EXPERIMENTAL RESEARCH ON INFLUENCE OF GEOMETRICAL CONFIGURATION ON HIGH PRESSURE HYDROGEN OUTFLOW IGNITION PROCESS

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Abstract

Hydrogen is regarded as a potential future fuel for various kinds of vehicles: fuel cell cars, trucks, buses etc. Storing and transportation issues are the crucial safety problems concerned with utilization of hydrogen. Because of its very low density hydrogen needs to be stored under very high pressure, in range of 35÷70 MPa, and this create hazard of sudden discharge of hydrogen leading to ignition and severe accident.

The aim of the presented research is an experimental investigation of hydrogen ignition as a result of a compression and heating of air by shock wave generated by the discharge of the hydrogen. Mixing of the air heated up by the shock wave and expanding hydrogen can produce combustible mixture of sufficiently high temperature and can lead to ignition. The critical conditions for ignition depend mainly on hydrogen discharge pressure, geometrical configuration, parameters of the ambient air, obstacles, etc.

Experimental research was conducted on a facility specially constructed in Combustion Laboratory, the Institute of Heat Engineering, Warsaw University of Technology. The facility consists from the pressure tank and high pressure hydrogen installation. To allow visualization the observation section is equipped with high quality optical windows. Schlieren visualization system and high speed digital camera was used to register high pressure hydrogen outflow and potential ignition. The high speed digital camera was used to take Schlieren or direct pictures of the process. Additionally, the experiment is registered with use of conventional digital camera. Experiments were conducted for different discharge pressure of hydrogen and outflow to "open space" as well to specially prepared obstacles. Critical condition for which ignition occurs were evaluated for both cases.

The high speed Schlieren and direct pictures taken during the experiments are presented in the paper. The influence of presence of obstacles on the feasibility of hydrogen ignition during outflow from high pressure installation is discussed and analyzed.

Keywords: *propulsion, safety, hydrogen, ignition, visual registration*

1. Introduction

The first investigations concerned with a problem of high pressure hydrogen outflow ignition were carried out nearly 40 years ago by Wolański and Wójcicki. The main reason of the research was a tragic accident in Chorzów Chemical Plant „Azoty”. During the investigation it was found that the ignition was initiated by hot air, heated by the shock wave created by outflowing hydrogen-nitrogen mixture from high pressure installation of ammonia synthesis.

At present, hydrogen is regarded as a one of future fuels which potentially will replace gasoline and other conventional fuels. Research centers of many automotive companies conduct tests of prototype vehicles equipped with hydrogen installations. The prototypes are driven electric engines powered by fuel cells. Such system is considered by many as a future driving system for cars.

Storing and transportation are crucial safety problems concerned with utilization of hydrogen as a vehicle fuel. Because of its low density in gas phase hydrogen needs to be stored under very high pressure or in liquid state. The latter storage system is much more complex and expensive, so the former one probably will be more commonly utilized in vehicles. It is predicted that vehicle hydrogen tank pressure will be equal to 35, 70 or even 100 MPa, what generates a risk of sudden discharge of hydrogen leading to ignition and severe accident. In this paper experimental investigation of hydrogen ignition during outflow from high pressure installation will be described.

2. Experimental facility

In Fig. 2.1. scheme of the experimental facility specially constructed to conduct research concerned with high pressure hydrogen outflow ignition is presented. The main elements are high pressure hydrogen container and visualization chamber equipped with two glass windows allowing observation and registration of the hydrogen ignition and flame propagation process. In the research registration of the process can be conducted directly by fast digital camera Photron Fastcam SA1.1, or by use of Schlieren system and utilization of the same fast digital camera. In Fig. 2.2. scheme of the experimental facility and Schlieren system, and in Fig 2.3. view of the experimental facility are presented. Both, the hydrogen container and visualization chamber are equipped with pressure transducers.

