ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2016) 1–6

Available online at www.sciencedirect.com

ScienceDirect

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

Visualization of spontaneous ignition under controlled burst pressure

K. Yamashita [a], T. Saburi [b,*], Y. Wada [b], M. Asahara [a], T. Mogi [c], A.K. Hayashi [a]

[a] Graduate School of Science and Engineering, Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo-ku, Sagamihara-shi, Kanagawa 252-0206, Japan

[b] Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba-shi, Ibaraki 305-8569, Japan

[c] Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form
28 June 2016
Accepted 28 June 2016
Available online xxx

Keywords:
High-pressure hydrogen
Spontaneous ignition
Shock wave
High-speed camera

ABSTRACT

A high-pressure hydrogen jet released into the air has the possibility of igniting in a tube without any ignition source. The mechanism of this phenomenon, called spontaneous ignition, is considered to be that hydrogen diffuses into the hot air caused by the shock wave from diaphragm rupture and the hydrogen-oxidizer mixed region is formed enough to start chemical reaction. Recently, flow visualization studies on the spontaneous ignition process have been conducted to understand its detailed mechanism, but such ignition has not yet been well clarified. In this study, the spontaneous ignition phenomenon was observed in a rectangular tube. The results confirm the presence of a flame at the wall of the tube when the shock wave pressure reaches 1.2–1.5 MPa in more than 9 MPa burst pressure and that ignition occurs near the wall, followed by multiple ignitions as the shock wave propagates, with the ignitions eventually combining to form a flame.

Introduction

When emergencies occur in hydrogen stations and chemical plants, high-pressure hydrogen is released from a rupture disc through a pipe into the air. During this process, the high-pressure hydrogen may spontaneously ignite, yielding a flame that propagates without any ignition source. This phenomenon, called spontaneous ignition, is not caused by an ignition source but by a diffusion of hydrogen into heated by shock oxidizer, as experimentally confirmed by Wolański et al. [1]. However, the detailed mechanism of spontaneous ignition in a tube has not yet been well clarified. It is necessary to define safety criteria to prevent a flame from developing when high-pressure hydrogen is accidentally released in a hydrogen station or chemical plant. The spontaneous ignition process should be clarified in detail based on this background.

A variety of experimental and numerical studies have been conducted on this subject. An experimental shock tube system equipped with a diaphragm to release hydrogen using a rupture disc is generally used to study the phenomenon of hydrogen spontaneous ignition. The possibility of a hydrogen jet igniting because of a sudden release depends on the burst pressure of the diaphragm and the tube geometry [2–5]. The minimum burst pressure sufficient to cause spontaneous

* *Corresponding author*. Fax: +81 29 861 8760.
E-mail address: t.saburi@aist.go.jp (T. Saburi).
http://dx.doi.org/10.1016/j.ijhydene.2016.06.240

ignition decreases with increasing tube length to a certain critical length, then increases with further tube extension [5]. The tube geometry downstream of the diaphragm affects the ignition behaviour, whereas that upstream of the diaphragm does not [2]; however, the configuration of the tube and connectors may affect the downstream gas dynamics. The behaviour of the diaphragm rupture can be varied by changing various rupture and diaphragm characteristics, such as the rupture speed and the position, shape, and material of the diaphragm, allowing the possibility of ignition to be altered [6–8]. The flame structure and flammable range outside the tube have been investigated both experimentally [3,5,9], and numerically [4,7]. The ignition process in the tube has also been numerically simulated [7,8,10–12], and experimentally investigated [13] in recent years. However, the quantitative discussion remains insufficient because some experimental studies are not reproducible as a result of the inaccuracy of the rupture process and rupture pressure. In particular, only a few studies have focused on the visualization of the phenomenon of spontaneous ignition in a tube.

In this study, a shock tube experiment was conducted to clarify the processes of ignition and flame formation for a high-pressure hydrogen flow in a tube. A circular shock tube apparatus was equipped with a plunger system to control the burst pressure. A circular-to-rectangular conversion flange was used to avoid discontinuous changes in cross section, and a rectangular tube with glass windows was used for optical observation. Two high-speed cameras were used to simultaneously take shadowgraphs and direct photographs.

