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Self-ignition of hydrogen-air mixture during the interaction of a shock wave with a destructible granular screen or permeable wall

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The process of self-ignition of a hydrogen-air mixture during the interaction of a shock wave with a destructible granular screen or permeable wall was studied experimentally. The wall was made of polyurethane, the destructible screen was made of quartz sand with a small amount of binder. The parameters of incident, reflected and transmitted shock waves were determined at an initial pressure of 0.02 MPA and a molar hydrogen concentration of 14%. Conditions were determined under which the placement of the destructible screen may be appropriate to prevent spontaneous ignition of the mixture.

Keywords: destructible screen, shock wave, hydrogen, ignition.

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One of the crucial challenges of explosive safety consists in mitigating the effects of explosion of gas mixtures. The use of a destructible screen is one of the most efficient methods for reducing the shock wave intensity in the case of shock compression of a flammable mixture and its subsequent ignition [1–3]. Close attention is being paid currently to the process of interaction between a shock wave and sand. The effect of shock waves on sand has been examined in [4,5], and their attenuation by granular barriers has been studied in [6]. The efficiency of perforated plates has been evaluated in [7]. The coefficients of shock wave attenuation by destructible screens of a varying thickness have been determined [8]. Notably, the majority of published studies are focused on attenuation of a transmitted shock wave instead of a reflected one in an inert medium (see review [9] for details).

Although the ignition of hydrogen-containing [10,11] and other flammable mixtures behind reflected shock waves in shock tubes has been examined in detail, the interaction of a shock wave with a destructible granular screen in a flammable medium has not been considered. The aim of the present study is to examine the possibility of application of a destructible screen made of quartz sand for prevention of self-ignition of a hydrogen–air mixture behind a reflected shock wave. The efficiency of a quartz sand screen is compared to that of a porous polyurethane wall.

Experiments were carried out in a shock tube. A high-pressure chamber 2000 mm in length with an internal diameter of 50 mm was filled with helium. A low-pressure chamber with an overall length of 3942 mm and a rectangular cross section (40×40 mm) was filled with a hydrogen–air mixture.

Figure 1, a presents the schematic arrangement of a destructible screen (DS) and piezoelectric pressure transducers. This destructible granular screen or a porous wall (see Fig. 1, b) were positioned in the low-pressure chamber at a distance of 510 mm from its closed end. Thus, the influence of the closed end of the low-pressure chamber was neglected. Pressure transducers #2–#4 detected incident shock waves (ISW) and waves reflected from the screen (RSW). Pressure transducers #5–#7 detected shock waves transmitted through the screen (TSW). Figure 2 presents typical oscilloscope records produced by pressure transducers in interaction between a shock wave and the destructible screen in the case when the Mach number of the incident shock wave was $M_1 = 3.18$. Pressure P_5 behind the reflected shock wave and the pressure at the front of incident (P_2) and transmitted (P_2') shock waves were determined. In order to identify the conditions of mixture ignition in reflection from a rigid wall and obtain reference flow characteristics, an indestructible aluminum screen was mounted at the same position instead of the destructible screen.

Ignition of the hydrogen–air mixture was detected by a photomultiplier tube (PMT) positioned in the closed end of the high-pressure chamber. A ZWB1 optical filter with an effective passband width of 270–370 nm was used. The destructible screen dynamics was monitored with a Phantom Veo 710 high-speed digital camera. The frame rate was 24 000 fps at a resolution of 1216×256 and an exposure time of 1 μs. A 1000 W halogen lamp provided continuous illumination of the screen.

The destructible screen was made of quartz sand with a blue clay binder; the sand : clay : water mas ratio was 10 : 1 : 1.3. The size of sand granules was 0.6–0.8 mm. The permeable wall was made of polyurethane with open pores. This polyurethane was characterized by a pore density of 10 or 80 ppi (pores per inch). The mean values of thickness and mass of the screen and the permeable wall are listed in the table.