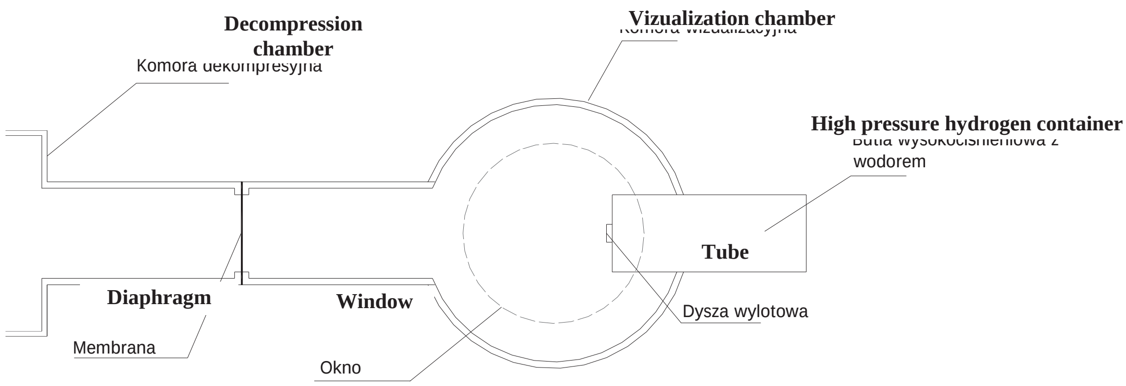
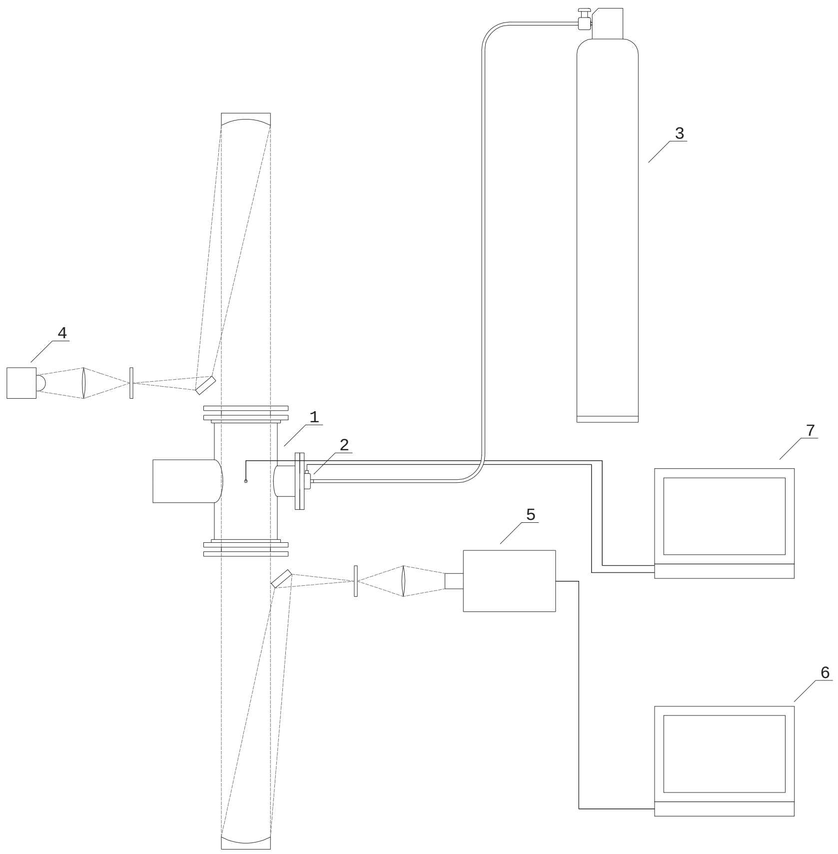


Fig. 2.1. Scheme of the experimental facility

The high pressure hydrogen container is closed by a diaphragm which bursts when desirable pressure inside the container is reached. To the container extension tube can be attached. Various lengths and diameters of the extension tubes were tested during this research. Fig 2.4 presents scheme of the extension tube. In the research tests with flat obstacle located at a distance from the extension tube were also conducted.



1. Visualization chamber
2. Hydrogen injector
3. Hydrogen bottle
4. Light source
5. Digital fast camera
6. Camera data acquisition system
7. Data acquisition system

Fig. 2.2. Scheme of the experimental facility

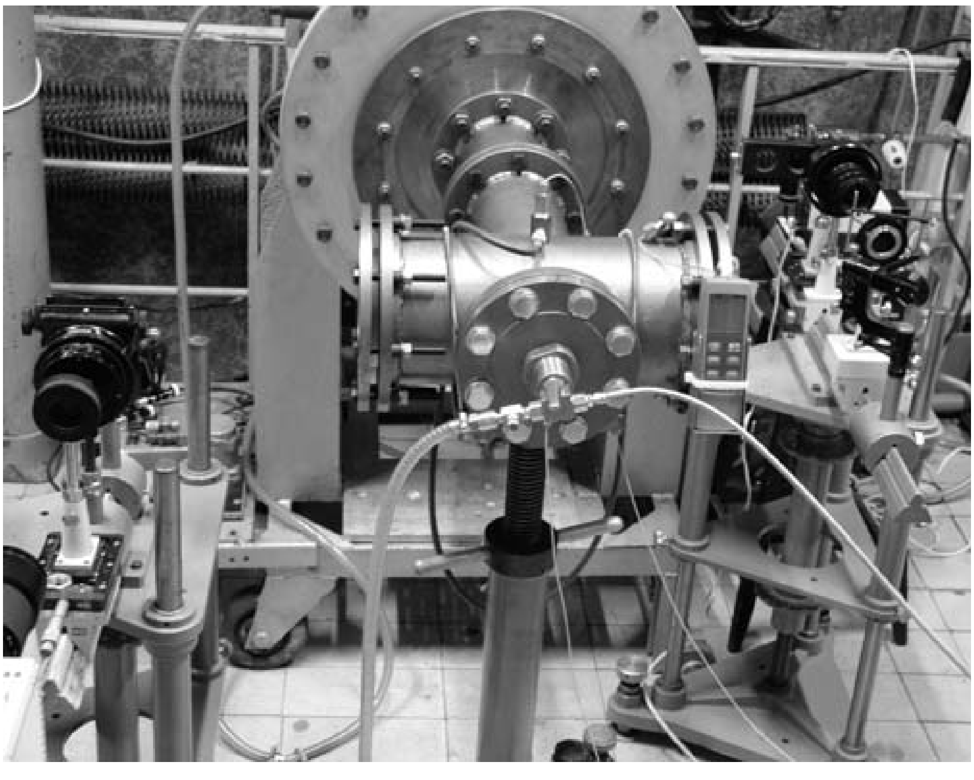


Fig. 2.3. View of the experimental facility

The visualization chamber is separated from decompression chamber by a plastic diaphragm. For safety reason pressure in decompression chamber never exceeds 0.3 bar. Plastic diaphragm (placed between test and expansion chambers) bursts almost immediately after hydrogen outflow and hydrogen, air and combustion products flows out from the visualization chamber. This reduces pressure rise inside the visualization chamber and amount of hydrogen combusted in the test and reduces noise generated by shock wave and hydrogen explosion.

