Propagation mechanism and transmission of quasi-detonations

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Introduction

The propagation of quasi-detonations in porous media is depended on interaction of distinct ignition mechanisms being responsible for sustaining the supersonic combustion mode under filtration conditions [1-3]. These are in the broad sense the local shock adiabatic compression resulting in auto-ignitions of the mixture [4] and reaction of unburnt products at elevated thermodynamic conditions in surroundings of the burnt material, usually referred as turbulent mixing mechanism [5]. In the case of adiabatic compression, hot spots in porous media can be formed via single or multiple reflections of the leading shock front, shock wave diffractions resulting in focusing phenomena inside a porous matrix, and interactions of shock headed transient gas jets from the adjacent pores. From experimental and theoretical point of view it is interesting to elucidate the dominating ignition mechanisms of quasi-detonation at different velocity ranges. This work presents experimental studies of the relative influence of normal shock wave reflections on ignition and propagation of quasi-detonations near the limit.

Quasi-detonation transmissions are also accompanied by the flow acceleration and formation of a leading shock wave, which is strongly coupled with a flame front. The interaction and propagation of transverse shock waves caused by individual hot jets across the random flow field downstream of a porous bed can create hot spots in a fresh mixture by means of shock wave focusing and diffraction on flow inhomogeneities. In addition, transverse waves enhance the mixing and deforms the turbulent interface between reacted and unreacted products, thus increasing local reaction rates. Both mechanisms can lead to the formation of localized explosions in unburnt materials, which are capable of sustaining the leading shock during its expansion into a large volume, and can significantly promote the transition or re-initiation of a detonation wave [6, 7]. The aim of these studies was to establish the critical conditions required for detonation re-initiations and elaborates the tools for their estimations.

Experimental Setup

Experiments were conducted in a square (35×35 *mm*) tube of 80 cm long attached to the smooth test part (40 cm long) of the same cross-section (Fig.1). A normal combustion e formed in a small pre-chamber initiated the propagation of quasi-detonation in a porous bed. Experiments were made in a stoichiometric oxy-acetylene mixture $C_2H_2+2.5(O_2 + \beta N_2)$, with different degrees of nitrogen dilution and at initial pressures varying from *0.02* to *0.3 MPa.* Commercial grade acetylene, oxygen and nitrogen of *99.9 %* purity were used for mixture preparations. A pressure meter controlled the initial pressure of the mixture in the tube with an accuracy of $\pm$ *0.4 mm Hg*. A porous filling comprised of *5.5-mm* steel balls was used in all tests.

Ion gauges and pressure transducers measured the velocity, and pressure of shock and reaction fronts. Ion sensors provided measurements of a quasi-detonation velocity in a porous medium before transmission into smooth sections of the tube. Pressure transducers and ion sensors controlled the arrival times of shock and combustion fronts at different locations along the smooth tube. The deflagration to detonation transition run-up distance was defined as the distance between the exit plane of the porous filling and the locations of pressure and ion gauges, at which the detonation velocity of transmitted wave was attained.

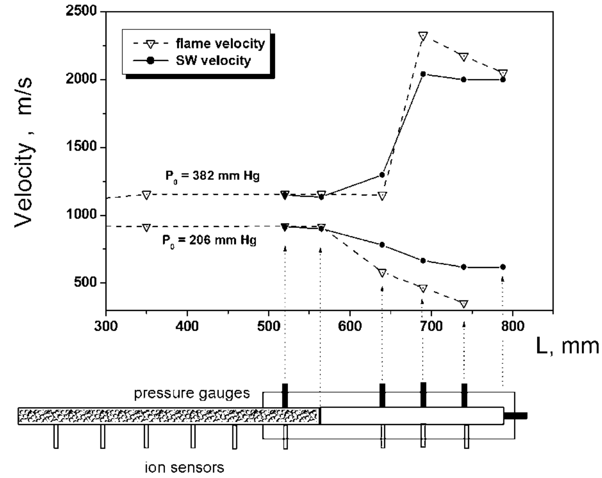
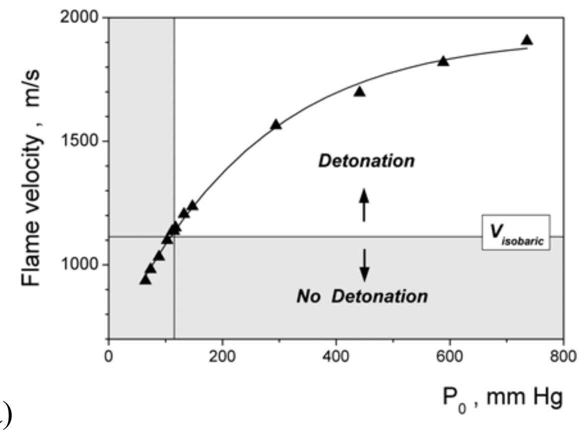


Fig. 1. The experimental setup for studying propagation and transmission of quasi-detonation and velocities of shock and reaction fronts for the cases of supercritical and subcritical transmissions from a porous bed.

