

# Flame front propagation in a channel with porous walls

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**Abstract.** Propagation of the detonation front in hydrogen–air mixture was investigated in rectangular cross-section channels with sound-absorbing boundaries. The front of luminescence was detected in a channel with acoustically absorbing walls as opposed to a channel with solid walls. Flame dynamics was recorded using a high-speed camera. The flame was observed to have a V-shaped profile in the acoustically absorbing section. The possible reason for the formation of the V-shaped flame front is friction under the surface due to open pores. In these shear flows, the kinetic energy of the flow on the surface can be easily converted into heat. A relatively small disturbance may eventually lead to significant local stretching of the flame front surface. Trajectories of the flame front along the axis and the boundary are presented for solid and porous surfaces.

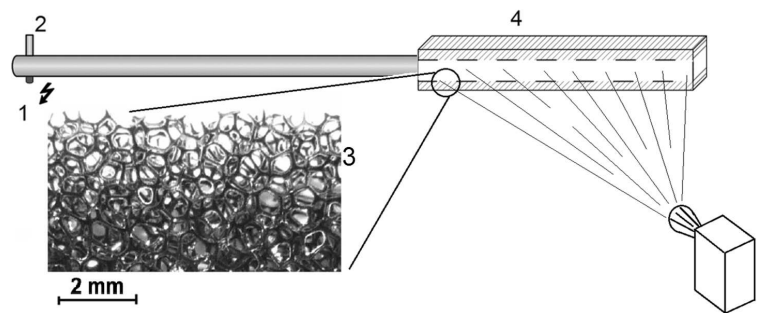
## 1. Introduction

For many practical purposes, including detonation studies, it is necessary to investigate the dynamics of detonation and combustion at atmospheric pressure undiluted by inert gas mixtures.

A detonation wave front has a cellular structure composed of transverse compression waves reflected from solid walls of a channel. The average detonation velocity in the channel of constant cross section with solid walls, determined by the Chapman–Jouguet condition, is constant. When the detonation wave front moves in an expanding channel or in a channel with acoustically absorbing walls, the motion of the detonation wave becomes non-stationary. First, it causes weakening of the initial shock wave, compressing the unreacted detonable gas, and as a consequence, deceleration of the shock wave. Second, the deceleration and the attenuation of the shock wave reduce the temperature of the compressed unreacted detonable mixture. This slows down the reactions and, as a consequence, decouples the detonation into a shock wave and a flame front.

The effect of porous walls on detonation was first considered in [1]. Due to the porous material covering the walls it was possible to double the DDT distance. At a much later time, the effect of walls on the already formed detonation wave was investigated with the help of high-speed photography. It was shown that the decomposition of the detonation is due to the suppression of the transverse waves at the front of the detonation wave [2]. This fact was confirmed in [3], by analyzing the Schlieren images. Effect of porous coatings on the walls becomes more visible in tubes of a critical diameter of the stationary detonation propagation [4]. Subsequently, various detonation suppression devices were compared in [5]. It was found that metal wool is much more effective in detonation suppression than perforated plates. However, in the work [6] the





**Figure 1.** Scheme of the experimental setup: 1—spark gap; 2—supply of the combustible mixture; 3—acoustically absorbing wall, 4—transparent rectangular section with acoustically absorbing walls, 5—high speed video camera.

authors have suggested that the weakening of the detonation wave due to the disappearance of the transverse wave occurs only for a detonable mixture having an irregular structure, while the detonation weakening in mixtures with a regular cellular structure occurs for other reasons, namely mass divergence into the porous material. It was investigated in details in [7].

The aim of this work was to study the dynamics of the flame front upon transition of a stationary detonation wave through a channel with acoustically absorbing walls at atmospheric pressure in hydrogen–air mixture undiluted by inert gases.

## 2. Experimental setup

Experiments were carried out in a steel tube. Figure 1 shows the experimental setup. The setup consisted of two sections: a cylindrical section of length 2 m and inner diameter 20 mm; and a rectangular  $20 \times 20 \text{ mm}^2$  section of length 500 mm. The hydrogen–air mixture was fed to the closed end of the cylindrical detonation tube. There was a spark gap at the closed end of the detonation tube. The second end of the detonation tube was open. Visual control of the flame front dynamics in the rectangular section was performed through transparent walls. The stationary detonation wave was formed before the rectangular section.