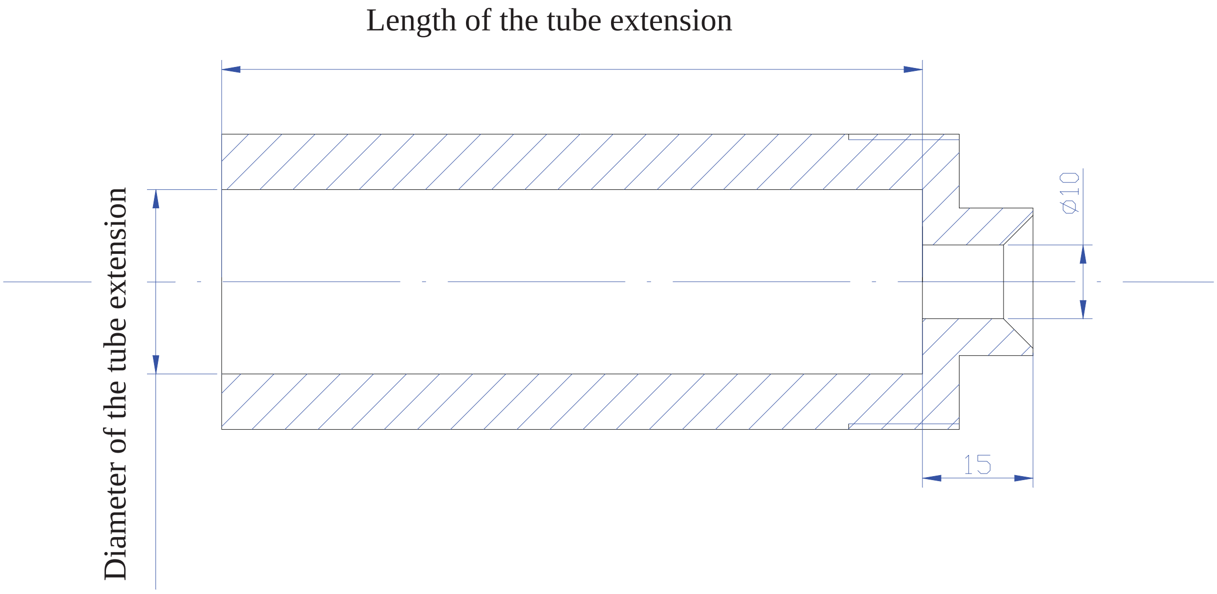


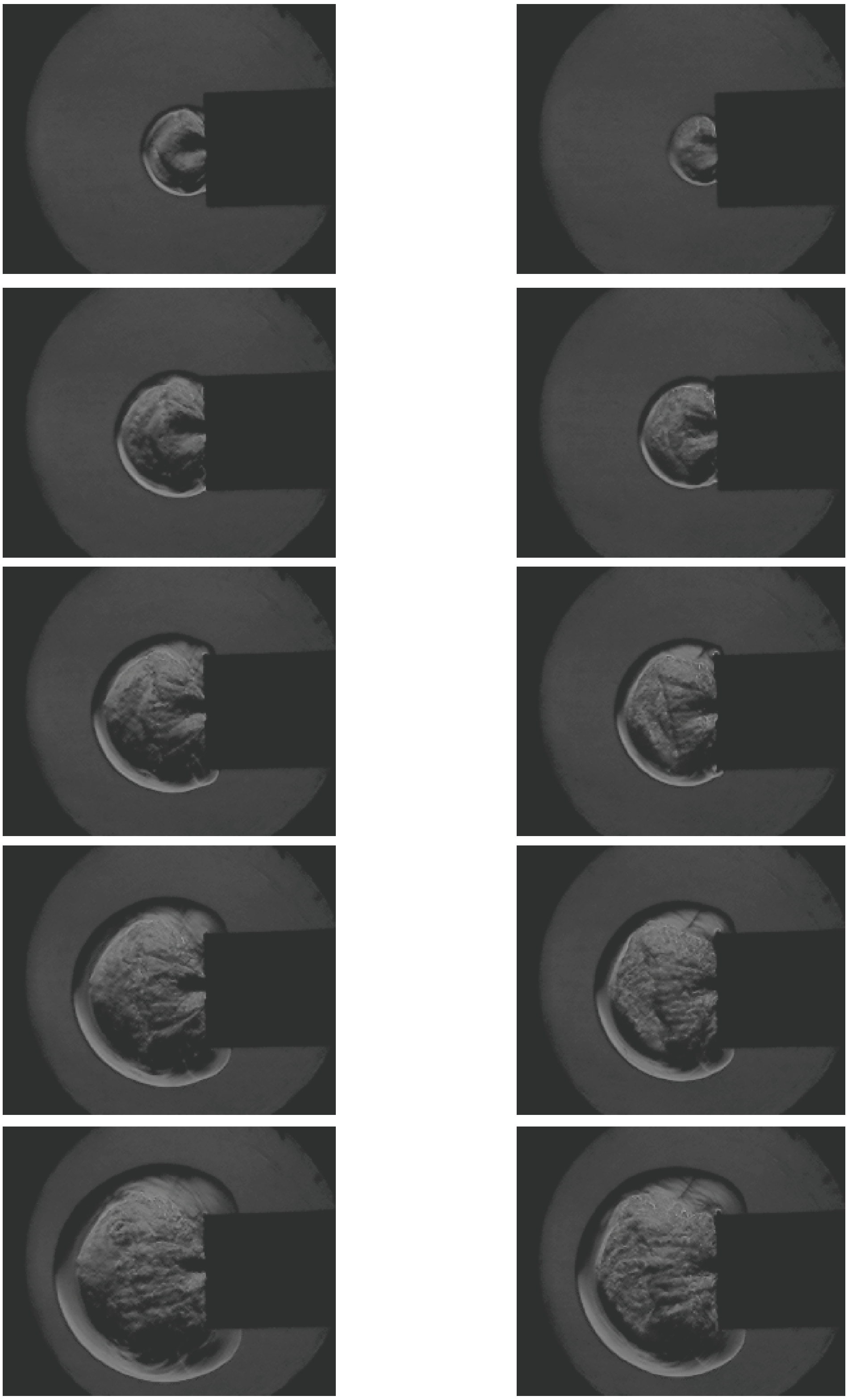
Fig. 2.4. Scheme of the extension tube with dimensions tested in the research

