5.6	72.9	-	-	-

5.4 Obstacle

For engineering applications, similar to many other combustible gases, obstacles could strongly influence the blast loading of hydrogen explosions. Many scholars have verified through experimental testings and numerical simulations that the shape, blockage rate, obstacle spacing, and obstacle position can all affect the blast loading of hydrogen explosions. Experiments showed that obstacles with sharp-edged cross-sections in the flow direction, such as squares and triangles, resulted in a higher flame acceleration, a longer flame propagation distance, and a greater blast overpressure [121, 181, 182]. For instance, Sheng et al. [174] studied the effect of different obstacle shapes on premixed hydrogen-air deflagration in the duct. The results showed that peak overpressure of triangular-shaped obstacles is about 7% and 30% higher than that of square and round shaped ones, respectively. The directions of the shape for the same obstacles would also affect blast loading [121, 181]. For instance, Coates et al. [173] tested special obstacles with one end in rectangular shape and the other being curved in forward and reverse directions respectively in tubes subjected to hydrogen explosions. It was found that the obstacles with forward rectangular shaped obstacles induced a higher overpressure than that with forward curved obstacles. The stiffness of the obstacle could also influence blast loading, where a flexible obstacle compared with a rigid one would cause the blast overpressure to decay quicker [183]. This is because the loading duration of hydrogen explosion is relatively long compared to solid explosives such as TNT. Thus, blast wave interaction with obstacle becomes non-ignorable, where a rigid obstacle would result in more intense blast wave reflection and thus increases the amplitude of reflected blast overpressure. As for the blockage ratio, an abundance of experiments has been conducted [184-186], which showed that as expected the higher the blockage ratio, the higher the peak blast overpressure and flame velocity. Meanwhile, the peak overpressure behind the obstacle will decrease with the increase of the blockage ratio. The existence of the obstacle also changes the propagation direction of the flame [187, 188], which could help to develop a blast wall/door against hydrogen explosion. Comparing the blockage ratio, the influence of obstacle spacing (gap distance between multiple obstacles) appears to be less significant. Some research shows that the peak blast overpressure increases with the decrease of obstacle spacing [185, 189]. Teodorczyk et al. [190] performed experimental study and identified optimum obstacle spacing to achieve the lowest blast overpressure with different blockage ratios. The influence of obstacle position on hydrogen explosion is more complex, where there is no consistent finding. The maximum blast overpressure sometimes increases with the distance of the obstacle from the ignition source [191, 192], while sometimes the peak blast overpressure may exist when the obstacle is near the middle of the duct [191, 193]. Besides, numerical modelling results also show that a staggered distribution of obstacles will reduce the flame propagation speed, while a symmetrical distribution of obstacles is most conducive to the occurrence of detonation [194].

Overall, the characteristics of obstacles could influence flame instability of hydrogen explosion, which leads to a larger flame surface area and turbulence as the downstream unburned mixture is forced around obstacles. It results in a higher mass burn rate, which causes a higher flame propagation velocity and stronger flame turbulence, thus higher blast overpressure. Since obstacle is unavoidable in engineering applications, which may also be used as protection structures (such as blast wall/door to mitigate blast loading in the event of an accidental explosion), a more thorough and systematic study is needed to quantify the influence of various obstacle characteristics for hydrogen-air cloud explosion.

5.5 Ventilation

Ventilation is one of the simplest and most effective ways to reduce and mitigate gas explosion. Ventilation can help to reduce the concentration of combustible gas, and relief the blast overpressure. Some studies are available in the literature on ventilation for hydrogen-air cloud explosion. In general, the blast overpressure in vented hydrogen explosion is found to decrease as the ventilation area increases and the distance from the ignition point to the vent increases [195]. For example, Zhang and his colleague [196] conducted explosion tests with hydrogen-air cloud in vented space. As shown in Fig. 17a), with the increase of vent size the peak blast overpressure reduces significantly. When the ratio of ventilation over wall area K_v increases from 0.01 to 0.1, the difference between peak internal overpressure can reach 88%. Fig. 17b) shows the overpressure distribution of a 6.0 m duct ignited at the closed end with different vent positions from the open end [193]. It can be found that the appearance of the side vent significantly reduces the peak overpressure, especially when the side vent is located near the closing end (closer to the ignition point) [193]. Since the ventilation size, activation pressure, concentration, and cloud size are all coupled influencing the overpressure time histories of hydrogen-air cloud explosion, there is no guideline or accurate correlation for predicting the mitigated overpressure of hydrogen-air cloud explosion with ventilation yet.

