Influence of an acoustic resonator on flame propagation regimes in spark initiated H₂ combustion in a cylindrical reactor near the lower detonation limit

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It is experimentally shown that an acoustic resonator like Helmholtz's resonator connected with a cylindrical reactor can provide a significant flame acceleration under spark initiation in lean (15%) hydrogen–oxygen mixtures close to the lower detonation limit.

Gas flame propagation in a pipe as a rule occurs with a constant velocity only along limited pipe site and under special conditions.[1] Otherwise, gas-phase combustion occurs under conditions of non-stationary currents, density and pressure fluctuations, *i.e.*, has a turbulent character.[2] At acceleration of a flame and, respectively, at intensification of combustion in pipes, a detonation wave, the wave of burning extending with a speed several times higher than sound speed in an initial gas mixture,[3] can arise. Prevention of flame acceleration and detonation is important in providing safe conditions in processing and mining industries.[4–7] However, experimental investigations of the regularities of acceleration of a flame are very incomplete.

Particularly limited is the experimental information on the influence of combustion reactor geometry on flame acceleration as well as on transition of subsonic combustion to supersonic regimes,[6] which is of interest for analysis of problems of explosion safety in volumes of complicated geometry, for example, in encumbered rooms. As was considered earlier,[8] detonation originates in hot spots – regions of lower density and increased rate of energy generation. Inside the region of this spatial gradient, unreacted material spontaneously ignites, and the reaction propagates in the direction of the gradient. The reaction spreads as an accelerating wave, and then it may undergo a transition to detonation. Density fluctuations leading to hot spot occurrence in the reactive media may be generated by acoustic oscillations arising in subsonic combustion.[9] This effect can be observed most clearly near detonation limit where combustible mixture is very sensitive to perturbations. It was shown[1,5,10,11] that both detonation and combustion limits are determined by the heat release rate and correspondingly, by the reaction kinetics. Thus, acoustic oscillations may spatially affect active centers concentration and, therefore, the probability of hot spot origination in reactive gas mixture.

Therefore, the generation of perturbations using obstacles or resonators in combustible gas atmospheres by changing resonator geometry is important for understanding of regularities of combustion and flame propagation. We have reported recently[12] that spark-initiated flames of diluted stoichiometric natural gas–oxygen mixtures in close-meshed aluminum spheres do not propagate through the spheres, but always propagate through planar meshed obstacles of the same mesh size. It was found that the features of flame propagation after simultaneous initiation at opposite butt-ends of the cylindrical reactor differed markedly from those after initiation from a single discharge.

In this work influence of the acoustic resonator like Helmholtz's resonator on intensity of combustion of lean (15%) hydrogen mixture with oxygen over pressures 200–300 Torr was investigated. The reactor geometry was chosen to provide only deflagration without a resonator after central spark initiation (see below). The composition of gaseous mixture was in the vicinity of the lower limit of hydrogen–oxygen detonation which corresponds to 13–15% H₂ in oxygen according to experimental data;[13–15] this provided a possibility of transition of deflagration to supersonic regime in a long tube.

Experimental installation consisted of the reactor of the constant volume in shape of the quartz cylinder 12 cm in height and 8 cm in diameter with optical windows at bott-ends and at lateral face of the cylinder, inlets for gas blousing and pumping out and ignition of gas mixture (Figure 1). The volume of the reactor was 690 cm³ taking into account the volume of flanges of optical windows and gas inlets. In a number of experiments the reactor was connected to a glass tube of 1 cm in diameter and 30 cm long, serving as an acoustic resonator. High speed recording of ignition dynamics and flame front propagation was carried out from the side and the top of the reactor with a Casio Exilim F1 Pro color high-speed digital camera, (frames frequency of 60–1200 s⁻¹), sensitive to light in the spectral range of 420–740 nm.[16] The video recording was turned on at an arbitrary moment before initiation. The video file was stored in computer memory and its time-lapse processing was performed.[17,18] Ignition was provided by means of the spark discharge ($E_0 = 1.5$ J) in the reactor center, the distance between electrodes was ~0.5 mm. Experiments were carried out using previously prepared gas mixture of 15% H₂ in oxygen over total pressure range 200–300 Torr. 2.5% of carbon tetrachloride (CCl₄), which in such quantities
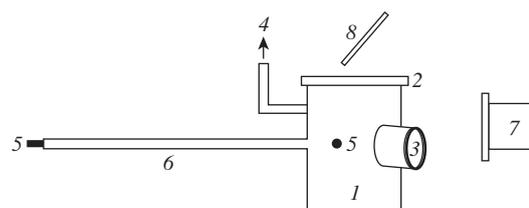