3. Results of the experiments

The first experiments were conducted with registration of hydrogen outflow by use of Schlieren system. Results of two tests conducted with use of the extension tube with length equal to 75 mm and diameter equal to 10 mm are presented in Fig. 3.1. Digital camera settings were: frame rate 80 000 f/s, shutter 1/607 000 s. There was an ignition of hydrogen in the test with initial hydrogen pressure equal to 7.03 MPa and in the test with initial hydrogen pressure equal to 7.14 MPa there was no ignition. Comparison of pictures presenting consecutive phases of the process shows difference between cases with and without ignition. In pictures no 3 for the case with ignition one can see a line located behind contact surface in some distance from the extension tube. In the same phase of the process in the test without the hydrogen outflow ignition the line is not observed. The line can indicate an additional pressure wave generated by the ignition of outflowing hydrogen. Similar waves were recorded in other tests with the hydrogen outflow ignition.

Results of the test conducted with the same geometry of the extension tube and direct registration with use of the fast digital camera are presented in Fig. 3.2. Digital camera settings are: frame rate 80 000 f/s, shutter 1/182 000 s. As it can be seen the ignition took place close to the edge of the extension tube.

Results of the tests conducted with the extension tube with length equal to 50 mm and diameter of extension equal to 10 mm are presented on picture in Fig. 3.3. Digital camera settings were the same as for pictures in Fig.3.1. and initial pressure of hydrogen was equal to 13.7÷13.8 MPa. As can be seen on the presented pictures the line indicating ignition is less visible then in previously presented, but it is observed closer to the extension tube. The difference between cases with and without ignition can be seen on pictures no 2 and 3, closer to the extension tube. It can be explained by shorter delay between outflow of hydrogen from the extension tube and hydrogen ignition for higher hydrogen initial pressure.



1
2
3
4
5

p_{H2} = 7.14 MPa
no ignition

p_{H2} = 7.03 MPa
ignition

Fig. 3.1. Schlieren pictures of the hydrogen outflow, extension tube length 75 mm, extension tube diameter 10mm. Frame rate 80 000 f/s, shutter 1/607 000 s