Experimental setup

The experimental apparatus used in this study is based on a shock tube system that consists of a high-pressure hydrogen section and an ambient pressure air section separated by a diaphragm (Fig. 1). The diaphragm, which is made of polyethylene terephthalate (PET) film (Melinex, Teijin DuPont), is used to keep the hydrogen section at a high pressure. The thickness of the PET film was adjusted according to the burst pressure such that the film could be expected to fail and rupture at a predetermined pressure, but thickness-based rupture control is generally insufficiently accurate. The plunger system used in this apparatus is composed of a barrel with a solenoid coil, a tungsten needle positioned at the coil end, and a step-up circuit and is mounted diagonally on the high-pressure side of the diaphragm flange. When the step-up circuit is switched on, a large pulsed current flows through the coil and forms a magnetic field along the barrel. The magnetic force pulls and accelerates the tungsten needle. The needle moves along the barrel, then hits and ruptures the diaphragm. The plunger system is able to precisely rupture the diaphragm by base pressure control, and the pressure is measured by a strain gauge pressure transducer (PHA-L-20MP, Kyowa Electronic Instruments). The rectangular test section, which is equipped with silica glass windows and sensors, is connected to the tube end of the ambient pressure section.

The high-pressure hydrogen propagation, ignition, and flammable behaviours were observed by high-speed cameras through the windows, and the pressure and luminescence histories were recorded at 30 mm intervals using pressure sensors (PCB M111A24, Piezotronics, Inc.) and light detectors (PDA25K, Thorlabs), respectively. When the step-up circuit is switched on, a trigger signal is sent to start recording with a data logger and high-speed cameras. Two high-speed cameras record the shadowgraph system to allow the visualization of the density gradient and direct flame images. The illumination source of the shadowgraph system is a xenon lamp (LS-75, KATOKOKEN). The light from the lamp is reflected and collimated off a Schlieren mirror, then passes through the windows of the measurement section. The image then passes through a Fresnel lens and is focused on the first shadowgraph

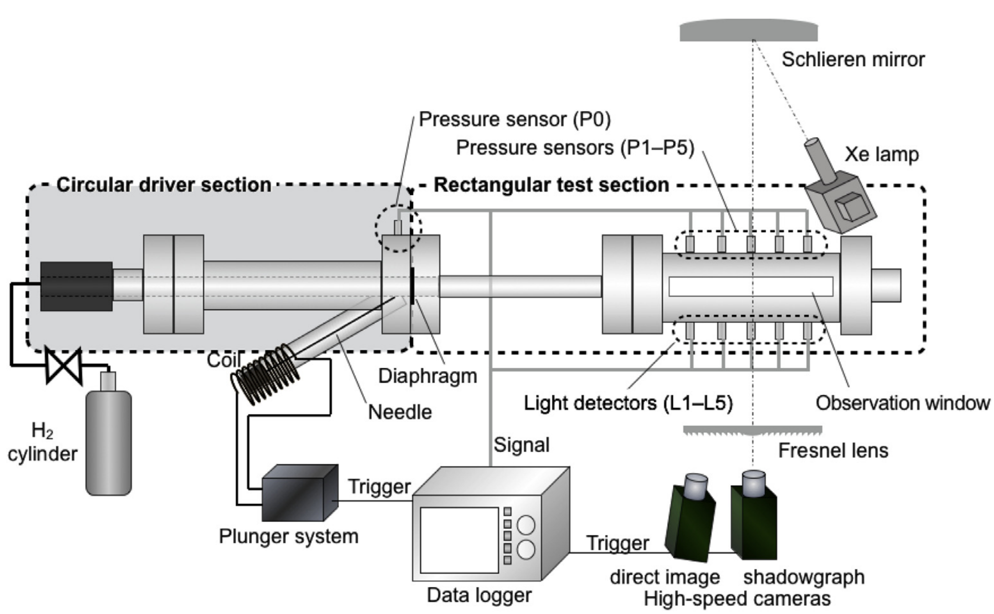

Fig. 1 – *Experimental schematic of entire system.* Left and right broken line areas indicate circular driver (high pressure) and rectangular test (ambient pressure) sections, respectively.