Figure 1 Experimental installation: (*1*) cylindrical quartz reactor, (*2*) removable top, (*3*) optical window, (*4*) outlet for reactor evacuation, (*5*) piezoelectric gage, (*6*) acoustic resonator, (*7*) high-speed video camera and (*8*) rotary mirror.
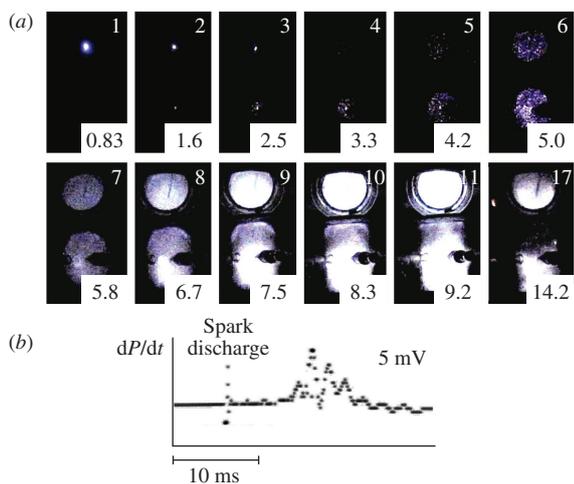
(a)

(b)

Figure 2 (*a*) Sequence of video frames of combustion of 15% of H$_2$ in oxygen initiated by a spark discharge without acoustic resonator. Total pressure, 300 Torr. 1200 frames per second, the time interval after discharge (ms) is shown in each frame, reference temperature 300 K; (*b*) oscillogram of the time dependence of the rate of pressure change in the combustion of 15% H$_2$ with oxygen initiated by a spark discharge at 300 Torr.

Figure 3 (*a*) Sequence of video frames of combustion of 15% of H$_2$ in oxygen initiated by a spark discharge in the presence of acoustic resonator. Total pressure, 250 Torr. 1200 frames per second, the time interval after discharge (ms) is shown in each frame, reference temperature 300 K. Video recording from the reactor top window was not conducted; (*b*) oscillogram of the time dependence of the rate of pressure change during combustion of 15% H$_2$ in oxygen initiated by a spark discharge at 250 Torr.
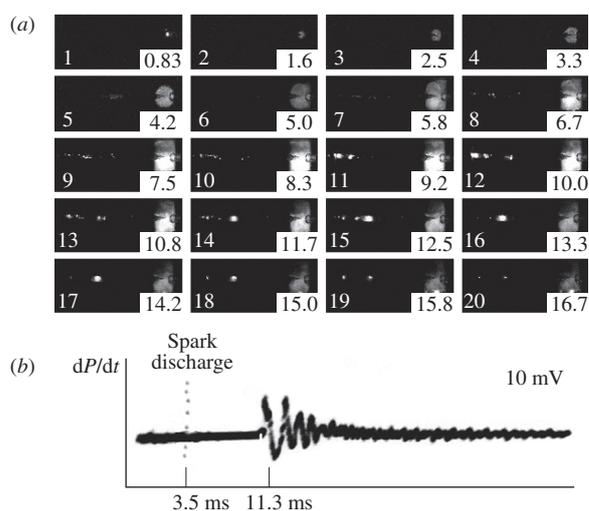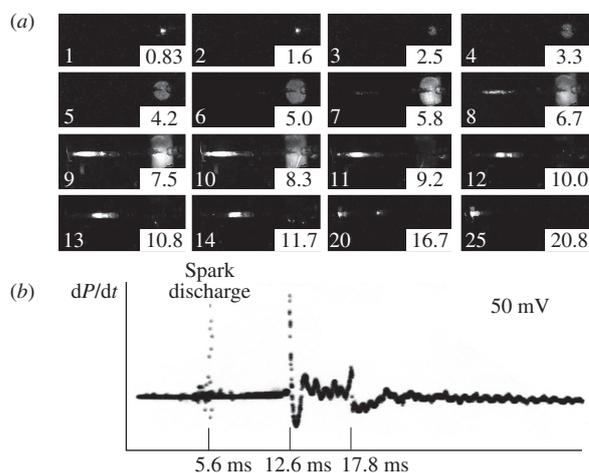
Figure 4 (a) Sequence of video frames of combustion of 15% of H$_2$ in oxygen initiated by a spark discharge in the presence of acoustic resonator. Total pressure, 300 Torr. 1200 frames per second, the time interval after discharge (ms) is shown in each frame, reference temperature 300 K. Video recording from the reactor top window was not conducted; (b) oscillogram of the time dependence of the rate of pressure change in combustion of 15% H$_2$ with oxygen initiated by a spark discharge at 300 Torr.

can be considered as an inert additive,[19] were added to the mixture for flame visualization. The rate of pressure change in the course of combustion was recorded by means of a piezo-electric gage synchronized with the discharge and connected to an end face of the acoustic resonator tube (Figure 1). In experiments without the resonator the gage was connected to the side reactor inlet. The signal was recorded using C9-16 oscilloscope and stored in a computer memory. Before each experiment the reactor was pumped down to 10^{-2} Torr. Pressure in the reactor was also controlled using ionization gauge and the vacuum gage. H$_2$, O$_2$ gases, and also CCl$_4$ were chemically pure (99.9%).

