Fire Safety Journal 97 (2018) 44–53

Contents lists available at ScienceDirect

Fire Safety Journal

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

Experimental study on spontaneous ignition and subsequent flame development caused by high-pressure hydrogen release: Coupled effects of tube dimensions and burst pressure

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ARTICLE INFO

Keywords:
Hydrogen
Spontaneous ignition
Tube dimensions
Shock wave
Flame development
Deflagration combustion process

ABSTRACT

Combined effects of tube dimensions and burst pressure on the spontaneous ignition caused by high-pressure hydrogen release into a semi-confined space are investigated experimentally. An important finding is that the influence of tube diameter on spontaneous ignition shows complex behavior. For tubes with different diameters, the minimum burst pressure for spontaneous ignition depends on not only the strength of the shock wave but also the mixing of hydrogen and air. A dimensionless parameter of tubes, L/D—which is defined as the ratio of the tube length to the tube diameter—is introduced to describe the effect of tube size. The results show that the possibility of spontaneous ignition increases with increasing L/D. Under appropriate conditions, spontaneous ignition leads to flame development. As the flame propagates into a semi-confined space, it first forms an envelope structure in front of the hydrogen jet. Since some amount of a partially premixed combustible mixture, created by the hydrogen jet, exists in the semi-confined space, the flame subsequently undergoes deflagration. The overpressure caused by deflagration is significantly greater than that caused by the leading shock wave. In addition, both the deflagration overpressure and the shock-wave overpressure increase with increasing tube diameter and initial release pressure.

1. Introduction

Hydrogen is widely considered as a high-efficiency, low-emission next-generation energy carrier. However, hydrogen has some unique hazardous properties [1], such as high diffusivity and a wide flammable range. In some hydrogen accidents, combustion was reported to have occurred without clearly identifiable ignition sources when pressurized hydrogen was suddenly discharged from a high-pressure reservoir [2]. This phenomenon is known as the spontaneous ignition of hydrogen, and it is highly likely to further develop into catastrophic fire and/or explosion accidents [3]. Therefore, spontaneous ignition caused by high-pressure hydrogen release or leak poses a major potential risk for the storage and transportation of pressurized hydrogen.

Recently, several postulated mechanisms of spontaneous ignition of hydrogen have been proposed [4,5]. Among these mechanisms, diffusion ignition theory has been the focus of recent studies. This mechanism has been demonstrated in several experimental [6–11] and numerical studies [12–16]. It was first proposed by Wolanski and Wojcicki [17], who conducted an experimental investigation using a shock tube. A shock wave was generated ahead of the high-pressure hydrogen jet during sudden discharge through the tube, which compressed and heated the oxidizer. Then, a combustible mixture was formed between hydrogen and the shock-heated gaseous oxidizer owing to the diffusion of mass and heat. Therefore, ignition might occur when the temperature of the combustible mixture exceeds the threshold of the ignition temperature.

In subsequent studies, factors influencing the possibility of spontaneous ignition, such as the burst pressure [8,18,19], length of the release tube [6,20,21], tube internal geometry [22–24], and diaphragm rupture rate [25,26], were investigated. It was found that spontaneous ignition is more likely to occur with an increase in burst pressure. Furthermore, the minimum burst pressure for spontaneous ignition was found to decrease with an increase in tube length to a certain critical length value

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https://doi.org/10.1016/j.firesaf.2018.03.001
Received 16 June 2017; Received in revised form 8 March 2018; Accepted 12 March 2018

($Lc = 1.2$ m) and then increase with a further increase in tube length [21]. Both experimental [6,23,24] and numerical [22] results demonstrated that the presence of internal geometries could significantly facilitate the occurrence of spontaneous ignition. Golub et al. [20] pointed out that spontaneous ignition can occur at a lower burst pressure in a rectangular tube than in a cylindrical one. Xu et al. [26] and Golovastov et al. [25] suggested that a faster diaphragm rupture rate reduces ignition delay and therefore triggers a faster ignition process.

Kim et al. [9] investigated the spontaneous ignition process and the subsequent flame propagation in a tube by using flow visualization. They found that the initial ignition is induced in the boundary layer of the mixing zone, which is in agreement with the results of numerical studies [12,15]. Moreover, Dryer [6] as well as Lee and Jeung [12] suggested that owing to the occurrence of shock–shock interactions, shock focusing, and vortex formation around a jet in a tube, a large amount of combustible mixture can be produced in the main flow region, thereby promoting the growth of the ignition kernel to a flame. Development of a flame in an open space after it exited a tube was observed in experimental studies [7,11]. Mogi et al. [7] observed that a fireball was first formed when the flame entered the free atmosphere, and it finally turned into a diffusion jet flame. Grune et al. [27] reported that a "local explosion" occurred in a hydrogen jet when spontaneous ignition developed into a full jet flame in an open ambient environment. This led to a detectable overpressure and thermal loads on the surrounding environment.

Although many studies have been conducted to investigate spontaneous ignition and flame propagation resulting from pressurized hydrogen release through a tube, the effects of tube dimensions, including tube length and tube diameter, on spontaneous ignition have not yet been fully understood. Moreover, previous studies mainly focused on the flame propagation following spontaneous ignition in an open space. However, hydrogen tends to accumulate in a confined/semi-confined space, which results in fast combustion or an explosion [28]. Nevertheless, several problems of flame dynamics in a semi-confined space arising from spontaneous ignition remain unsolved. In the present study, experiments are performed to investigate the spontaneous ignition caused by high-pressure hydrogen release through tubes of different dimensions. The effect of tube dimensions on the spontaneous ignition is discussed. The minimum burst pressure for ignition is examined under different release conditions. Furthermore, flame development and overpressure characteristics in a semi-confined space are analyzed.