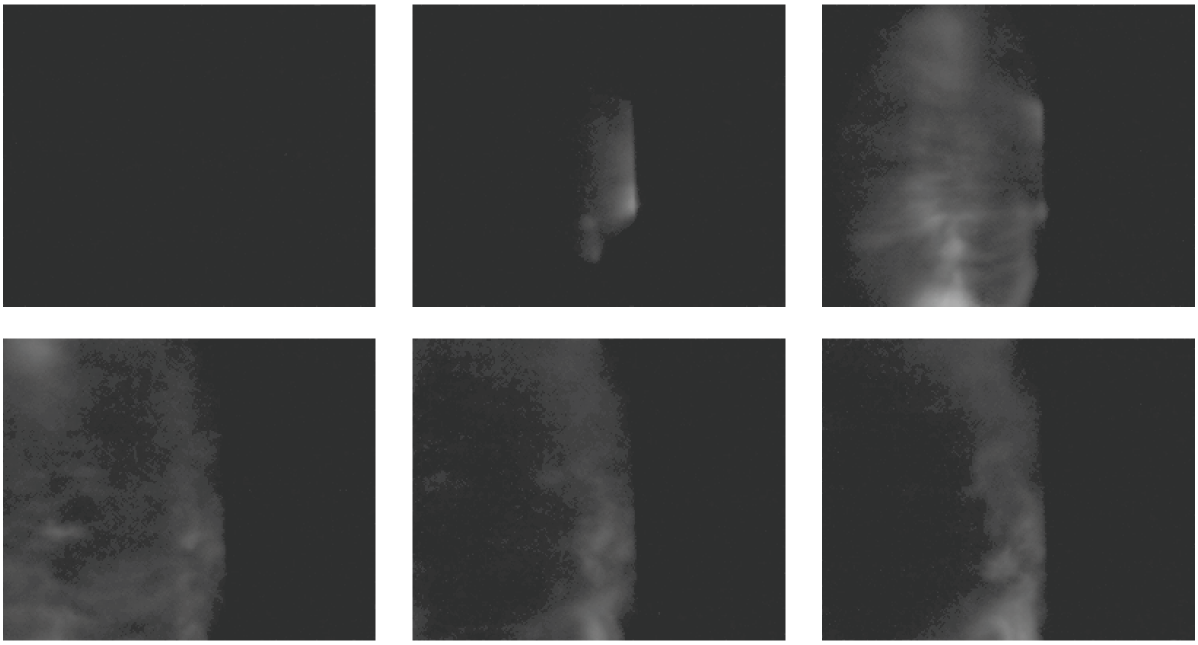


Fig. 3.2. Direct pictures of the hydrogen outflow, extension tube length 75 mm, extension tube diameter 10mm, initial hydrogen pressure equal to 6.8 MPa. Frame rate 80 000 f/s, shutter 1/182 000 s

Pictures in Fig. 3.4. shows consecutive phases of the hydrogen outflow ignition registered directly with the same digital camera settings as in Fig. 3.2. Comparing pictures in Fig 3.4. with pictures in Fig. 3.2. it can be seen, that in the first phase a hydrogen flame is more intense for higher hydrogen pressure and there is no significant differences in further flame propagation.

Graph in Fig. 3.5. presents map of tests conducted with the extension tube diameter equal to 10 mm and various extension tube lengths. During the research in some tests the hydrogen ignition was observed with long delay after burst of the diaphragm closing the hydrogen container. In the presented paper only results of tests with ignition observed on the extension tube just after the burst of the diaphragm are regarded as tests resulted with ignition. Exemplary pictures of the ignition are presented in Fig. 3.2. and Fig. 3.4.

Increase of the extension tube length results with decrease of minimal value of initial hydrogen pressure required for ignition and simultaneously increases probability of ignition. For hydrogen pressure range 7÷12 MPa and the extension tube length equal to 75 mm most of conducted tests resulted with ignition and for shorter extension tube, with length equal to 45 mm only about half of tests conducted with initial pressure of hydrogen in a range 9÷13 MPa resulted with ignition.

Fig. 3.6. presents minimal hydrogen outflow ignition pressure in function of the extension tube length. There is a significant change of the minimal hydrogen outflow ignition pressure between the extension tube length equal to 65 mm and 75 mm. Above and below these two values, change of the tube extension length has much smaller influence on the minimal pressure.

Next graph, presented on Fig. 3.7, shows map of tests conducted with the extension tube length equal to 45 mm and various tube extension diameters. As can be seen on the graph, increase of the diameter of the extension tube has minor influence on minimum hydrogen outflow ignition pressure.

Increase of the extension tube diameter from 10 mm to 25 mm and further to 32 mm significantly decreases probability of hydrogen ignition. For the extension tube diameter equal to 10 mm ignition was obtained in about half of all conducted tests and for diameter equal to 32 mm only one test resulted with hydrogen ignition.