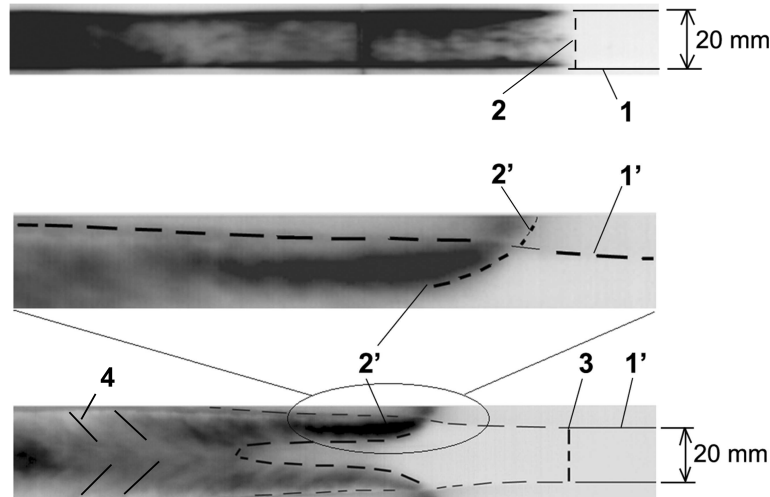
The width of the transparent Plexiglas region was 40 mm and the width of the steel side was 20 mm. To study the propagation of the detonation in the channel with solid walls, two steel plates were inserted into the channel so that the cross-sectional dimensions were equal to  $20 \times 20 \text{ mm}^2$ . To study the propagation of the detonation in the channel with acoustically absorbing walls, two foam rubber elements were inserted into the channel so that the cross-sectional dimensions were also  $20 \times 20 \text{ mm}^2$ . So, the width of the acoustically absorbing surface was 10 mm. We used polyurethane foam having a density of  $0.03 \text{ g/cm}^3$ , porosity of 0.90, average pore size of 0.8 mm, and an acoustic amplitude attenuation factor of 0.20.

To observe the detonation wave front, we used a high-speed video camera Videosprint. Single shooting captured the details of the flame front and the streak-shooting captured the dynamics of the flame front. The frequency in the single-shot mode was 10000 Hz, with  $1 \mu\text{s}$  exposure and  $1280 \times 100$  resolution. In the streak mode, the frequency was 170000 Hz, with  $1 \mu\text{s}$  exposure and  $1280 \times 3$  resolution. The camera detects radiation in the range of 400–1000 nm. Up to 75% of the radiation energy is in the visible range.

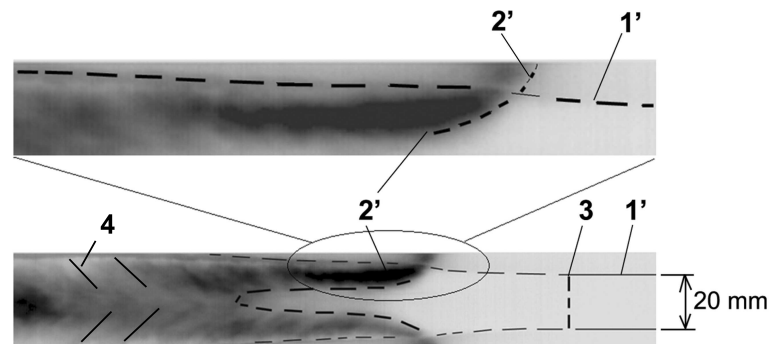
## 3. Experimental results. Discussion

Figures 2 and 3 present negative frames of the flame front in the rectangular channel for ER = 1.5: top and bottom—solid walls (figure 2); top and bottom—acoustically absorbing walls (figure 3).

As expected, in the channel with solid walls, the propagation of the Chapman–Jouguet detonation was observed to be stationary. The flame front was plane. The front was followed by hot detonation products. The luminescence of the flame front and the combustion products is



**Figure 2.** Frames of the flame front in the rectangular channel with top and bottom solid walls for  $ER = 1.5$  (negative) at  $80 \mu s$ : 1—solid boundary; 2—detonation front.



**Figure 3.** Frames of the flame front in the rectangular channel with top and bottom acoustically absorbing walls for  $ER = 1.5$  (negative) at  $120 \mu s$ : 1'—absorbing boundary; 2'—flame in channel/pores; 3—shock wave, 4—Mach perturbation.

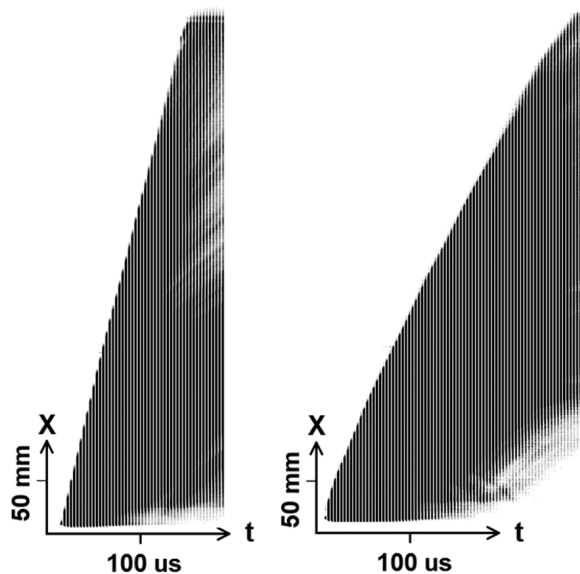
substantially uniform throughout the volume of the channel. An intensive flow of the detonation products was observed near the boundary layer.

