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Short communication

Self-ignition of hydrogen jet discharged under high pressure into a perforated channel

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ABSTRACT

The self-ignition of a hydrogen jet during spontaneous release from a high-pressure chamber into a perforated channel was investigated experimentally. The experiments were devoted to the investigation of the possibility of preventing the self-ignition of hydrogen by using the perforated channel. Two lateral orifices with diameters of 2–6 mm were located in a side surface of a rectangular cross-section channel. The length of the channel was 180 mm and its sides were 2 and 10 mm. The initial hydrogen pressure varied from 3 to 9 MPa. Maps of the possibility of hydrogen self-ignition depending on the Mach number of the incident shock wave, the distance between the position of the orifices and the rupture diaphragm, and the orifice's cross-sectional area are presented. Using the perforated channel as a pressure-relief device can be effective under certain conditions.

1. Introduction

One of the key problems when using and storing compressed hydrogen is its ability to self-ignite on sudden discharge from a high-pressure cylinder. In some cases, the self-ignition can occur in the absence of external ignition sources. Pressure relief devices are used (Sunderland, 2008) to avoid a rupture of the pressure vessel. Specifications applicable to such devices must ensure the safe discharge of a pressurized hydrogen jet leaving out the possibility of self-ignition.

The mechanism of such self-ignition of the pulsed hydrogen with the surrounding air was investigated in the papers of Wolanski and Wojcicki (1972), Golub et al. (2008), Xu et al. (2008), Yamada et al. (2011), and Mironov et al. (2015). The ignition delays for the non-premixed mixtures were presented in the papers of Sakurai (1986), Xu et al. (2009), and Golovastov and Bocharnikov (2012). The minimum values of pressures and temperatures that cause the ignition of hydrogen are presented in the papers of Dryer et al. (2007), Mogi et al. (2008), Lee and Jeung (2009), and Grune et al. (2014).

One of the ways to prevent the self-ignition of hydrogen during the discharge into a channel filled with air can be by constructing the lateral orifices in the channel side. These orifices can be placing to attenuate the intensity of the shock wave. However, the orifices on the sides of the channel means that an obstacle is present in the supersonic flow of hydrogen or compressed air. This can lead to an additional increase in pressure and temperature behind the incident shock wave. The influence of obstacles and variable cross-section on the self-ignition of hydrogen is presented in the papers of Mogi et al. (2008) and Lee and Jeung (2009). The actions of obstacles, channel cross-section, and channel length are presented by Baev et al. (2000) and Luikov et al. (2011). Numerical studies of spontaneous ignition were carried out in a tube with local contraction by Xu and Wen (2012), with an obstacle plate by Xu et al. (2011), in a T-channel by Bragin et al. (2013), and in a long channel by Kitabayashi et al. (2013). Kaneko et al. (2015) showed that the ignition centres are located on the inner surface of the channel. Thus, the presence of orifices can have a significant influence on the dynamics of hydrogen ignition.

The aim of the present work was to experimentally investigate the influence of the orifice parameters on the self-ignition of a hydrogen jet during the pulse discharge from the high-pressure chamber into the channel. The limit values of the Mach number of the generated shock wave were determined at which the spontaneous self-ignition of hydrogen occurs:

1 Depending on the position of two lateral orifices;
2 Depending on the area of two lateral orifices placed in a fixed location.

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2. Experimental set-up

The scheme of the experimental set-up is presented in Fig. 1. Compressed hydrogen from the balloon (1) was supplied into the chamber (2) by a manual adjustment with the use of a regulating valve (3). Pressure in the chamber grew at a speed of 0.2 MPa/s and was measured by a precise manometer (4). When the required pressure was reached, a diaphragm (5) between the chamber and channel was broken, and hydrogen was discharged into the perforated channel (6). The air pressure in the open channel was 0.1 MPa.

The length of the high-pressure chamber was 400 mm, which made it possible to avoid the influence of rarefaction waves on the characteristics of the hydrogen jet and the generated incident shock wave in the 180-mm-long channel. For example, for minimum value of the Mach number 3.3 (see below, Fig. 6) the velocity of the contact surface between air and hydrogen can be estimated by Equation (1):

$$u = \frac{2a_{air}}{\gamma + 1}\left(M - \frac{1}{M}\right) = 856\frac{m}{s}, \quad (1)$$

where a_{air} – sound speed in air for temperature 293 K, M – Mach number, $\gamma = 1.4$ – heat capacity ratio. The maximum period of moving of the contact surface through the channel is equaled to $\frac{180mm}{856m/s} = 210\mu s$. It suffices to note that this value does not exceed even the period of moving of the rarefaction wave from the diaphragm to the closed end of the high pressure chamber $\frac{400mm}{a_{H_2}} = \frac{400mm}{1305m/s} = 307\mu s$, where a_{H_2} – sound speed in hydrogen. The real delay of interaction of the rarefaction wave with the contact surface will be significantly higher – see, for example, book of Gaydon and Hurle (1963).

The internal diameter of the high-pressure chamber was 8–10 mm, and the diameter of the rupture diaphragm was 5 mm. The scheme of connection of the chamber with channel is shown in Fig. 1. Detailed photographs of the rectangular cross-section channel and its main elements can be found in the paper of Golub et al. (2008).