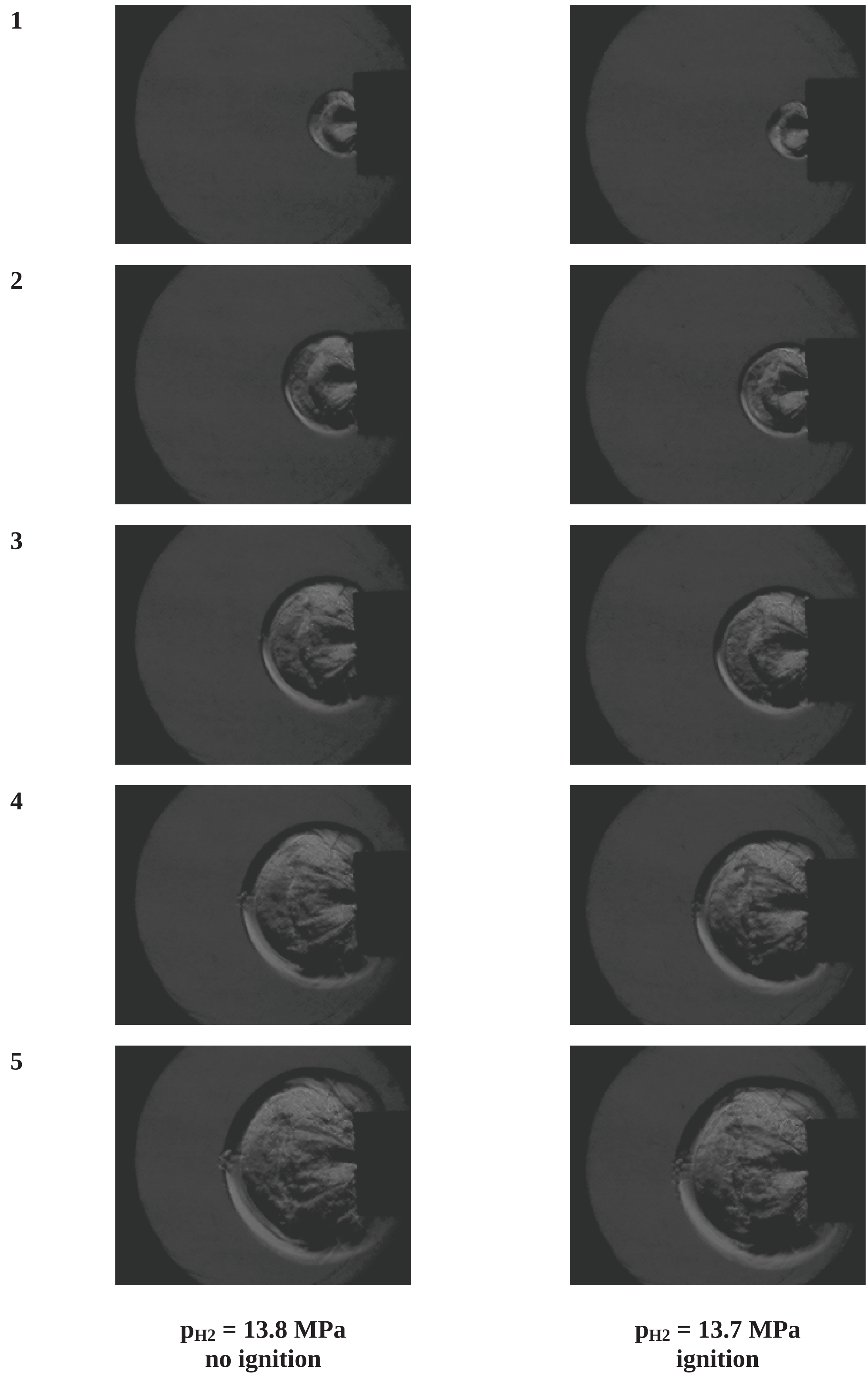


Fig. 3.3. Schlieren pictures of the hydrogen outflow, the extension tube length 45 mm, the extension tube diameter 10mm. Frame rate 80 000 f/s, shutter 1/607 000 s

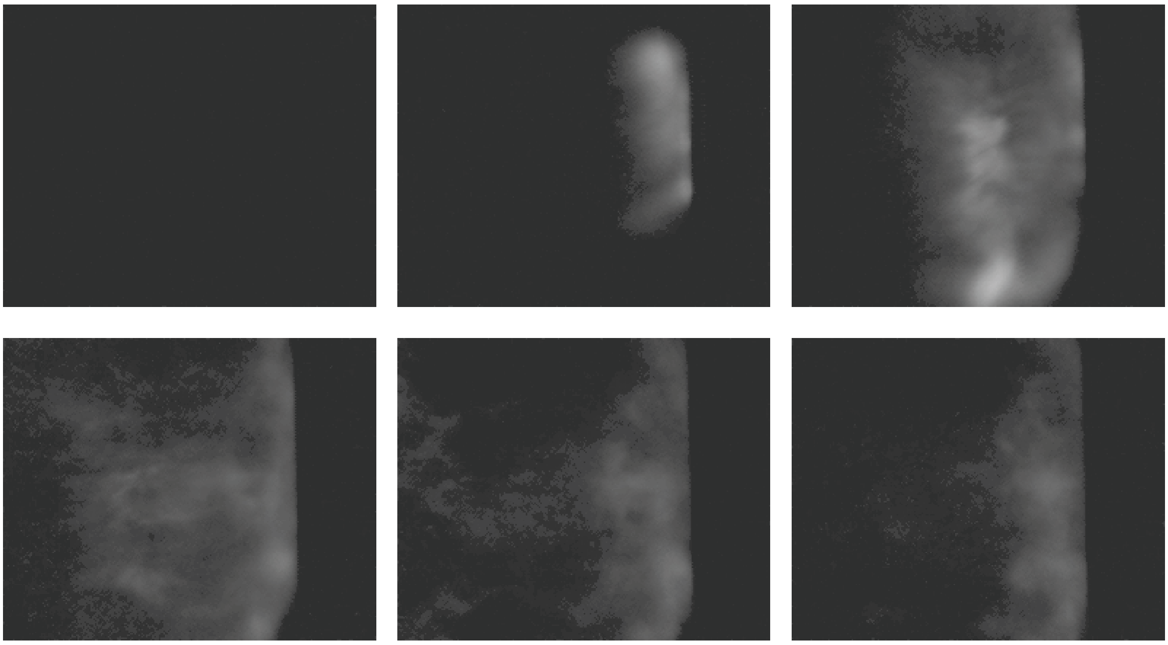


Fig. 3.4. Direct pictures of the hydrogen outflow, the extension tube length 45 mm, the extension tube diameter 10mm, initial hydrogen pressure equal to 13.8 MPa. Frame rate 80 000 f/s, shutter 1/182 000 s

