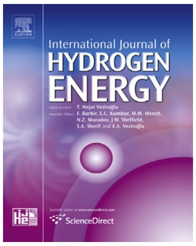
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 5749–5762

Available online at www.sciencedirect.com

ScienceDirect

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



Self-ignition and explosion of a 13-MPa pressurized unsteady hydrogen jet under atmospheric conditions

V.N. Mironov[*], *O.G. Penyazkov*, *D.G. Ignatenko*

A.V. Luikov Heat and Mass Transfer Institute, NAS, 15, P. Brovka Str., Minsk 220072, Belarus

ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
1 February 2015
Accepted 3 February 2015
Available online 18 March 2015

Keywords:
Hydrogen safety
Hydrogen jet
Self-ignition
Diffusion ignition
Explosion

ABSTRACT

The process of unsteady high-pressure hydrogen release observed on local vessel rupture is investigated experimentally. The flow structure during the formation of a supersonic free hydrogen jet is studied. The obtained data correlates well with the numerical simulation of sonic underexpanded hydrogen jet released into the atmosphere. In particular, it has been confirmed that the Mach disk fluctuates in the case of unsteady outflow of underexpanded hydrogen jet. It has been shown that in order to provide diffusion self-ignition, it is necessary to focus an air shock wave, formed after the vessel rupture, within the studied initial hydrogen tank pressure range. Lab and ground tests on self-ignition and explosion of hydrogen that outflows through a 15-mm opening when the flow interacts with a 37-mm-radius hemispherical cavity are described. A comparison of the diffusion combustion dynamics of releasing hydrogen in self-ignition and induced ignition scenarios is made. The observed visible flame front velocities of 150–220 m/s can result in dangerous blast waves in the case of large-scale hydrogen release. Measures to reduce the risk of explosion of unsteady high-pressure hydrogen jets releasing into an encumbered space are proposed.

Introduction

The prospects of a wide use of hydrogen, especially, in power plants and propulsion systems pose the problem of its storage and transportation. Experts have predicted a pressure level up to 70 MPa and even higher [1,2], required for hydrogen efficient storage and transportation. With the development of the hydrogen technology and of the infrastructure of the hydrogen power engineering, the problems associated with the safe operating conditions will increase.

One of the important tasks of hydrogen safety is the assessment of the possibilities and conditions of self-ignition and explosion of high-pressure hydrogen in the case of accidental hydrogen release into the atmosphere because of the break of a pipeline or a high-pressure vessel, failure of stop or control valves, etc. Wolanski and Wojcicki

---

[*] *Corresponding author.*
E-mail address: mirvit33@gmail.com (V.N. Mironov).

http://dx.doi.org/10.1016/j.ijhydene.2015.02.021

[3], who were the first to study this area, suggested a possible “diffusion ignition mechanism” of the process. In the majority of literature related to hydrogen self-ignition, some construction elements that connect with the atmosphere are usually located closely behind a diaphragm with a diameter D, whose rupture causes unsteady hydrogen release. These elements are a pipe (diameter D) whose bottom has an opening of diameter $d < D$ [4], a pipe nipple mounted behind the diaphragm that can be equipped with reducer fittings [5], either a pipe of length $L >> D$ [6,7] or a perforated channel [8]. Thus, self-ignition in the above cases is attributable to the configuration of the channel behind the ruptured diaphragm, where air is shock-compressed and heated. Following this, the hot air is mixed with the hydrogen jet outflowing into the atmosphere.

This paper considers the effects observed in hydrogen outflow through an opening directly into the environment. This type of hydrogen release was modeled in Refs. [3,9–11]. Some authors argue that at certain initial parameters of hydrogen release (hydrogen stagnation pressure $P_0 \geq 40$ MPa, $D \geq 4$ mm [10], $P_0 = 15–40$ MPa, $D \geq 3$ mm [11]), a hydrogen–air mixture will self-ignite in the region of contact surface behind the bow shock wave in the displaced air. However, according to [12], the possibility of self-ignition of a hydrogen jet released into the atmosphere has not yet been confirmed experimentally.

Unsteady hydrogen jets are studied experimentally in Refs. [13–15]. In Ref. [13], the hydrogen jet startup was studied using the high-speed Schlieren flow photography. Unfortunately, experiments were conducted at low stagnation pressures of hydrogen P_0 (up to 1.1 MPa). Furthermore, the design of the device used could not provide the study of the initial phase of hydrogen release on formation of a shock wave in air.