A channel with a rectangular cross-section with sides of 10 and 2 mm was connected to the high-pressure chamber. Thus, the cross section area of the rectangular channel was $S_0 = 20.0$ mm^2. The orifices (7) were located on the surface of the 10-mm side. Diameter of two symmetrically located orifices varied: 2 mm, 3 mm, 4 mm, and 6 mm. The full area of two orifices S^* was respectively: 6.3 mm^2, 14.1 mm^2, 25.1 mm^2, and 56.5 mm^2. Thus, the channel of the rectangular cross-section provides the opportunity to vary the area ratio $\sigma = S^*/S0$ of two symmetrically located orifices and channels in a wide range $\sigma = 0.32–2.83$.

Technical hydrogen, contained in a cylinder with a volume of 40 l at a pressure of 15 MPa, was used. Air was blown through the channel and the room was ventilated before each experiment. The rupture of the copper diaphragm occurred at the moment when the pressure difference reached a certain value, which depended on the thickness of the diaphragm (5) and the depth of the cuts. The extent of the diaphragm rupture was controlled. Only experimental data obtained after the full opening of the diaphragms were used.

For determination of the Mach number of the incident shock wave, two piezoelectric pressure transducers PCB 113A24 (8) were used, mounted along the channel. PD-256 photodiodes (9), mounted were used to register the flame. Fig. 2 shows typical readings from the pressure transducers and photodiodes, when orifices are located at a distance of 40 mm.

In addition to the photodiodes, a digital video camera with a recording speed of 30 fps and resolution of 640 × 480 was used (Fig. 1, pos. 10). Fig. 3 shows a photograph of the flames during the self-ignition of the hydrogen jet discharged into the channel with two lateral orifices. The orifices were located at a distance of 40 mm (a) or 90 mm (b) from the diaphragm. The photograph shows the single flame flash along the axis of the channel for the distance of 40 mm and two lateral flame flashes for the distance of 90 mm. Location of the orifices at a distance of 140 mm gives the results like in Fig. 3b (90 mm).

3. Experimental results and Discussion

Fig. 4 shows a map of the self-ignition data in dependence on the Mach number of the incident shock wave and the distance between the lateral orifices and the rupture diaphragm. Two orifices, 4 mm in diameter, were placed at distances X of 40, 90, and 140 mm. Fig. 4 also shows the critical values of the initial pressure

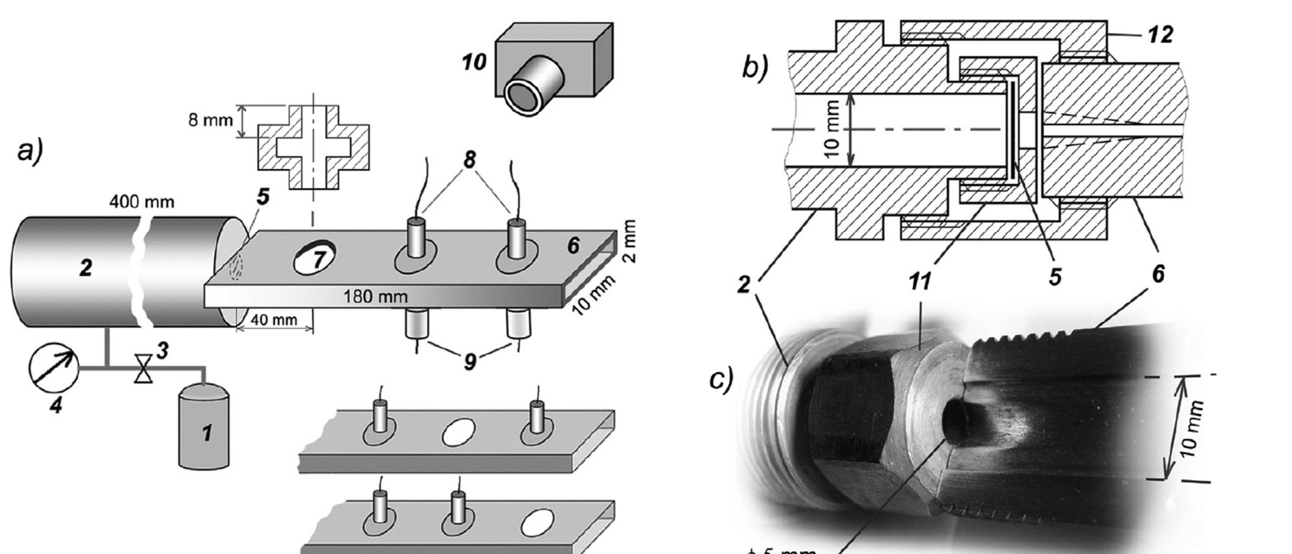

Fig. 1. Scheme of the experimental set-up (*a*), drawing of the diaphragm mounting (*b*) and photo of the connection (*c*). 1: balloon; 2: high-pressure chamber; 3: regulating valve; 4: manometer; 5: rupture diaphragm; 6: perforated channel; 7: orifices; 8: piezoelectric pressure transducers; 9: photodiodes; 10, videocamera; 11, locking nut; 12, coupling.