It follows from the above that the reactor is small enough to provide flame acceleration and detonation in lean mixture H$_2$ + O$_2$ at a given spark discharge power.[20] It was of interest to ascertain whether an acoustic resonator connected with the reactor could provide the acceleration of combustion process.

A typical sequence of video frames of combustion of 15% H$_2$–oxygen mixture initiated by a spark discharge at 300 Torr without the acoustic resonator is shown in Figure 2(*a*). One can see that at central initiation the spherical flame front propagates in the reactor; when the flame front reaches reactor walls (6th shot) the flame decays. The dependence of the rate of pressure change on time is shown in Figure 2(*b*) where damped pressure oscillations are observed.

A typical sequence of video frames of combustion of 15% H$_2$–oxygen mixture initiated by a spark discharge at 250 Torr in the presence of the acoustic resonator is presented in Figure 3(*a*) which reveals that at the central initiation the spherical front of a flame propagates in the reactor. Thus, on the 5th shot (4.16 ms) a combustion wave appears in the resonator and fluctuates in the resonator until the combustion in the quartz cylinder comes to an end.

At increase in the total pressure of combustible mixture to 300 Torr in the presence of the acoustic resonator, the spherical flame front propagates in the reactor approximately with the same speed as in the previous experiments [*cf.* Figures 2(*a*), 3(*a*) and 4(*a*)], and also during an entire process the oscillating combustion wave in a glass tube occurred [Figure 4(*a*)]. A visible combustion wave originates in the distant end of the resonator (6th shot) and propagates towards quartz cylinder. The reasons for such behaviour of combustion wave in the resonator need further investigation. As is seen in Figure 4(*a*) in the 10th shot two bright vertical traces, one of which is still noticeable in the 11th shot, originate in the

lower part of the quartz reactor. The experiment is accompanied by a sharp characteristic sound, indicating the reactor collapsed. Figure 3(*b*) shows that after 13th shot the quartz reactor image on video recording disappears [*cf.* Figure 3(*a*) in which the cylindrical reactor is visible during the entire time of video recording]. Note that two similar experiments (in new reactors) under the same experimental conditions as those of Figure 4(*b*) also led to reactors destruction that testified to reproducibility of the obtained result. Therefore, in combustion under the conditions of Figure 4(*b*) strong flame intensification caused by acoustic oscillations of flame in the resonator occurs.

Oscillograms of the time dependence of the rate of change of the general pressure are given in Figures 3(*b*), 4(*b*) for conditions of Figure 3, in which only combustion or combustion intensification are observed. The maximum value of the first pressure derivative at combustion intensification [Figure 4(*b*)] is about 7 times larger than in deflagration [Figure 3(*b*)]. The

peak at 12.6 ms in Figure 4(*b*) is observed when the first explosion in the resonator occurs (shot 8), the second peak at 17.8 ms corresponds to the reactor destruction (shot 12). Note that sharp change of d*P*/d*t* in the resonator results in reactor destruction first of all.

As distinction between processes in Figures 3(*a*) and 4(*a*) was particularly set to destroying ability of a combustion wave formation, it is possible to tell unequivocally only about the occurrence of the fast flame acceleration upon the central spark initiation of 15% of $H_2 + O_2$ mixture at 300 Torr in the presence of the acoustic resonator, which is in accordance with pressure measurements (see above). Only deflagration is observed without the resonator or at lower pressure. Note that, in the presence of the acoustic resonator at 300 Torr, deflagration takes place [Figure 4(*a*)]. Only at a certain stage of combustion the interaction of the spherical front of a flame with the flame in the acoustic resonator results in combustion acceleration and probably, quasi-detonation regime, which leads to reactor destruction. The observed phenomenon is to some extent comparable with the results[8] of calculation for interaction of a shock wave with the front of the subsonic combustion. Anyway, the phenomenon observed needs further investigation with the use of high speed (up to 10^5 frames per second) cinematography.

In conclusion, it is experimentally demonstrated that the acoustic resonator (Helmholtz's resonator) connected to a cylindrical reactor can cause reactor destruction at spark initiation of deflagration in lean (15%) hydrogen mixture with oxygen. This points to a possibility of transition of deflagration to supersonic regime mode near the lower concentration limit of detonation even for small reactor where detonation is obviously impossible. Thus, in the case when the reactor is small enough to provide flame acceleration and detonation in lean mixture of $H_2 + O_2$ at given spark discharge power, the use of an acoustic resonator connected with the reactor leads to strong acceleration of combustion process.

This result is important for problems of explosion safety in volumes of complicated geometry as well as in hydrogen energy systems. For example, for the minimization of damages caused by an explosion in the working room, it is necessary to close the doors connecting this room to long corridors: thus, the doors have to open into the room.

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