Detonation Decay and Flame Propagation Through a Channel with Porous Walls

G. Yu Bivol, S. V. Golovastov, and V. V. Golub

Abstract Detonation decay and flame propagation in hydrogen–air mixture were experimentally investigated in the channels with solid walls and two types of porous materials on the walls: steel wool and polyurethane foam. Shock wave pressure dynamics inside the section with porous coating were studied using pressure sensors; flame front propagation was studied using photodiodes and high-speed camera. For all mixtures, the detonation wave was formed before entering the section with porous coating. In both porous materials, the stationary detonation wave was decoupled in the porous section of the channel into the shock wave and the flame front with velocity around the Chapman–Jouguet acoustic velocity. By the end of the porous section, the velocity and shock wave pressure were significantly lower in case of using steel wool.

1 Introduction

Hydrogen is considered to be one of the most promising types of environmentally friendly fuel. However, some of the physical and chemical properties of hydrogen make its use extremely explosive.

Suppression of the detonation wave by porous coating on the channel walls has been studied over the decades [1–5]. Different methods have been used for flame deceleration, like porous media [6], channel obstacles [7], or a combination of the two [8]. The propagation of fast flames through porous media was studied in [9]. Metallic wool was used as an explosion-attenuating material since it has a big surface area per unit volume and high thermal conductivity [10]. In the work [11], steel wool was found to be more effective at detonation attenuation than perforated plates, although different types of porous materials were not compared. The mixture composition and porous material thickness can also significantly change the flame

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propagation parameters [12–15]. Presence of the porous material can also change the flame propagation mechanism [16].

Analyzing the combustion inside porous material could reveal the mechanism of flame quenching in porous materials, which is not fully understood. The main reasons for flame quenching seem to be the disappearance of transverse waves, heat losses into porous media, flame stretching, and increased curvature [17].

The aim of this work was to study the dynamics of the flame front and shock wave overpressure in a channel with porous walls and the dynamics of the porous material under shock waves, to study the flame propagation in porous material, and to compare the detonation parameters in channels with solid walls and two types of porous materials on the walls.

2   Experimental Setup

Figure 1 shows the scheme of the experimental setup. Experiments were carried out in a channel consisting of two sections: a 2000-mm-long cylindrical section with an inner diameter of 20 mm and a rectangular section with a length of 500 mm. The top and bottom opposing walls of the rectangular section were covered with porous material or steel plates, while the side walls were made of transparent Plexiglas for photo registration. 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 other end of the detonation tube was opened. Before each experiment, the detonation tube was filled with three tube volumes of a hydrogen–air mixture at atmospheric pressure and 295 K temperature. The hydrogen–air mixture was held in a vessel with a volume of 3 l at a maximum pressure of 0.5 MPa. Stoichiometric mixture of hydrogen with air was used. Immediately after filling the detonation tube, the mixture was ignited to form the detonation. To study the propagation of the detonation in the channel with solid walls, two steel
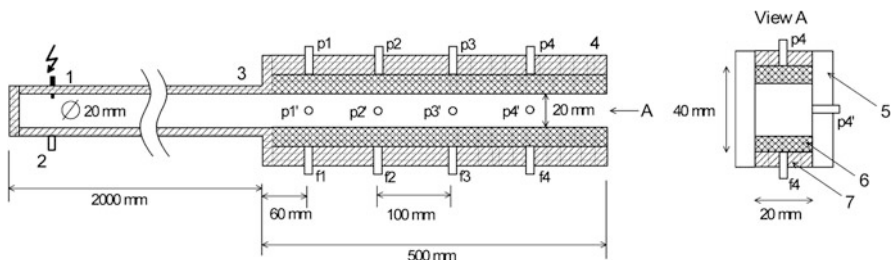

Fig. 1 Scheme of the experimental setup. 1, spark gap; 2, supply of the combustible mixture; 3, cylindrical section for detonation initiation; 4, transparent rectangular section with acoustically absorbing walls; p1–p4′, pressure sensors; f1–f4, photodiodes; 5, Plexiglas wall; 6, 10-mm-thick porous or steel plate, 7, solid wall

plates were inserted into the channel so that the cross-sectional dimensions were equal to 20*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*20 mm. So the thickness of the porous material was 10 mm. Two kinds of absorbing materials were used: polyurethane foam, which is characterized by a density of 0.03 g/cm^3, porosity of 0.95, thermal conductivity of 0.043 W*m^{-1}*K^{-1} for $t = 300$ K, and steel wool, which is characterized by a density of 0.15 g/cm^3, porosity of 0.99, and thermal conductivity of 80 W*m^{-1}*K^{-1}.

