Influence of Diaphragm on Self-Ignition of Hydrogen at Spontaneous Release into Air

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Special properties of diffusion self-ignition of hydrogen were studied experimentally at a pulse discharge into a channel filled with air. Self-ignition of hydrogen occurred at a contact surface of the jet of hydrogen. Required temperatures for self-ignition of hydrogen were reached due to heating the air by a shock wave which appears as a result of the non-stationary supersonic discharge of hydrogen from the high pressure vessel. Formation of a shock wave flow structure at the pulse discharge of compressed hydrogen into the channel with air was studied, and ignition delays of hydrogen were determined.

1 Introduction

The work is devoted to investigation of the diffusion self-ignition occurred at the contact surface of fuel and hot oxidizer. A necessary concentration ratio between the components is ensured due to the diffusion and intermittent. One of such cases is diffusion self-ignition of hydrogen or another combustible gas at a pulse discharge from a chamber under high pressure into air. With this releasing a shock wave is formed in air which heats air to a temperature more then one thousand degrees. It creates sufficient conditions for igniting of the combustible gases if it are in contact with hot air [1].

The large part of recent investigations is devoted to determination of thermodynamic parameters and boundary conditions with which the diffusion self-ignition of hydrogen is possible. The experimental and numerical minimum values of pressures and temperatures which cause the ignition of hydrogen are represented in [2,3]. The actions of obstacles, channel cross section and channel length are presented in [4,5]. The kinetic mechanisms of the ignition of hydrogen with different boundary conditions are given by [6].

Both for the preliminarily mixed mixtures and not mixed ones the characteristic parameter of ignition is ignition delay. The ignition delays of the preliminarily not mixed mixtures exceed the delays for preliminarily mixed 4-5 times in the range 1000-1400 K [7]. There is a significant difference between experimental and numerical values of ignition delays [8].

In the case of diffusion self-ignition the most actual criterion can prove to be a duration of decompression and formation of the hydrogen jet. The role of the rupture rate of a diaphragm on the possibility of self-ignition of hydrogen was investigated numerically in [9]. However, this statement has not been confirmed experimentally.

The goal of this work was determination of the ignition delays of hydrogen at pulse discharge from a high pressure chamber (the chamber) into a straight open channel of low pressure (the channel) behind

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an incident shock wave. Influence of the opening rate of the diaphragm on the formation of the shock wave was studied.

This setting of experiment gives the possibility to test one of models of a pressure release device for the discharge of hydrogen into atmosphere.

2 Experimental technique

For modeling of the spontaneous discharge of hydrogen into the channel the rupture of diaphragm was used between the chamber and channel. The schematic of the system work, organized according to the principle of a shock tube, and X-t-diagram are illustrated on Fig. 1.

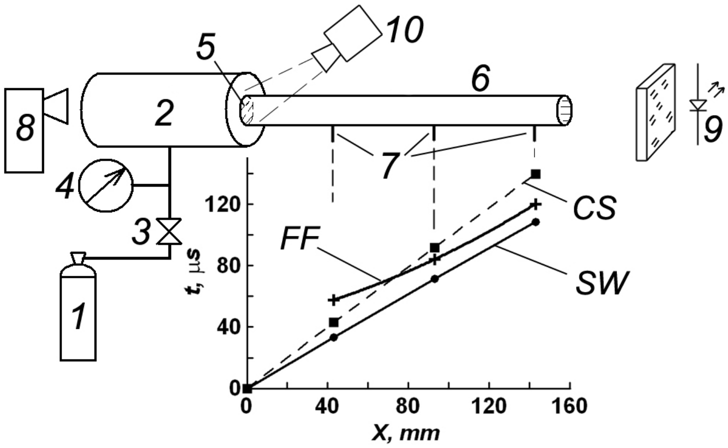

Figure 1. Experimental setup and X-t-diaphragm of diffusion self-ignition.

Compressed hydrogen from a balloon (*1*) was given into the chamber (*2*) by a manual adjustment with the using of a regulating cock (*3*). Pressure in the chamber was growing with the speed of 0.1 MPa/s and was measured by a manometer (*4*). With reaching of the required pressure a diaphragm (*5*) was broken, and hydrogen discharged into the channel (*6*) filled by air at 100 kPa with forming the shock wave propagated through the channel.