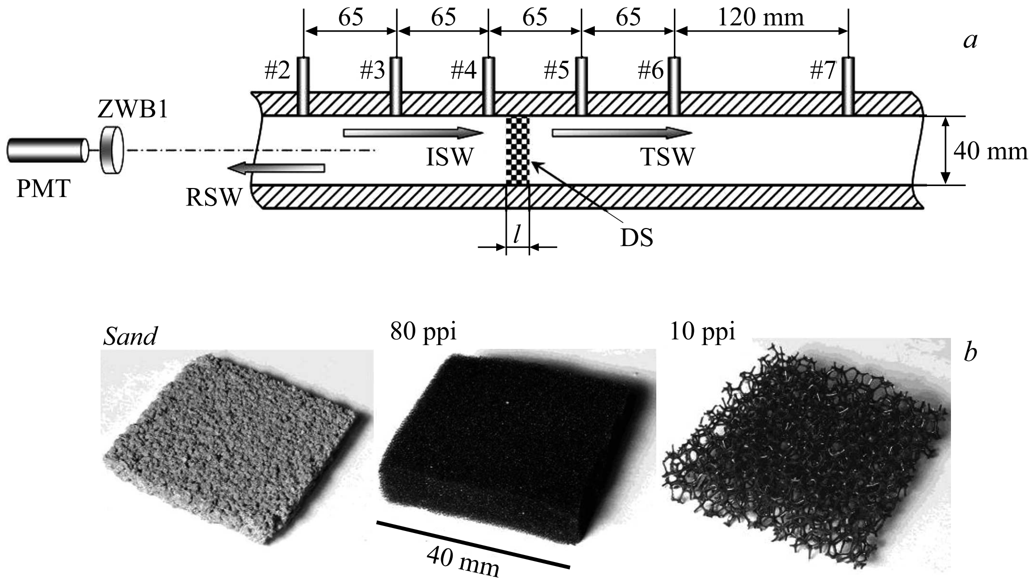

Figure 1. *a* — Positioning of the destructible screen (DS), pressure transducers (#2–#7), and a PMT in the shock tube; *l* — screen thickness. *b* — Photographic images of the destructible screen and polyurethane walls.

The hydrogen–air mixture was prepared in advance in a separate vessel 3 l in volume according to partial pressures and mixed with a brushless fan. The maximum pressure in the mixing vessel was 0.6 MPa. Three compositions were used in preliminary experiments: a stoichiometric mixture in volumetric ratio $H_2 : O_2 : N_2 = 2:1:3.76$ (30 vol.% of hydrogen) and two mixtures with $H_2 : O_2 : N_2 = 0.77:1:3.76$ (14 vol.% of hydrogen) and $H_2:O_2:N_2 = 0.59:1:3.76$ (11 vol.% of hydrogen).

Subsequent experiments were performed with the mixture containing 14 vol.% of hydrogen. On the one hand, this mixture under initial pressure $P_1 = 0.02$ MPa did not ignite behind an incident shock wave within a wide range of Mach numbers. On the other hand, limit Mach numbers of an incident shock wave inducing ignition behind the reflected wave could be determined. The range of Mach numbers $M_1 = 1.98-2.10$ in the table corresponds to experiments in which self-ignition of the mixture behind a shock wave reflected from the indestructible screen was not observed; at Mach numbers $M_1 = 2.29-3.44$, self-ignition was detected. Temperature T_5^* and pressure P_5^* behind the reflected shock wave prior to the moment of ignition in experiments of the latter kind may be estimated in the one-dimensional approximation using the following well-known gas dynamics equations:

$$\frac{T_5^*}{T_{298}} = \frac{[2(\gamma-1)M_1^2 + (3-\gamma)][(3\gamma-1)M_1^2 - 2(\gamma-1)]}{(\gamma+1)^2 M_1^2}, \quad (1)$$

$$\frac{P_5^*}{P_1} = \frac{2\gamma M_1^2 - (\gamma-1)}{\gamma+1}\,\frac{(3\gamma-1)M_1^2 - 2(\gamma-1)}{(\gamma-1)M_1^2 + 2}. \quad (2)$$

Here, $\gamma = 1.4$ is the adiabatic exponent for a mixture of diatomic gases. The calculated values of temperature T_5^* are listed in the table. At Mach numbers $M_1 = 1.98-2.10$ and no ignition, pressure P_5 behind the reflected shock wave corresponded to the calculated P_5^* value. However, at Mach numbers $M_1 = 2.29-3.44$, pressure P_5 achieved during subsequent ignition was 50–60% higher than the calculated one. This pressure rise is attributable to combustion of the shock-compressed mixture. Figure 3 shows the combustion region (light-colored) emerging behind the shock wave reflected from the screen. The screen in this experiment was destroyed completely and disintegrated into separate granules 0.6–0.8 mm in size. The mean velocity of granules at a distance roughly equal to one tube diameter was calculated by examining sequential frames to be around 120 m/s.