2. Experimental setup

The experimental apparatus is schematically shown in Fig. 1. It consists mainly of a high-pressure tank, diaphragm holder, release tube, semi-confined chamber, high-speed video camera, and data logging system. A detailed description of the experimental apparatus and procedure can be found in our previous paper [23].

The volume of the high-pressure tank is 0.44 l. A nickel burst disk (Dalian Ligong Safety Equipment Co., Ltd) is used as a diaphragm. The burst pressure (P_b), which is varied from 2 MPa to 11 MPa, depends on the thickness of the disk. A pressure transducer (Kulite, ETM-375M-20 MPa) is installed in the high-pressure tank to measure the burst pressure. Three cylindrical tubes with diameters of 10 mm, 15 mm and 20 mm are used in the experiments. The rupture caliber of the burst disk is equal to the tube diameter. Three different lengths of each of the three tubes are employed: 160 mm, 240 mm, and 360 mm. Several pressure transducers (PCB Piezotronics, 113B22) are installed on the tube wall to measure the pressure dynamics. Meanwhile, to detect the occurrence of ignition inside the tube, light sensors (Thorlabs, Si photodiode, FDS010) are mounted on the opposite side of the wall mounted with the PCB transducers, as shown in Fig. 2(a). The intensity level of light signal can indicate the flame intensity in the tube.

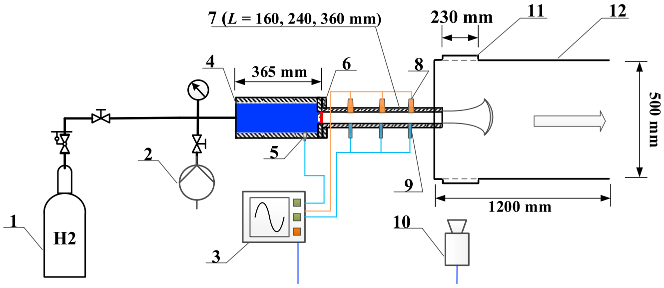

Fig. 1. Schematic of experimental apparatus: (1) compressed gas cylinder, (2) vacuum pump, (3) data recorder, (4) high-pressure tank, (5) strain gauge pressure sensor, (6) burst disk, (7) release tube (8) light detector, (9) piezoelectric pressure transducer, (10) high-speed video camera, (11) viewport, (12) semi-confined chamber.

The semi-confined chamber is a rectangular cavity 1200 mm × 470 mm × 500 mm in size. The end attached to the release tube is closed, and the opposite end (right end in Fig. 2(b)) is open to the atmosphere. The walls of the chamber are made of stainless steel. To observe flame propagation near the tube outlet, two observation windows (230 mm × 230 mm) are set up on two sides of the chamber, as shown in Fig. 2(b). This structure of the chamber can model a semi-confined space, such as a garage or tunnel. The ratio of the leak size to the cross-section of the chamber is so small that the chamber can provide sufficient space for the hydrogen jet and/or flame to extend freely in all directions at the initial stage of discharge. Meanwhile, in a short period after leakage, the chamber can also facilitate hydrogen accumulation in the semi-confined space. A high-speed video camera (Phantom, v710) is used to record the flame development through the observation windows.

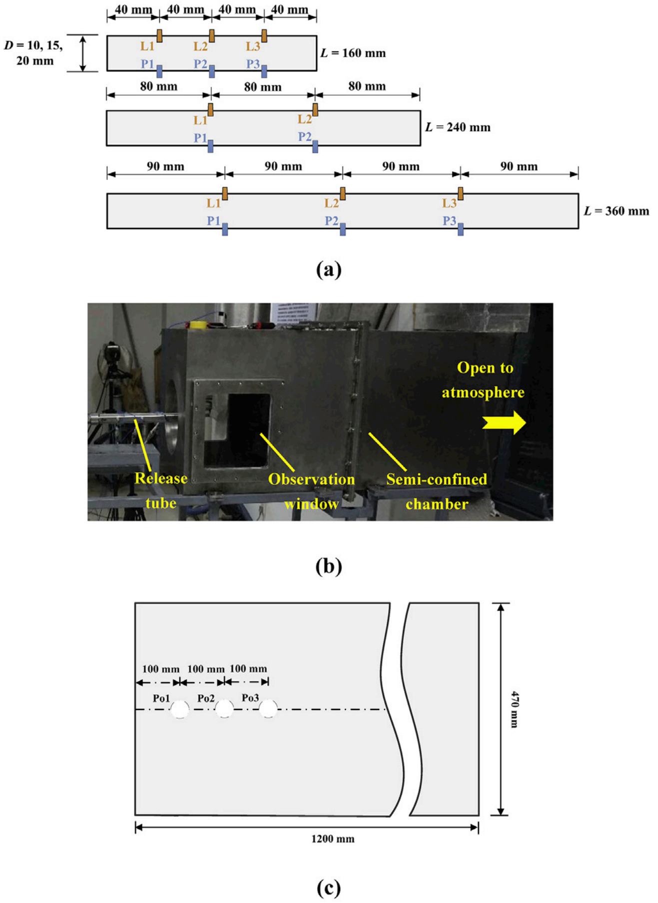

Fig. 2. (a) Schematics of different release tubes, (b) photograph of semi-confined chamber, (c) positions of pressure transducers mounted on top wall of semi-confined chamber.