The channel with 60 mm in length and 18 mm in diameter was used to investigate the shock wave formation. This channel and another one with length 65-185 mm and 5 mm in diameter were used to investigate the influence of opening rate of the diaphragm on the possibility of self-ignition. Ignition delays were determined in channels of round and rectangular (2*10 mm^2) cross sections.

The pulse discharge of hydrogen leads to the formation of the shock wave (*SW*), behind which the theoretical contact surface (*CS*) moves. A flame front (*FF*) appears on the contact surface.

For registration of the shock waves piezoelectric pressure transducers PCB (*7*) were used, located along the channel. For registration of the moment of ignition and flame propagation photodiodes were established. Photomultiplier tube (*8*) and light diode (*9*) arranged along the axis of the channel were used to register the opening rate of the diaphragm. A high speed frame digital camera (*10*) was used to register the process of breaking of the diaphragm.

3 Rupture of diaphragm. Shock wave formation

The less the duration of opening, the more rapidly the shock wave formation and the faster the heating of the contact surface. Therefore besides initial pressure and temperature the self-ignition delays of hydrogen is determined by duration of the opening of diaphragm as well.

To vary the duration of opening the diaphragms of copper, brass, aluminum and steel of different thickness and depth of cuts were used. The thicknesses of diaphragms was changed from 0.10 to 1.00 mm.

Different moments of frame high-speed registration of the opening copper diaphragm are shown on Fig. 2 at initial pressure of hydrogen 6 MPa. For this case the duration of opening was 50-60 μs.

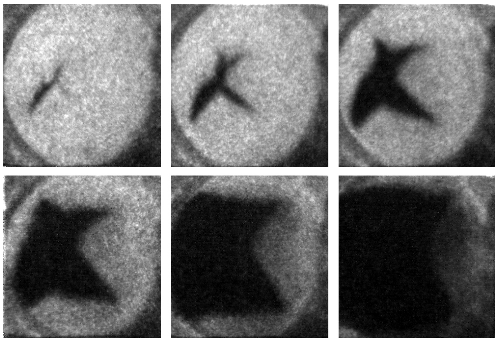

Figure 2. Different moments of rupture of diaphragm. Left to right: 0 μs; 10 μs; 20 μs; 30 μs; 40 μs; 50 μs.

In the range of initial pressures 2-10 MPa the durations of the opening of diaphragms are determined by the photomultiplier tube. The duration was ranged from 80 to 12 μs. Map of possibility and impossibility of self-ignition of hydrogen in dependence on duration of diaphragm rupture and initial pressure of hydrogen are represented on Fig. 3. Duration of opening was correlated with the relationship:

$$\Delta t = N\sqrt{\frac{\rho H\delta}{P_0}} \quad [10],$$

where N = 0,9506 – gas parameter at γ = 1,4, H = 1.41d – effective diameter for round diaphragm with cuts, ρ – density of metal, δ – thickness of the diaphragm, P_0 – initial pressure in the high pressure chamber.