No ignition was detected in interaction of a shock wave with the destructible screen at Mach numbers $M_1 = 2.29-2.30$. At screen destruction, pressure P_5 behind the reflected shock wave was 0.9 of the calculated P_5^* value, and pressure P_2' behind the transmitted shock wave was 0.4 of the initial P_2 value. In the case of ignition of the mixture at higher Mach numbers $M_1 = 2.9-3.44$, the pressure behind the reflected shock wave rose to 1.2–1.4 of the calculated value. This pressure is only slightly lower than the one determined in the experiment with ignition as a result of reflection from the rigid wall. The pressure behind the transmitted shock wave was 0.5–0.6 of the initial value.

The use of polyurethane (polyurethane foam) with a pore density of either 80 or 10 ppi resulted in ignition of the hydrogen–air mixture, although the intensity of the reflected shock wave decreased to 0.6–0.9 of the calculated value (see the table). Ignition then occurred within the porous wall, and the reduction of intensity of the reflected shock wave was governed by the wall permeability.

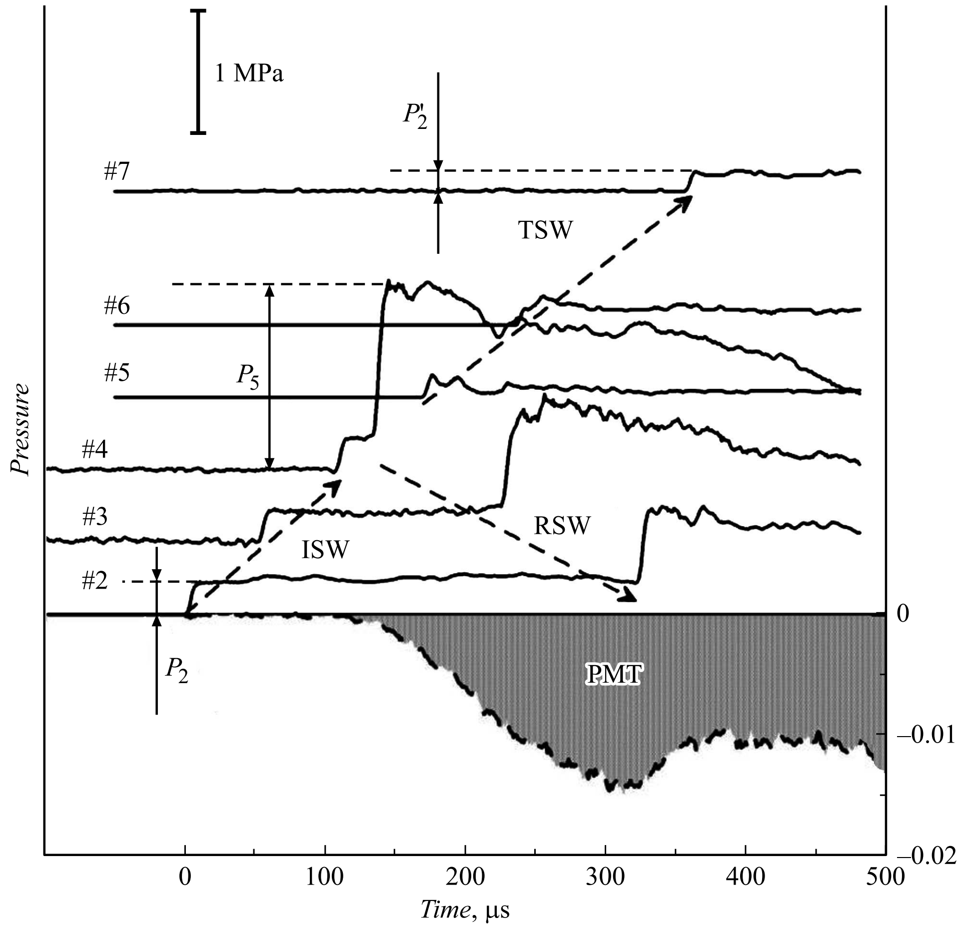

Figure 2. Oscilloscope records of signals from the PMT and pressure transducers in front of the destructible screen (#2−#4) and behind it (#5−#7): diagram of the shock interaction with the destructible screen.