To determine the attenuation of the detonation wave, four pressure sensors manufactured by PCB (111A, 113B) and four FD-256 photodiodes were inserted into the section under the absorbing layer. Another four pressure sensors were placed in the same cross section in the transparent plexiglass wall. The time measurement error of the sensors was less than 1 μs.

To observe the detonation wave front, a Videosprint high-speed video camera was used. The frame rate was 170,000 fps. The camera detects radiation in the range of 400–1000 nm.

3   Experimental Results: Discussion

For all mixtures, the detonation wave was formed before entering the transparent section. In the channel with solid walls, the stationary propagation of Chapman–Jouguet detonation was recorded.

Figure 2 shows the evolution of the pressure and flame front along the absorbing section with polyurethane foam (a) and steel wool (b) for a stoichiometric mixture. By the end of the absorbing section with polyurethane foam, the pressure drops to around 1 MPa. In the case of steel wool, the pressure drops below 0.6 MPa and no longer resembles the detonation wave front. The pressure sensors under the porous material and on the solid wall allowed us to compare the arrival times of the shock waves. The pressure readings from Fig. 2 show us that the shock wave under the polyurethane foam arrives later than the incident shock wave on the solid wall ($t'1 = 12$, $t'2 = 16$, $t'3 = 27$, $t'4 = 30$ μs, respectively). That means that the shock wave front in case of polyurethane foam is curved rather than flat. When using steel wool, the difference in the arrival time of the shock wave on covered and uncovered wall remains only on the pair of pressure sensors ($t'4 = 14$ μs).

Since the pressure sensor and the photodiode are located in the same cross section, it allowed us to measure the difference between arrival times of the shock wave and the flame front. The time difference is $\Delta t1 = 18$, $\Delta t2 = 21$, $\Delta t3 = 18$, and $\Delta t4 = 16$ μs for the polyurethane foam and $\Delta t1 = 20$, $\Delta t2 = 28$, $\Delta t3 = 45$, and $\Delta t4 = 82$ μs for the steel wool. The decoupling of the detonation wave into the shock wave and the flame front can be observed as the shock wave arrives before the flame front in both foam polyurethane and steel wool. The difference between the
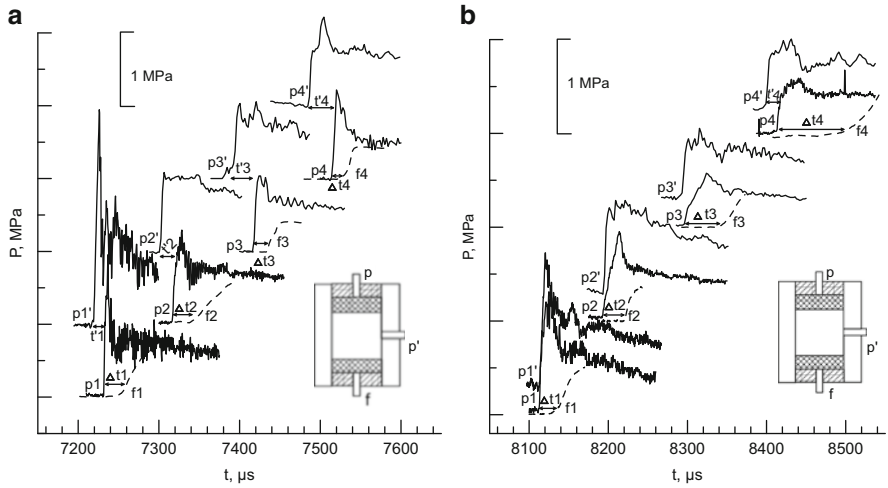
Fig. 2 Evolution of the pressure (solid line) and flame front (dashed line) along the absorbing section with different porous materials for ER (equivalence ratio) = 1: (**a**) polyurethane foam, (**b**) steel wool. Pressure sensors p1–p4 were placed under the porous material, pressure sensors p1′–p4′ were placed on the solid wall
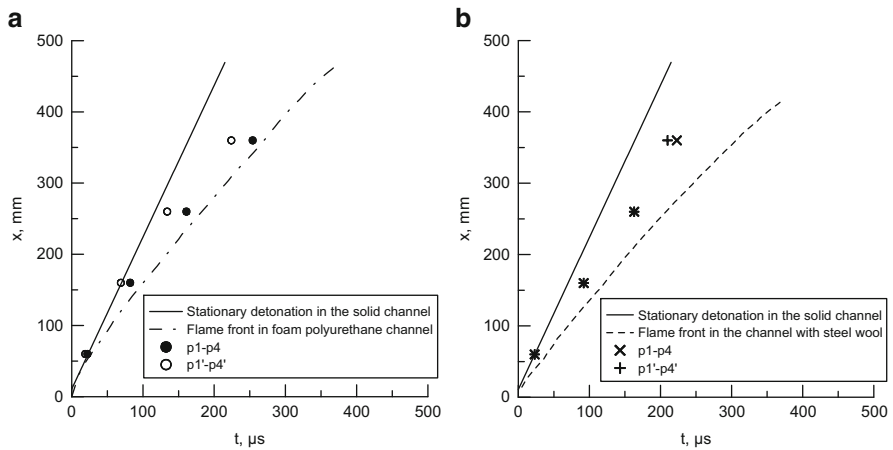