This phase was examined in Ref. [15] in the case of shock-compressed hydrogen outflow into oxygen through a rectangular opening. However, several factors do not allow one to use these results for predicting the dynamics of high-pressure hydrogen release into atmosphere. Among them there are the low oxidant pressure ($P_\infty = 3.5$ kPa), small pressure ratio $P_0/P_\infty \approx 14$, inability of capturing the flow near the opening, and the moderate value of the ratio of the control section height to the opening slit. Furthermore, in Ref. [15] practically two-dimensional outflow was studied (the cross-section channel side ratio is around 10).

There are literature sources that describe the unsteady outflow of supersonic and sonic jets of other gases (usually N_2, CO_2, and Ar). Flow patterns were recorded either by Schlieren [16–18] or by interference [10] techniques. However, a jet usually outflows into the chamber at the pressure $P_\infty < 6$ kPa. When hydrogen jet outflows into the atmosphere, P_0 does not exceed 3.4 MPa.

Due to the lack of information about the dynamics of an unsteady hydrogen jet, Hydrogen jet formation section is devoted to the study of this phenomenon. The experiments have determined the direction of the study to focus on the self-ignition and the explosion of hydrogen, with the results presented in Section Self-ignition and combustion of a hydrogen jet outflowing into an encumbered space. In addition, the explosion dynamics of unsteady hydrogen release into the atmosphere, in self-ignition and induced ignition scenarios, has been investigated.

Hydrogen jet formation

Experimental setup

All experiments were carried out on the facility whose main part (Fig. 1) is a vertical stainless steel cylindrical vessel 1 with an inner diameter of 80 mm and height of 240 mm. The upper lid 2 of the vessel has an attachment unit for diaphragm 3 with a holder 4. A striker 6 with a four-face point, intended for cross rupture of the diaphragm, can move along a shaft 5.

The diaphragm is ruptured under the impact of high-pressure hydrogen. The striker is controlled by a system that contains a pneumatic control valve and a pneumocylinder 7. Two displacement sensors on its case are used to synchronize the initiation of the system recording the process in time when the piston edge passes the given points along the cylinder axis. The pneumatic control valve is turned on after the vessel is degassed and filled with hydrogen via pipe nipple 8 ($P_{0\ \max} = 13.4$ MPa) and after the recording system is ready for operation. The pressure sensor 9 records the dynamics of the pressure drop during jet outflow. In order to install focusing obstacles in the path of the jet, four double-ended bolts 10 over the upper lid 2 had the length 225 mm with thread (in Fig. 1 the bolts are cut off).

A total volume of the gas cavity of the cylindrical vessel is 1 dm^3. To reduce the high-explosive and fire loads during the explosion of a hydrogen–air mixture in lab experiments, the gas volume has been decreased to 0.5 dm^3 using an annular insert.

Diaphragm 3 is composed of several (up to seven) 45-μm-thick layers of stainless steel foil, or three 100-μm-thick layers

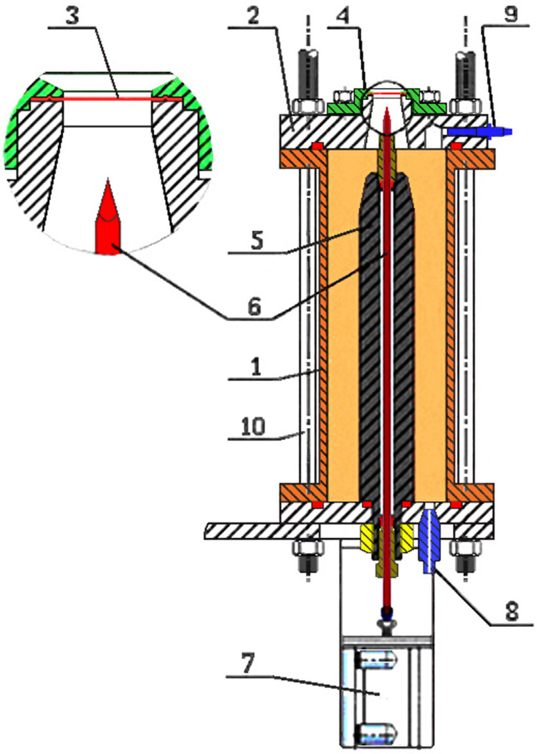


Fig. 1 – Cylindrical vessel for hydrogen jet formation.