Self-ignition (symbol „+") or no-self-ignition (symbol „−") conditions for the hydrogen–air mixture in the case of shock wave reflection from the screen and parameters of reflected P_5/P_5^* and transmitted P_2'/P_2 shock waves (number of symbols corresponds to the number of experiments)

Screen type (thickness l, mass)	Mach number M_1 of an incident shock wave (temperature T_5^*)			
	1.98−2.10 (740−800 K)	2.29−2.30 (910−920 K)	2.9−3.2 (1340−1560 K)	3.28−3.44 (1650−1790 K)
Rigid wall	− − − $P_5/P_5^* = 1.0$	++ $P_5/P_5^* = 1.5$	+++ $P_5/P_5^* = 1.5{-}1.6$	++ $P_5/P_5^* = 1.5$
Sand ($l = 4$ mm, 6−7 g)		− − $P_5/P_5^* = 0.9$ $P_2'/P_2 = 0.4$	++++ $P_5/P_5^* = 1.2{-}1.4$ $P_2'/P_2 = 0.5{-}0.6$	+ $P_5/P_5^* = 1.2$ $P_2'/P_2 = 0.6$
Polyurethane foam, 80 ppi ($l = 10$ mm, 0.6 g)				++ $P_5/P_5^* = 0.9$ $P_2'/P_2 = 0.6$
Polyurethane foam, 10 ppi ($l = 10$ mm, 0.4 g)				++ $P_5/P_5^* = 0.6{-}0.9$ $P_2'/P_2 = 1.0{-}1.2$
No screen	− −	− − −	− − − − − −	− − − − − −

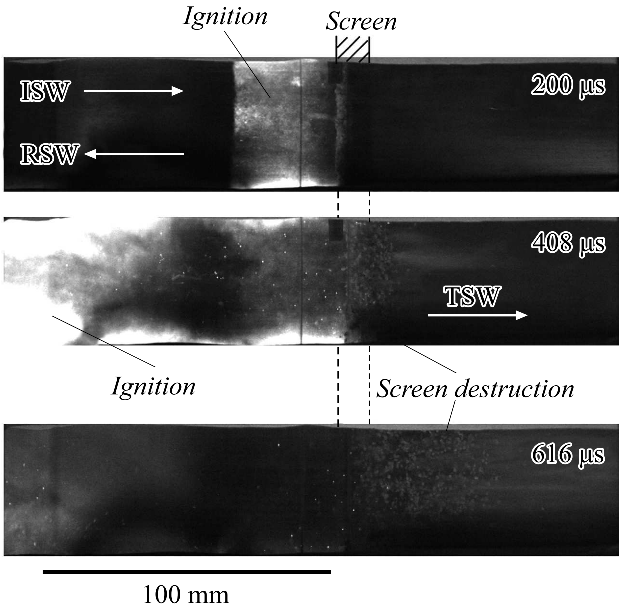

Figure 3. Sequential photographic images of screen destruction and ignition of the flammable mixture behind the reflected shock wave.

When polyurethane with a pore density of 80 ppi was used, the attenuation of the transmitted shock wave was comparable to its attenuation behind the destructible screen. In the case of the wall with a pore density of 10 ppi, the transmitted shock wave intensity is comparable to the intensity of the incident wave or exceeds it by 20%. This pressure rise is attributable to self-ignition of the flammable mixture in the course of propagation of the shock wave through the porous wall.

It follows from the presented experimental data that a destructible screen may prevent the ignition of a hydrogen–air mixture (14 vol.%) within a narrow range of Mach numbers of an incident shock wave $M_1 = 2.29-2.30$. At higher Mach numbers M_1, heating of the mixture behind the reflected shock wave induces ignition not only in the event of screen destruction, but also when a porous permeable wall is used.

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Conflict of interest

The authors declare that they have no conflict of interest.

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