Effects of the pore size on hydrogen–air detonation propagation in the channel with porous walls

G Yu Bivol, S V Golovastov and V V Golub
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: grigorij-bivol@yandex.ru

Abstract. We considered the problem of detonation suppression and weakening of the blast wave effects occurring during the combustion of hydrogen–air mixtures in the confined spaces. Detonation decay in hydrogen–air mixture was experimentally investigated in rectangular cross-section channels with four types of foam polyurethane with a number of pores per inch ranging from 10 to 80. Shock wave pressure dynamics inside the section with porous coating were studied using pressure sensors. For all mixtures, the detonation wave was formed before entering the section with porous coating. The number of pores per inch was found to significantly affect the detonation wave parameters. Non-monotonic evolution of the shock wave pressure and velocity was discovered while using porous materials with bigger pores. By the end of the porous section, the shock wave pressure in porous material with 10 pores per inch was 100% higher compared to polyurethane with 80 pores per inch. The evolution of the shock wave pressure and velocity along the porous section for different types of porous material is presented.

1. Introduction
Hydrogen is the most promising environmentally friendly fuel because of the absence of harmful emissions from its combustion. However, its use is associated with the danger of an explosion. Hydrogen is a light gas that can quickly fill open spaces. On the other hand, its molecular-kinetic properties allow it to ignite in very wide concentration limits. This fact limits the widespread use of hydrogen and requires a detailed study of the dynamics of its combustion, as well as methods of suppressing the explosion. The dynamics of the detonation wave and its intensity depend strongly on the presence of absorbing coatings on the channel walls [1–7]. The presence of the porous material in the channel can also change the mechanism of flame propagation [8]. It is assumed that the main mechanisms of detonation decay are the disappearance of transverse waves, heat loss in a porous medium, and expansion of the flame front [9]. Most of the existing work on detonation suppression used low pressure combustible mixtures (less than 0.1 MPa) diluted with inert gases (argon, etc). But for the practical use of porous materials, it is necessary to get information on the detonation attenuation in undiluted mixtures of atmospheric pressure.

Previously, the degree of detonation attenuation as a function of the mixture composition [10] and the thickness of the porous coating [11] was studied. The effect of the pore size on the propagation of slow combustion was studied in [12,13] and it was found that the pore size can significantly affect the dynamics of the slow flame. However, the dependence of the degree of attenuation of the detonation wave on the parameters of the porous material was not obtained. The aim of this work was to study the influence of such parameters of a porous material as the
pore size on the propagation of a detonation wave in a mixture of hydrogen and air in tangential propagation.

2. Experimental setup
Figure 1 illustrates the scheme of the setup. Experiments were carried out in a channel consisted of two sections: a cylindrical section of 2000 mm long with an inner diameter of 20 mm and a rectangular section with a length of 500 mm open to the atmosphere. The top and bottom walls of the rectangular section were covered with polyurethane foam. The hydrogen–air mixture was fed in at the closed end of the cylindrical detonation tube. The spark gap was also located at the closed end of the detonation tube. The stationary detonation wave was formed before the rectangular section.

The width of the transparent glass window was 40 mm and the width of the steel side was 20 mm. To study the propagation of the detonation in the channel with porous walls, two types of porous coatings were inserted into the channel so that the cross-sectional dimensions were also $20 \times 20$ mm$^2$. So the thickness of the porous surface was 10 mm. Several types of porous coatings were used in the work: porous polyurethane foam with an amount of pores per inch (PPI) in the range of 10 to 80 was used, with a density ranging from 28 to 35 kg/m$^3$. To determine the attenuation of the detonation wave, four pressure sensors manufactured by PCB (111A, 113B) were inserted into the sidewall. The distance between sensors was 100 mm. The first three sensors were placed 60 mm from the entrance of the porous section. The time measurement error of the sensors was less than 1 µs. The hydrogen–air mixture was held in a vessel with a volume of 3 litres at a maximum pressure of 0.5 MPa. Before each experiment, the detonation
tube was filled with a hydrogen–air mixture at the atmospheric pressure and a temperature of 295 K. The equivalence ratio was equal to 1 (stoichiometric mixture). Immediately after filling the detonation tube, the mixture was ignited to form the detonation.

3. Experimental results and discussion

Figures 2 and 3 show pressure oscillograms of the detonation propagation in a channel with porous materials on the wall, the number of pores per inch is 10 and 80, respectively. It can be seen that when using a coating with a small pore size (PPI = 80), the shock wave pressure is 1.1 MPa at the first sensor, located at a distance of 60 mm (3 channel widths) from the beginning of the porous section, and then drops to 0.6 MPa. The wave profile is a profile of a plane shock wave already on the second sensor. When using polyurethane foam with a large pore size (PPI = 10), the pressure on the first sensor is 1.4 MPa, then it falls to 1 MPa on the second pressure sensor and increases to 1.3 MPa at the last one. In this case, the pressure profile at the last sensor is detonation. This indicates the reinitiation of detonation takes place when using this coating.

