Attenuation of the detonation wave in hydrogen–air mixture

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Abstract. The deceleration and attenuation of a detonation wave in hydrogen–air mixture was experimentally studied in a cylindrical channel. Inner walls of the wide section of the channel were covered with an acoustically absorbing layer. Experiments were carried out in hydrogen–air mixture at atmospheric pressure. Initially detonation was formed as a result of a deflagration to detonation transition. The dependence of velocity and pressure at the front of the detonation or shock wave on the thickness of the acoustically absorbing material and mixture composition (equivalence ratio) was presented. The results demonstrate that increasing the thickness of the porous material on the walls lead to further attenuation of the detonation wave to the point where it is not re-initiated at the distance of 15 calibers from the porous section. It was found that the recovery of the detonation wave after the passage of the acoustically absorbing section can happen if the shock wave velocity does not drop below Chapman–Jouguet acoustic velocity.

1. Introduction
Ensuring hydrogen safety at industrial sites is one of the most important goals in the field of hydrogen energy. When analyzing the explosion all the features of hydrogen combustion in closed volumes must be taken into account. The most relevant method of preventing or attenuating the detonation is chemically active inhibitors [1] or special elements like channel obstructions [2] or porous coating on the wall [3] that can weaken the intensity of the shock or detonation wave. Since the detonation wave has a cellular structure, one of the ways to prevent the detonation could be the use of particular forms of coating, to diminish the intensity of transverse perturbations. The first time porous wall effect on detonation was considered in [4]. Due to the porous covering of the walls it was able to double the deflagration to detonation transition distance. Noticeably later the effect of walls on the already formed detonation wave was investigated with the help of high-speed photography, and it was shown that the decomposition of the detonation is due to the suppression of the transverse waves on the front of the detonation wave [5]. This fact was confirmed in the [6], by analyzing the Schlieren images. Effect of porous coatings on the walls increases in tubes of a critical diameter for detonation propagation [3]. Subsequently, various devices to suppress detonation were compared [7]. It was found that the metal wool is much more effective detonation suppressor than the perforated plates. However, in the work [8] the authors have suggested that the weakening of the detonation due to the disappearance of the transverse wave occurs only for a detonation mixture with irregular structure. While the detonation weakening in mixtures with a regular cellular structure occurs for other reasons, namely due to the mass divergence into the porous section. More
details on this question have been studied in [9] where the authors considered the detonation transition from the tube into the open space. In published comparisons of different devices used for detonation suppressing the diluted mixtures of hydrogen or hydrocarbons with oxygen at low pressure were usually used. It does not quite meet the conditions of the possible applications of such structures to prevent or at least mitigate the detonation in hydrogen–air. Also, the effect of the thickness of the absorbing material at a constant inner diameter of the channel has not been studied. It is known, that sudden change in channel diameter can lead to detonation decay [10]. But it requires certain conditions for channel diameter and recovery of detonation wave is possible after sudden expansion [11]. The goal of this work was to determine the parameters of the hydrogen–air detonation wave in channels with acoustically-absorbing coatings with open pores. The parameters were determined in dependence on the hydrogen concentration and the thickness of the absorbing layer. Also, the goal of the investigation was to determine the conditions for recovery of the detonation after the passage of the absorbing section.

2. Experimental setup

Experiments were carried out in a steel tube of circular cross section. Figure 1 shows the scheme of the setup. The inner pipe diameter was 20 mm and the length was 2000 mm. The hydrogen–air mixture was fed to the closed end of the detonation tube. The spark gap was also located at the closed end of the detonation tube. The second end of the detonation tube was opened. The energy released in the spark did not exceed 0.1 J, which is significantly less than the energy of the direct initiation of detonation. The transition from deflagration to detonation took place in the detonation tube.

At a distance of 2000 mm from the closed end of the detonation tube a steel section with an inner acoustically-absorbing layer on the walls was placed. The stationary detonation wave was formed before the absorbing section. Absorbing section length was equal to 500 mm. A set of the sections with different inner diameters (20, 26, 30, 40 mm) was used. The entire inner surface of the section was covered with acoustically absorbing material. The coating thickness was selected so that the inner diameter of the channel was 20 mm. To determine the attenuation of the detonation wave two pairs of pressure sensors by PCB (111A, 113B) were used, installed before and after the acoustically absorbing section. Location of the pressure sensors is shown...
Figure 2. Signals from pressure sensors and photodiodes before and after the absorbing section for three thicknesses of the absorbing material: 3 mm (a), 5 mm (b) and 10 mm (c). Lean (ER = 0.8) hydrogen–air mixture. Dashed line—photodiodes readings; solid line—pressure readings.

3. Experimental results. Discussion

Results are shown in figures 2, 3 and 4 for lean (ER = 0.8), stoichiometric (ER =1) and rich (ER = 1.5) hydrogen–air mixtures for three thicknesses of the absorbing material: 3 mm, 5 mm and 10 mm. In all three cases, at the entrance of the absorbing section the sensors detected the stationary detonation wave. A velocity of the wave was equal to 2000–2200 m/s, the von Neumann peak pressure was equal to 2.5–4 MPa (solid line) for all mixtures. The flame front was registered simultaneously with the shock wave (dashed line). After passing through the absorbing section the parameters of the waves were decreased. Figure 2 shows the signals from pressure sensors and photodiodes installed before the section with acoustically absorbing material and after the section for ER = 0.8.