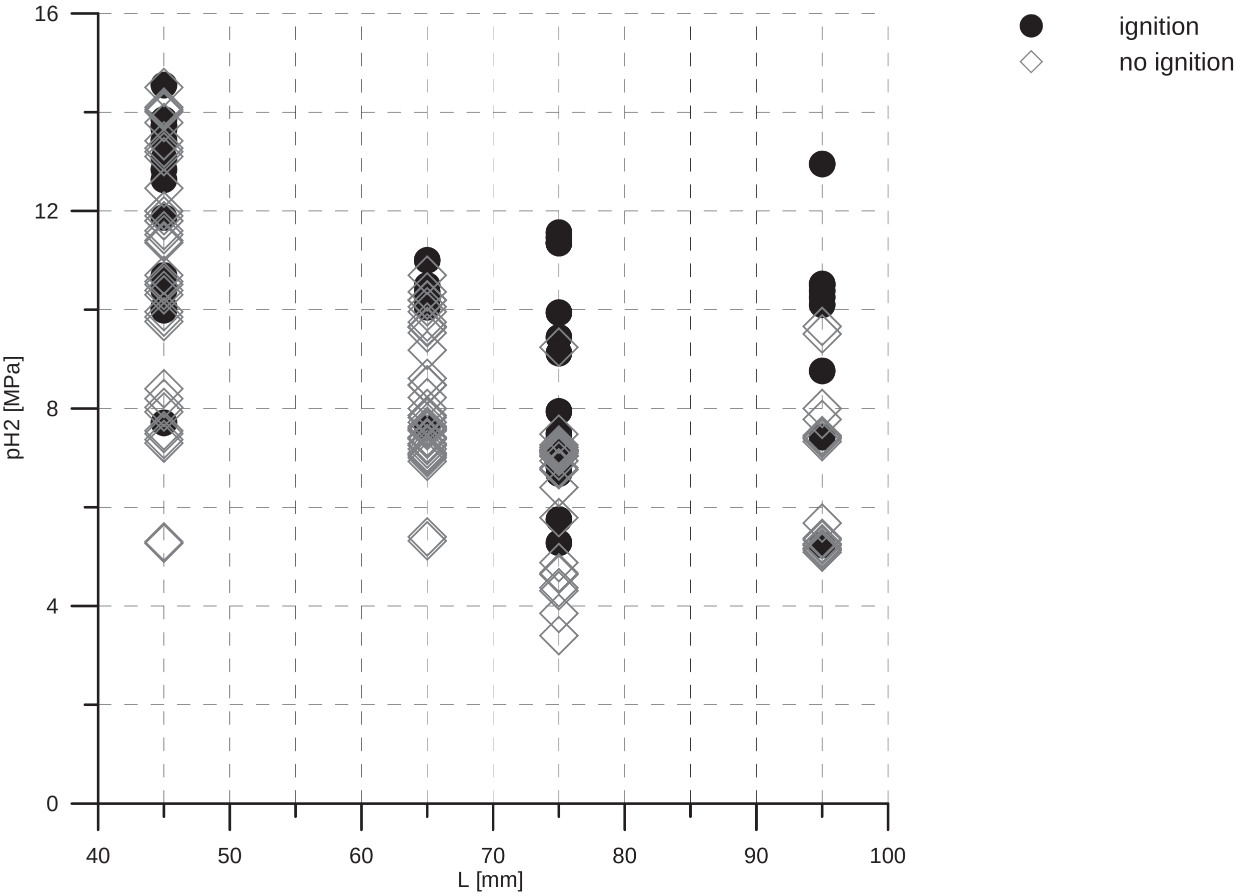


Fig. 3.5. Results of the test as a function of initial hydrogen pressure p_{H2} and the extension tube length. The extension tube diameter equal to 10 mm