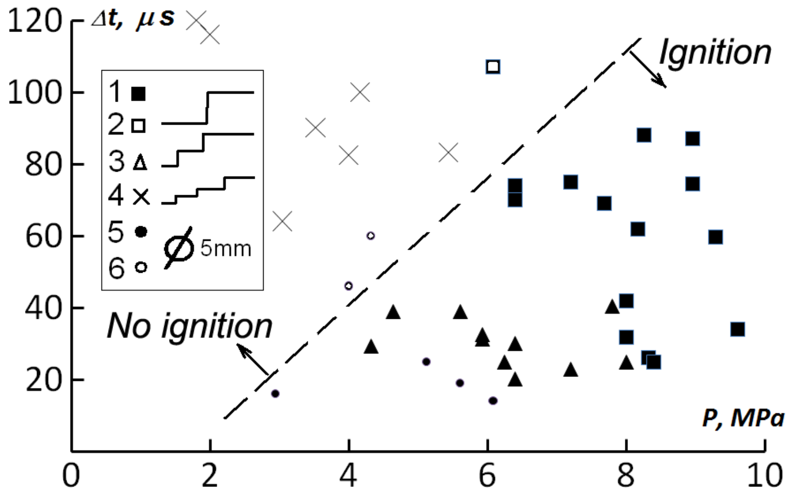

Figure 3. Map of self-ignition / no self-ignition of hydrogen in dependence on duration of diaphragm rupture and initial pressure of hydrogen. *1* – one-stage shock wave formation in 18 mm channel, ignition, *2* – no ignition in 18 mm (in diameter) channel; *3* – two-stage shock wave formation in 18 mm channel, ignition; *4* – three-stage shock wave formation in 18 mm channel, no ignition; *5* – ignition in 5 mm (in diameter) channel; *6* – no ignition in 5 mm channel.

Due to this the speed of releasing hydrogen is non-uniform in cross section of the channel. Finite rate of the opening led to the fact that a system of shock waves appeared in the channel, rather than a single shock wave. Also, as a result of the prolonged opening of the diaphragm the contact surface can be smeared.

For example, at the initial pressure P_0 = 6.3 MPa the diaphragm with a thickness of δ = 0,2 mm was used. The time of the rupture Δt was 73 μs. In this case the distance of the formation of the incident shock wave in the channel was 43 mm (2.4 tube diameters). Readings of pressure transducers and photodiodes in channel are presented on Fig. 4. First pressure transducer didn't register a shock wave, but the second one registered the shock wave. Readings of the photomultiplier tube corresponded to area of breaking of the diaphragm.

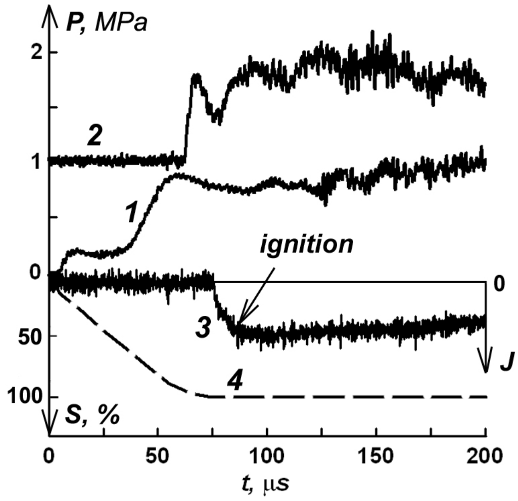

Figure 4. Shock wave formation in the channel of 18 mm in diameter. *1*,*2* – pressure readings (*P*, MPa) in the channel at the distances of 10 and 50 mm from the diaphragm, *3* – photodiode readings (*J*, u.r.) of hydrogen self-ignition behind the shock wave, *4* – photomultiplier tube readings (*S*, *%*) of opening of the diaphragm.

Three basic ways of formation of the shock wave were determined: single-step, two-step and three-step. Single step: only one front of shock wave was observed in the channel. Two step: two consecutive fronts of the wave was observed. Three step: three and more fronts of wave were generated in the channel. For each way the possibility of self-ignition is considered on Fig. 3.

4 Ignition delays in the channel

In the present work the ignition delays of hydrogen τ were determined relative to the moment of formation of the shock wave after opening of the diaphragm. The moment of self-ignition of hydrogen in the channels was registered by photodiodes and by the photomultiplier tube. The error in the determination of the ignition delays of hydrogen did not exceed 15%. Ignition delays were determined as a function of the initial pressure and the temperature behind the shock wave.

Since the ignition of hydrogen occurred after the formation of a shock wave, the motion of gases can be considered as one-dimensional at the distances, which exceed the distance of the formation of shock wave. Therefore the temperatures *T* of gas behind the incident shock wave were calculated in the approximation of ideal gas. A relative error in the determination of the temperature did not exceed 10%.

Ignition of hydrogen occurred if temperature at the contact surface with air is not lower than auto-ignition temperature during the period exceeding an induction period. Therefore in short channels self-ignition did not have time to arise.

Fig. 5 (left) presents the experimentally determined ignition delays depending on the initial pressure of hydrogen at discharge into the channel of round cross section (*3*) and the channel of rectangular cross section (*2*). Increasing in initial pressure of hydrogen from 3 MPa to 10 MPa leads to decreasing in ignition delay up to 40 μs.