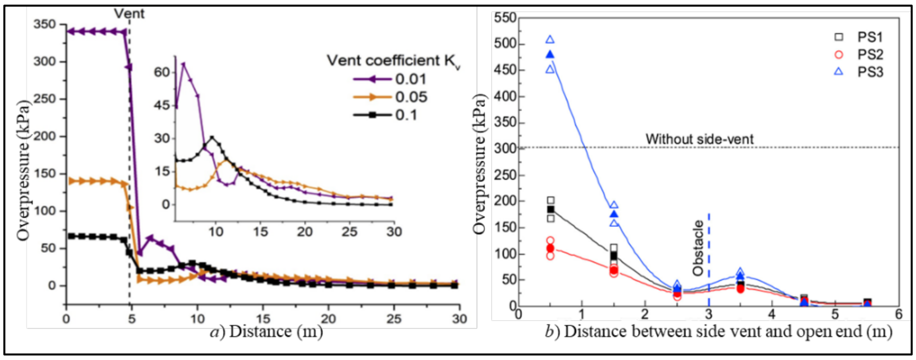

Fig. 17. Influence of ventilation [193, 196]: (a) overpressure vs. vent area; (b) overpressure vs. distance from vent to ignited point.

5.6 Water and inert particles

To mitigate the blast loading of hydrogen explosions, water and inert particles are usually used in accidental gas explosions. For hydrogen explosion, some studies showed that a water spray system can be an effective method to reduce the blast loading of hydrogen explosion [197, 198]. For example, Wen et al. [197] found that water mist has a significant mitigation effect on hydrogen explosions, because the water droplets will absorb heat and dilute the hydrogen concentration by evaporation which will thus reduce the combustion speed of the flame and reduce the explosion overpressure. However, some other studies found that water droplets in the flame region (before the large droplets break) could increase the turbulence level and the combustion speed, which leads to an increase of the peak blast overpressure [199].

Inert particles such as carbon dioxide and nitrogen in the hydrogen-air cloud also can effectively mitigate the blast overpressure of hydrogen explosion [198, 200, 201]. It is found that the flame propagation speed will decrease when inert gas is added. Fig. 18 shows the schlieren photo at the time when the critical flame radius reaches 2.0cm and 4.0cm respectively [201]. The surface of the flame will become unstable due to the addition of inert particles, and the outward propagation rate of the flame will decrease with the increase of instability. This may be due to the enhancement of the diffusion heat effect.

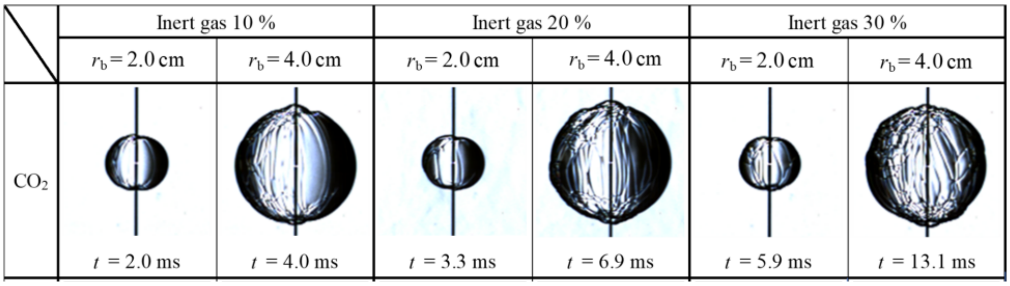

Fig. 18. Schlieren images of H_2/air/CO_2 flames [201]

5.7 Explosion-suppression materials/structures

Engineered explosion-suppression materials/structures have received increasing interest for mitigation of hydrogen-air cloud explosion in confined space. In general, explosion-suppression materials are made of mesh or porous structures, which are filled into the confined vessel or duct. With the specially designed shapes and dimensions, these structures will reduce the flame velocity and hydrogen concentration, and thus mitigate the blast effect. Fig. 19 shows typical explosion-suppression materials/structures, including mesh aluminum alloys (MAA), polyurethane foam, and spherical nonmetallic balls. MAA is a widely used explosion suppression material/structure for combustible gas [123, 198]. However, for the hydrogen explosion, Pang et al. [202] conducted laboratory testing and found that MAA increased the blast overpressure in the testing tube compared to the reference empty tube, which is therefore not suitable for hydrogen explosion-suppression. Song et al. [123] examined the performance of MMA and pointed out that MAA has a dual effect of promoting as well as suppressing hydrogen explosion, where with a larger filling density and larger diameter of MAA in hydrogen filled tube, it could help to effectively mitigate DDT. Thus, it is necessary to properly engineer the appropriate shape, structure, and filling density for the hydrogen-air cloud in different hydrogen concentrations. Polyurethane foam is another popularly used explosion-suppression structure for combustible gas, which could help to slow down flame propagation [203, 204]. Spherical nonmetallic material as shown in Fig. 19c) is a new developed structure for a better explosion suppression effect. The performances of these materials/structures for hydrogen-air cloud explosion still require more study, while considering the different characteristics of hydrogen explosion compared to other combustible gases, new explosion-suppression materials/structures could be developed.