Fig. 3 x–t diagram of the stationary detonation in the solid channel and the decelerating flame front in the porous channel with polyurethane foam (**a**) and steel wool (**b**) on the walls. ER = 1. Shock wave arrival times from Fig. 2 are also shown

arrival of the shock wave and the flame front grows as the flame propagates along the steel wool and stays the same while using polyurethane foam.

Figure 3 shows the x–t diagram of the stationary detonation in the channel with solid walls and the decelerating flame front in the channel with polyurethane foam and steel wool on the walls. The x–t diagram was based on the streak images taken

with high-speed camera. Shock wave arrival times based on the pressure readings from Fig. 2 are also shown. The detonation front in the channel with solid walls propagates with steady velocity. The decrease in flame velocity along the channel while using foam polyurethane and steel wool on the channel walls can be explained by the heat loss and friction in the porous material. The final flame front velocity was equal to 1000 m/s for the polyurethane foam, which is 50% lower than Chapman–Jouguet detonation velocity (1970 m/s) and 10% lower than Chapman–Jouguet acoustic velocity (1100 m/s). The final flame front velocity for the steel wool was equal to 750 m/s, which is 60% lower than Chapman–Jouguet detonation velocity and 30% lower than Chapman–Jouguet acoustic velocity. The difference in final velocity can be explained by the higher porosity and thermal conductivity in the steel wool.

4 Conclusions

Detonation decay through an acoustically absorbing channel was studied experimentally. Two types of porous materials were compared: polyurethane foam and steel wool. Decay of the detonation wave into the shock wave and the flame front was observed in the porous section of the detonation tube with both materials. The difference in arrival times of shock wave and flame front reached 16 μs for polyurethane foam and 82 μs for steel wool at a distance of 360 mm from the beginning of the porous section. The pressure peak by the end of the porous section with steel wool was five times lower than in the channel with solid walls. The flame velocity by the end of the porous section was less than 50% of the Chapman–Jouguet detonation velocity and was equal to 1000 m/s and 750 m/s in the foam polyurethane and steel wool, respectively. Significant shock wave curvature by the end of the porous section was found when using foam polyurethane. The difference in arrival times of shock wave under foam polyurethane and on solid wall was discovered. This difference reached 30 μs by the end of porous section with foam polyurethane on two walls. While using steel wool on the walls, the difference in shock wave arrival times under the steel wool and on the solid wall appeared only on the last pair of pressure sensors and was equal to 14 μs.

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