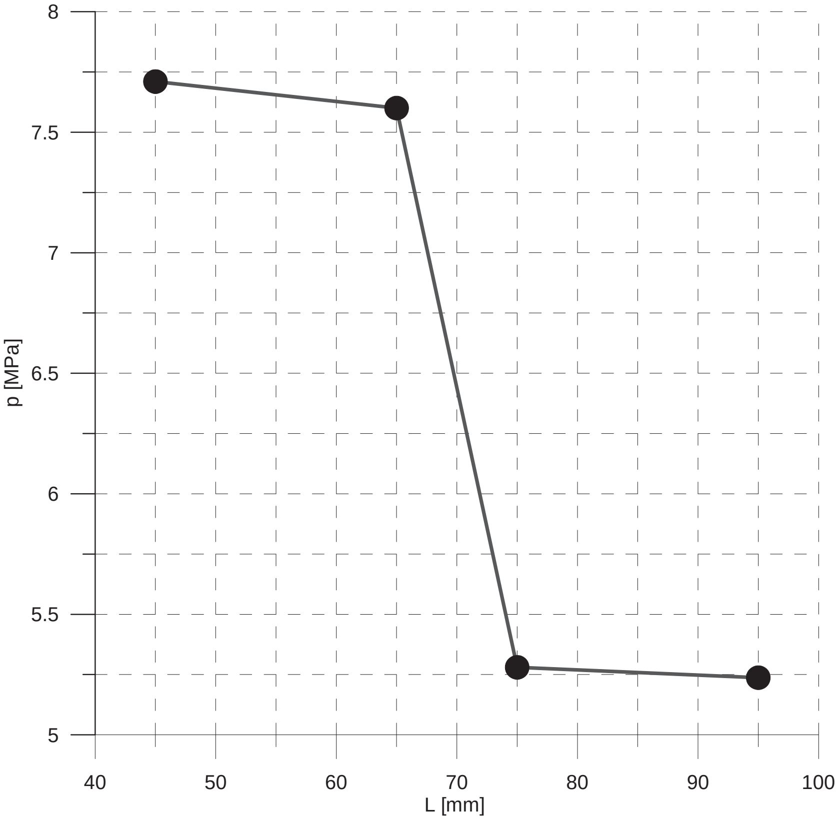


Fig. 3.6. Minimal hydrogen outflow ignition pressure as a function of length of the extension tube. The extension tube diameter equal to 10 mm

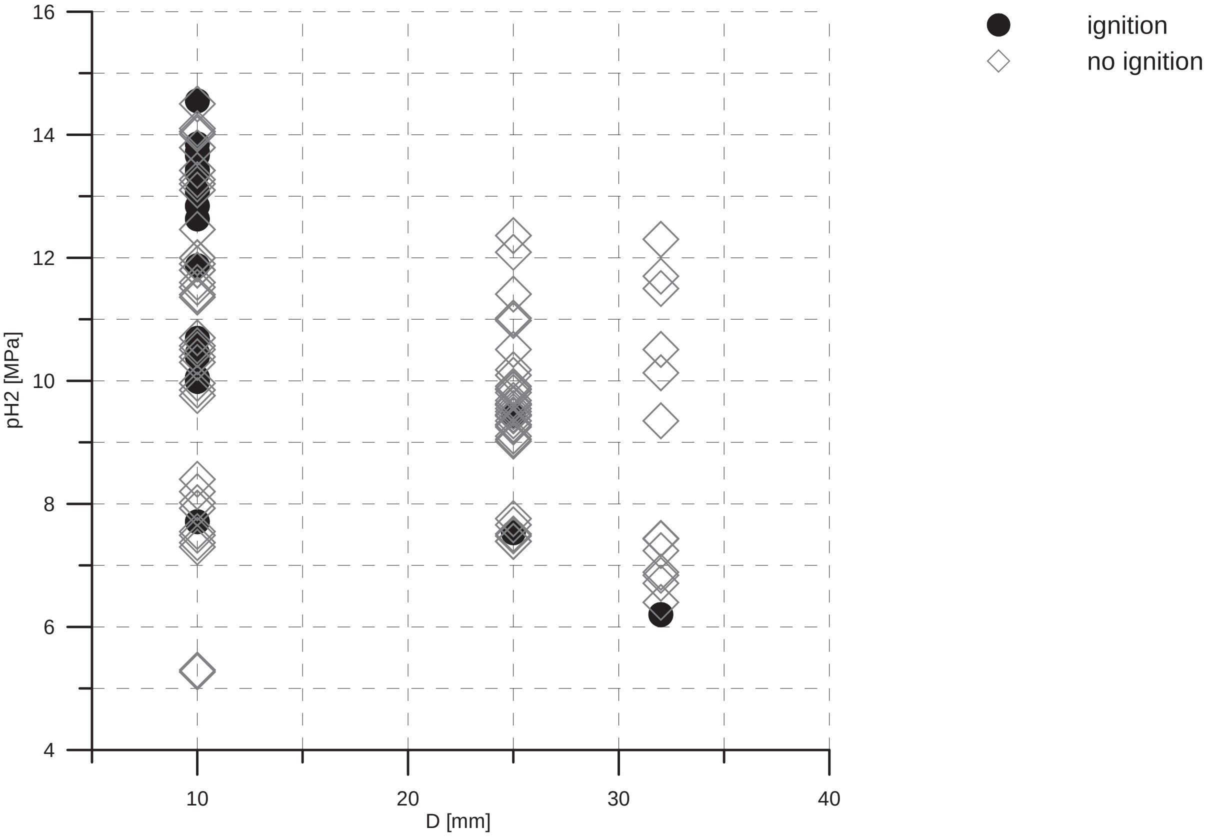


Fig. 3.7. Results of the test as a function of initial hydrogen pressure p_{H2} and the extension tube diameter. The extension tube length equal to 45 mm

4. Conclusions

From conducted experiments the following conclusions can be stated:

- Hydrogen ignition takes place behind the contact surface of the wave generated by hydrogen outflowing from high pressure installation, due to mixing of air heated by created shock wave with expanding hydrogen.
- On Schlieren pictures ignition is indicated by the presence of additional wave located behind contact surface.
- Geometry of the extension tube significantly influences ignition process during outflow of the high pressure hydrogen. For increased length of the extension tube value of the minimal pressure required for ignition decreases.
- The extension tube diameter has less significant effect on ignition parameters then the length of the tube.

Ignition process shows stochastic behavior, since it depends very much on random processes associated with opening of the diaphragm (membrane), so more research is necessary to explain complicated nature of this phenomenon.

5. References

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