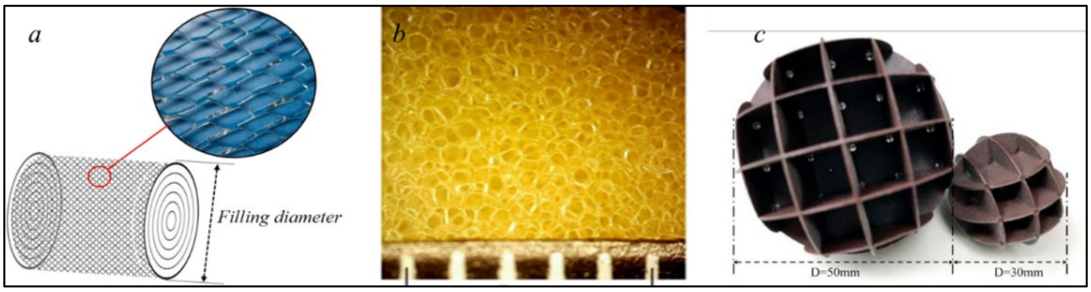

Fig. 19. Explosion-suppression materials: (a) mesh aluminum alloys; (b) polyurethane foam; (c) spherical nonmetallic balls [123, 203]

6 Conclusions and Future Outlook

This paper presents a comprehensive review on the safety of hydrogen. Potential hydrogen explosion throughout the production, storage, transportation, and consumption are considered. The blast loading characteristics of hydrogen explosions are focused in this paper. Different types of hydrogen explosions including deflagration, detonation and deflagration to detonation are reviewed in this paper. Existing studies including experimental analysis, numerical modelling and theoretical derivation on loading characteristics of hydrogen explosion are reviewed and summarized. Empirical load prediction approaches including TNT equivalent method, TNO multi-energy method, and Baker-Strehlow-Tang method are reviewed for their suitability and accuracy in predicting blast loading of hydrogen-air explosion. Influencing factors including hydrogen-air cloud size and heterogeneity, ignition intensity and location, ambient temperature and pressure, obstacle, ventilation, water and inert particles, and explosion-suppression materials/structures on hydrogen explosion are all reviewed. Gaps between existing researches on hydrogen explosion are identified. Concluding remarks and future outlooks are summarized as follow:

1. Existing studies on BLEVE and PVB of hydrogen explosion are very limited. Since hydrogen will primarily be store and transported in liquid form at low-temperature, or under pressure states, BLEVE and PVB are more likely to occur for hydrogen explosion. It is therefore necessary to more systematically understand the mechanism, loading characteristics and mitigation strategies for hydrogen BLEVE and PVB.
2. Despite of existing research on VCE of hydrogen-air cloud explosion, more testing data and results are still needed to form a reliable data pool to predict blast loading of hydrogen VCE accurately and to develop effective and efficient mitigation and structural protection approaches.
3. Hydrogen-air cloud deflagration would also generate a considerable negative overpressure since 2 hydrogen molecules and 1 oxygen molecule only form 1 water molecule. Therefore, when designing specific structures such as laminated glass that are sensitive to negative blast pressure, special attention should be paid against hydrogen-air cloud explosion.
4. Available studies primarily focused on hydrogen deflagration and detonation, while studies on deflagration-to-detonation transition is very limited due to the difficulty of experimental and numerical approaches.
5. CFD modeling tools are available to simulate hydrogen explosion. However, the accuracy of these existing tools varies, which thus needs to be improved with better understanding on the blast loading characteristics and more testing data.
6. Existing blast load predicting methods include TNT-EM, TNO MEM, and BST methods. TNO MEM performed better than TNT-EN and BST in predicting the peak overpressures, while the TNT-EM method gives the worst prediction. These traditional methods are designed for a symmetrical barrier-free environment, which differs from the particular scenario with hydrogen explosions in confined space. Moreover, hydrogen is more active than traditional combustible gas, which releases more energy

and thus produces higher blast overpressure and impulse. Existing model parameters of TNO MEM and BST for hydrocarbon fuels may not be suitable for hydrogen. Overall, these conventional methods could not accurately predict blast loading of hydrogen-air cloud explosions. Some improvements could be made with suitable model parameters to apply these traditional methods for hydrogen-air cloud explosion, which nevertheless do not exist yet.

7. Hydrogen-air cloud size effect and heterogeneity effect. Most existing studies performs small scale testing in the laboratory or field. The hydrogen-air clouds were mostly approximated as a premixed uniform gas cloud, the obstacles around the explosion are simulated as regular squares, and the leak source is approximated as a point source. However, in engineering application, the hydrogen concentrations are different at different locations. Therefore, more studies are needed to investigate size effect and hydrogen heterogeneity effect to properly interpret existing understanding on the blast loading characteristics of hydrogen explosion.
8. Effective and efficient mitigation approaches and structural protection methods. With the wide application of hydrogen as green renewable energy, accidental leakage and explosion become inevitable. It is therefore important to properly understand the blast loading characteristics, to accurately predict blast loading from accidental explosion, and to design protection plans. Studies existing on investigating the effectiveness of conventional ventilation device for hydrogen storage tanks. However, there is still a lack of systematic analysis. More effective and efficient mitigation and strengthening approaches are badly needed.

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