The dependence of the ignition delay on the temperature behind the incident shock wave is represented on Fig. 5 (right). Also, comparison of the obtained results with the previously obtained results of the hydrogen ignition in the preliminarily mixed gases [11,12] behind the reflected shock waves is presented on Fig. 5.

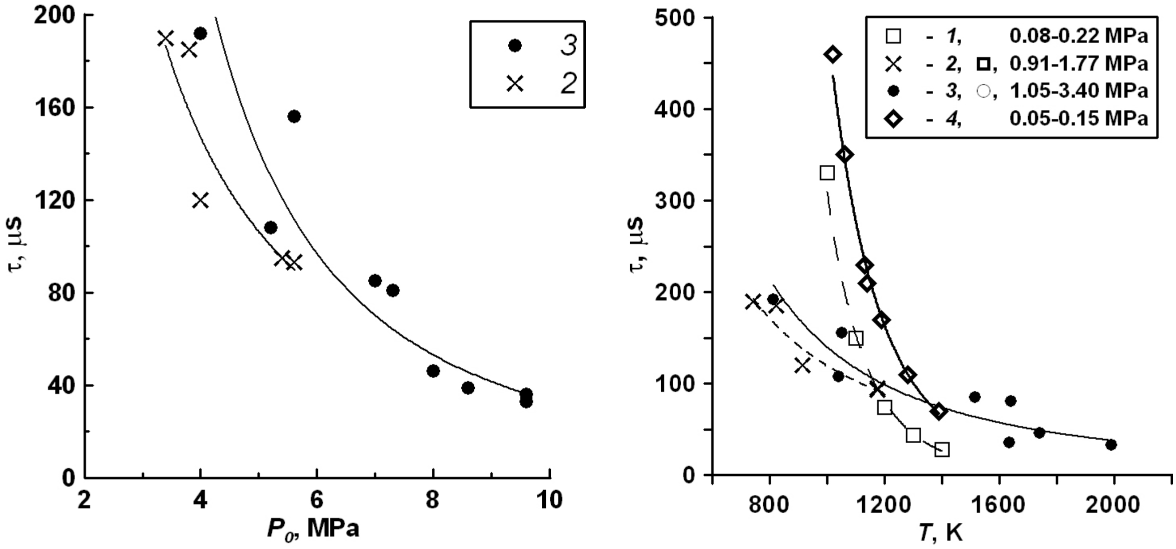

Figure 5. Dependences of self-ignition delays of hydrogen on the initial pressure in the chamber (left) and the temperature behind the shock wave (right): *1*[11], *4*[12] – preliminary mixed mixture (pressures are shown behind the reflected shock wave); *2* – channel with rectangular cross section (pressures are shown behind the incident shock wave); *3* – channel with round cross section (pressures are shown behind the incident shock wave).

It was shown that the dependence of ignition delays on the temperature has exponential character. Ignition delays for the preliminarily mixed gases (dots *1* and *4*) exceed the same for the preliminary unmixed gases (dots *2*-*3*) in the range of temperature 800-1100 K. This difference reached 200 μs. If temperatures behind the waves is 1100-1400 K the difference in ignition delays was not observed.

5 Conclusions

Formation of the shock-wave flow structure at the pulse discharge of compressed hydrogen into the channel with air was studied. The rate of opening of the diaphragm was investigated. In the range of initial pressures of hydrogen 2-10 MPa the durations of the opening of diaphragms varied from 80 to 12 μs.

Influence of the duration of the opening of the diaphragm on the formation of the shock wave, and as consequence, on the intensity of the shock wave was experimentally studied.

Ignition delays of hydrogen at pressures of more than 1 MPa were determined experimentally at the contact surface with air in dependence of the initial pressure and in dependence of temperature at the contact surface. It was shown that the ignition delay can be decreased up to 40 μs behind the shock wave.

Acknowledgments

This work was supported by Rosnauka MK-872.2010.8and RFBR 10-08-00214-a. Authors thank BIFO Company for help in high speed video registration.

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