The pressure evolution for porous materials with different pore sizes is shown in figure 4. The pressure at the first sensor was in the range 1–1.4 MPa for all porous materials, with the highest

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**Figure 2.** Evolution of the pressure of the shock wave during the detonation motion along the channel with the polyurethane foam with PPI = 10 on the wall. Hydrogen–air mixture, ER = 1.
Figure 3. Evolution of the pressure of the shock wave during the detonation motion along the channel with the polyurethane foam with PPI = 80 on the wall. Hydrogen–air mixture, ER = 1.

pressure in the porous material with large pores. The final pressure showed a direct dependence of the pressure on the pore size: the lowest pressure was observed when using polyurethane foam with PPI = 40 and PPI = 80 (about 0.6 MPa), the largest when using polyurethane foam with PPI = 10 (1.3 MPa). It is important to note that in the case of polyurethane foam with PPI = 40 and PPI = 80, a monotonic pressure drop was observed, while in larger types of polyurethane foam a pressure minimum at the distance of 160 mm (8 channel widths) from the beginning of the porous section is observed, followed by a pressure increase.

The evolution of the velocity of the shock wave is shown in figure 5. Similarly to the pressure dependence on the pore size, the highest wave velocity was observed in polyurethane foam with PPI = 10. The initial velocity was 1.15 km/s, the final velocity was 1.25 km/s. As the pore size decreases, the wave propagation velocity also decreases: for the polyurethane foam with PPI = 80, the final speed is 0.9 km/s, which is less than half of the Chapman–Jouguet velocity (1.95 km/s). Similarly to the amplitude of the shock wave, in the case of a polyurethane foam with PPI = 10 and 20, the increase in propagation velocity of the wave after the initial decrease is observed. In foam with PPI = 40 and 80 shock wave velocity decreases monotonically. In the porous material with 80 pores per inch slight pressure decrease is observed on the last sensor, yet the wave velocity increases. Mean wave velocity readings were calculated between pressure
Figure 4. Evolution of the detonation wave pressure during propagation along a porous material with different number of PPI. Hydrogen–air mixture, ER = 1.

sensors, thus the pressure and velocity values are given for different coordinates along the length: pressure readings are given for the location of the sensors, and the velocity readings are located between the sensors. The growth of the velocity of a wave in the foam with smallest pores is less than the measurement error. Taking into account the fact that the decay of the detonation wave is a nonstationary process, such oscillations of velocity and pressure are possible.

One of the main mechanisms of the attenuation and decay of a detonation wave is the dying-out of transverse waves because of their scattering in a porous material. In the case of using a porous material with large pores, the transverse waves pass through the porous material without attenuation and are reflected from the solid wall, this allows the detonation wave to be re-initiated. The pore size affects the unobstructed light path length, that is, the distance that light can pass (and therefore the wave) without encountering any obstacles on the way. For foam with PPI = 20 and 40 this distance is 5 and 2.5 mm, respectively [14]. For the foam with PPI = 80 this distance is less than 1 mm, for foam with PPI = 10 this distance is more than 10 mm, which corresponds to the thickness of the porous material in this experiment. This allows the transverse waves to pass through the porous material without attenuation, reflect from the rigid wall and affect the propagation of the detonation front. In the porous material with smallest pores the transverse waves experience multiple reflections and thus slow down and
Figure 5. Evolution of the detonation wave velocity during propagation along a porous material with different number of PPI. Hydrogen–air mixture, ER = 1.

get weakened. A weakened reflected wave leaves the porous material with a delay and can no longer sustain detonation combustion. This is why we observe a flat shock front in the case of polyurethane foam with small pores and a detonation profile in the case of porous material with large pores.

For porous materials where a monotonic pressure drop (40 and 80 pores per inch) is observed, the pressure impulse also drops, for at least 300 µs, after which steady-state pressure is observed. For porous materials, where detonation is reinitiated toward the end of the porous channel (10 and 20 pores per inch), the growth of the pressure impulse is also observed. The pressure impulse after 300 µs after the front on the first pressure sensor was 237, 190, 178 and 150 Pa s for the porous material with 10, 20, 40 and 80 pores per inch, respectively. The pressure impulse after 300 µs after the front at the last pressure sensor was 220, 180, 140 and 128 Pa s for the porous material with 10, 20, 40 and 80 pores per inch, respectively.

The drop in velocity and pressure at a distance from 60 to 160 mm can be explained by the detonation wave entering the section with a porous coating. When a detonation wave enters the porous section, the transverse waves travel a greater distance to the rigid wall and do not affect combustion at the initial moment. With further propagation of the wave along a porous section with large pores (PPI = 0–20), the reflected transverse waves return to the reaction zone, so we
see an increase in pressure and velocity. With an increase in the length of the channel, it can be expected that the wave parameters will return to detonation in the case of porous materials with large pores.

4. Conclusion
The process of the detonation propagation in the channel with porous coating on the walls was experimentally studied. A non-monotonic influence of the parameters of the porous coating on the evolution of the detonation wave in the channel was observed. When a porous material with large pores (PPI = 10 and 20) is used, the pressure and wave velocity decrease first, after which the pressure and velocity of the wave increase over a distance of more than 300 mm (15 channel widths) from the beginning of the porous section. When the wave propagates in a polyurethane foam with small pores (PPI = 40 and 80), a monotonic decrease in pressure is observed. The final pressure in polyurethane foam with PPI = 10 is twice as high as in polyurethane foam with PPI = 80, and the final velocity is 40% higher. Such a large difference in the parameters of the detonation wave can be explained by the weakening of the transverse waves in the foam with PPI = 40 and 80, while in the foam with PPI = 10 and 20 the transverse waves pass through the porous material without attenuation, are reflected from the solid wall and support detonation combustion in the channel.

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