In the case when the top and bottom walls of the rectangular channel were covered with the absorbing material, the camera recorded deceleration of the flame front. The profile of the flame front was V-shaped. The most intense luminescence was observed at the boundaries of the absorbing material with the open porous surface.

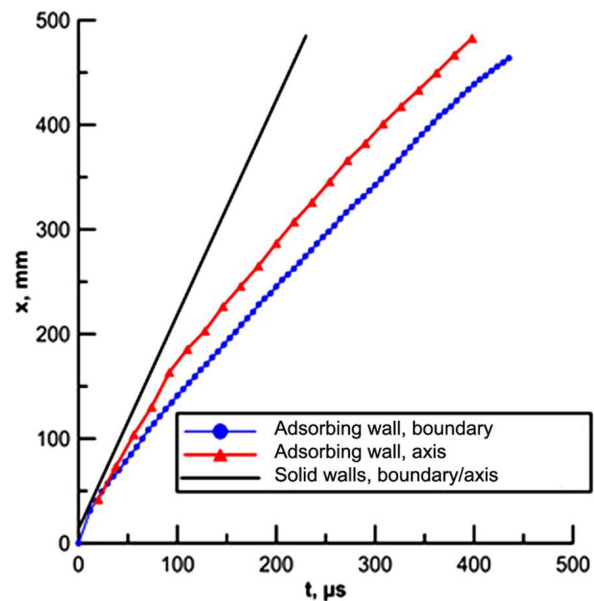
Figure 4 presents streak-images of the detonation and flame front after the decoupling of the detonation in the acoustically absorbing channel. The trajectory of the detonation is a straight line. The velocity of  $2100 \text{ m/s}$  is close to the Chapman–Jouguet velocity. Figure 5 shows  $x-t$ -diagrams of detonation and flame front dynamics. The trajectories were built on the first pixels obtained from the digital camera. The trajectory of the detonation front for the solid walls is a straight line. Figure 5 shows the  $x-t$ -diagram of the decelerating flame front along the axis of the channel (axis) and the trajectory of the flame front along the boundary of the channel (boundary). Trajectories of the flame front along the axis and the boundary of the absorbing surfaces were obtained in different experiments with identical conditions.

The formation of the V-shaped flame front can be attributed to the friction under the surface due to open pores. The gas after the decoupling of the detonation complex involved in the movement before the flame front is located in the region between the flame and the shock wave traveling in front of it, as shown in figure 3. Figure 5 shows that the velocity of the reaction front slows down to a minimum value of  $1200 \text{ m/s}$ . Meanwhile, the front shock wave also slows down after the decoupling of the detonation. The value of the shock wave velocity can be estimated from the data presented in [8]. For  $ER = 1.5$ , the value of the shock wave velocity can be about 0.8 of the Chapman–Jouguet detonation velocity. This means that the distance between the reaction front and the front shock wave is about 2–3 tube diameters. Thus, the unreacted mixture forms a flow characterized by a velocity of  $1000\text{--}1200 \text{ m/s}$  and duration of  $30\text{--}50 \mu s$ .

Under these conditions, the friction may have a significant impact on the reaction front near the open pores. Interaction of the supersonic flow with the porous surface results in the formation of oblique shock waves. The Mach lines observed in figure 3 form an angle of  $40^\circ$  to the channel surface. In these shear flows, the kinetic energy of the flow on the surface can be easily converted into heat. Thus even a relatively small disturbance may eventually lead to significant local stretching of the flame front surface.



**Figure 4.** Streak image of the flame front and detonation products for  $ER = 1.5$  along the axis (negative): channel with solid walls (left); channel with absorbing walls (right).



**Figure 5.**  $x-t$  diagrams of the flame fronts for  $ER = 1.5$ : solid walls; acoustically absorbing (boundary); acoustically absorbing (axis).

#### 4. Conclusions

The shape of the flame front in the rectangular cross section was investigated experimentally. The flame front was observed to have a V-shaped geometry. The shape is attributed to surface friction with gas heating in pores. Above the porous surface, one can observe Mach perturbations, the presence of which may result in the local stretching of the flame front surface.

#### Acknowledgments

The authors are grateful to Tatiana Zezyulina for English improvement of the paper. The work was supported by the Russian Science Foundation, grant No. 14-50-00124.

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