For all mixtures the level of attenuation of velocity and pressure corresponds with the absorbing layer thickness.

In case of stoichiometric mixture (figure 3) the detonation decay with recovery happens using the absorbing layer of 5 mm thickness and decay without recovery happens using the layer of 10 mm thickness. When the thickness of the absorbing material was 3 mm the velocity of the shock wave was equal to 2000 m/s, as figure 3a shows. The flame front was detected simultaneously with the shock front.

When the thickness of the absorbing material was 5 mm the velocity of the shock wave was equal to 1450 m/s, as figure 3b shows. The photodiode at a distance of 100 mm from the absorbing section registered a 50 µs delay between the shock wave and flame front. However, at the last position of the pressure sensor and photodiode (at the distance of 300 mm from the absorbing section) the delay was reduced to 10 µs. Moreover, the intensity of the shock wave was increased up to 0.8 of the Chapman–Jouguet pressure. It can lead to a recovery of the detonation wave.

When the thickness of the absorbing material was 10 mm the average velocity of the shock wave was equal to 1000 m/s, as figure 3c shows. The photodiode at a distance of 100 mm from
Figure 3. Signals from pressure sensors and photodiodes before and after the absorbing section for three thicknesses of the absorbing material: 3 mm (a), 5 mm (b) and 10 mm (c). Stoichiometric (ER = 1) hydrogen–air mixture. Dashed line—photodiodes readings; solid line—pressure readings.

Figure 4. Signals from pressure sensors and photodiodes before and after the absorbing section for three thicknesses of the absorbing material: 3 mm (a), 5 mm (b) and 10 mm (c). Rich (ER = 1.5) hydrogen–air mixture. Dashed line—photodiodes readings; solid line—pressure readings.

the end of the absorbing section registers a 75 $\mu$s delay between the shock wave pressure and the flame front. Moreover, at the distance of 300 mm from the end of the absorbent section the delay increased to 120 $\mu$s. The delay between the shock wave and the flame front reaches such values at which the recovery of the detonation wave does not occur. In lean hydrogen–air mixture (figure 2) the absorbing layer of 3 mm leads to almost no attenuation of the detonation wave. When the thickness of the absorbing material was 5 mm the shock wave velocity was 1000 m/s. Also a significant delay between a shock wave and a flame front was observed at 100 mm distance from the absorbing section. At the distance of 300 mm from the end of the absorbing section the delay was increased to 100 $\mu$s which means, that the detonation wave decay happened. In lean mixture detonation wave can be significantly attenuated using 5 mm thick absorbing layer.

Finally, in mixture rich with hydrogen (figure 4) significant delay between shock wave and front appears happens using 5 mm, but detonation wave recovers by the time it arrives at the second pressure sensor. Full detonation decay only happens when using 10 mm thick absorbing layer. Thus, the pressure drop of the shock wave after the absorbing section depends on the thickness of the absorbing material.
Figure 5 shows different combustion modes obtained in the experiments in cylindrical channel. Detonation wave was considered decaying if the delay between the shock wave and the flame front increased from the first photodiode to the second (III). Detonation wave was considered reinitiated when the delay between the shock wave and the flame front was observed at the first photodiode (II), but disappeared by the second one. And finally the detonation wave was considered stationary if there was no delay observed between the shock wave and the flame front (I). As we can see, 3 mm thick coating does not lead to detonation decay in any used mixture. 5 mm thick absorbing layer only leads to decay in lean mixture, in stoichiometric and rich mixtures detonation manages to reinitiate itself. And 10 mm thick absorbing layer leads to detonation decay in all mixtures.

The graph on figure 6 summarizes the velocity data for different ER and different absorbing layer thickness. The recovery of the detonation wave is possible when the shock wave velocity is more than 1100 m/s. Three distinct areas are visible: stable detonation (with velocity over 1500 m/s), detonation recovery and decay (with velocities of 1500 m/s and lower). Detonation wave decay is observed at speeds below Chapman–Jouguet acoustic speed. The absence of detonation in rich mixture when using 3 mm thick absorbing layer can be explained by the fact, that the detonation cell in rich mixture becomes bigger, than the channel diameter [12] and detonation wave becomes unstable and easier to attenuate.

When entering a porous section the shock wave spends energy on friction and expansion of the channel due to the compressibility of the porous coating on the walls. Thus, the speed of the shock wave and the temperature drop behind the front. Since the reaction speed depends on temperature, even a small attenuation of the shock wave results in slowing the reaction and the flame front, respectively. Slowing down the front in turn leads to an increase in losses due to heat dissipation, and a further weakening of the shock wave. Increasing the thickness of the porous layer at the wall increases the losses of the shock wave due to the greater expansion and greater friction. Therefore, we are witnessing drop in the shock wave speed and amplitude by increasing the thickness of the porous layer.
4. Conclusion

Detonation propagation in undiluted hydrogen–air mixture in acoustically absorbing channel at atmospheric pressure was investigated experimentally. Velocities and shock wave pressures were determined after the passing through the acoustically absorbing section. The effect of the porous coating thickness on the detonation wave propagation was investigated. The inner diameter of the channel was maintained the same. The wave velocity can drop to 0.5 of the initial velocity.

There were three possible modes of flame propagation, depending on the coating thickness and composition of the mixture. It was found that the recovery of the detonation wave can occur after the absorbing section. The recovery of the detonation wave is possible when the velocity of the shock wave is higher than Chapman–Jouguet acoustic speed.

Acknowledgments

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