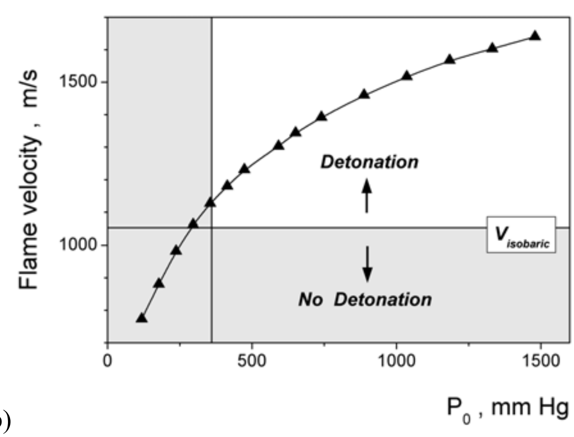
1. Transmission of quasi-detonation into a smooth tube

Two different transition scenarios in a smooth tube were observed in the experiments. At initial pressure higher than the critical one, the transmission of quasi-detonations led to the direct initiation of detonation downstream of the porous medium. At lower pressures, the leading shock wave decoupled from the reaction front and propagated with a continuously decreasing velocity to the reflecting wall of the test section. The flame behind the shock wave decelerated more rapidly and this resulted in an increasing detachment zone between them. Figure 1 presents velocity histories of the leading shock and reaction waves along the smooth tube for sub- and supercritical transmissions. Experiments showed that a venting of spatial distributed flame jets formed in a porous bed into a smooth section facilitates significantly the onset of detonations. The deflagration to detonation transition run-up distance downstream of the porous medium was less than one diameter of the tube within a wide range of compositions and initial pressures of the mixture.

Special attention was paid in the experiments to critical parameters of the venting gas flow, which result in the detonation onset behind the porous bed. It was established that a necessary quasi-detonation velocity required for re-ignition of detonation downstream of the porous medium is equal to the adiabatic sound speed of the combustion products to an accuracy ± *40* m/sec. Figure 2 shows parametric domains for sub- and supercritical initiations of detonation in a smooth tube in stoichiometric oxyacetylene mixtures with *25%* and *50%* nitrogen dilutions. As is seen in the figure, the velocities of quasi-detonation in a porous bed required for successful detonation initiations correlate well with the isobaric sound speed of the combustion products calculated for critical initial pressures in both mixtures from thermochemical equilibrium codes. This critical venting speed generates the necessary conditions to trigger the onset of detonation downstream of the flow. For subsonic outflows, the leading shock wave decouples from the reaction front and detonation occurs after reflection of the shock wave from the end flange of the tube (Fig.1).



a)



b)

Fig. 2. Parametric domains for sub- and supercritical initiations at quasi-detonation transmission into a smooth tube vs. initial pressure in oxyacetylene mixture with *25%* (a) and *50%* (b) of nitrogen dilutions.

Thus, using an empirical equation for quasi-detonation velocity [5, 7] one can formulate the necessary requirements for direct detonation initiation behind a regular porous bed comprised of spherical particles

$$V_{isobaric} < V_{CJ}\,[1 - 0.33 \cdot \log\,(d_c\,/\,d_p)\,], \qquad (1)$$

where $V_{isobaric}$ is an adiabatic sound velocity estimated for the critical initial pressure of the mixture where $d_c = 13\lambda$ – critical tube diameter for this mixture, λ – detonation cell size, d_p – pore size, estimated as $D/3$, were D is the diameter of steel balls, comprising the porous bed.

2. Propagation mechanism of quasi-detonations in a porous medium

The velocities of shock and reaction fronts after transmissions were measured by using a set of ion and pressure gages (Fig. 1) located along the test section. Two different transition scenarios were observed in experiments. At initial pressure higher than the critical one, the transmission of quasi-detonations led the direct initiation of detonation downstream the porous medium (Fig. 1). At lower pressures, the leading shock wave (SW) decupled from the reaction front and propagated with a continuously decreasing velocity to the reflecting wall of the tests section. The flame behind the shock wave decelerated more rapidly and this resulted in the increasing of detachment zone between themes. Figure 3 presents the velocity of leading shock front before its reflection from the end wall in comparison with speeds of quasi-detonation in porous bed and normal detonation at equivalent initial conditions. As is seen in the figure, at some points the leading SW velocity at subcritical regimes coincides with the speed of quasi-detonation near the limit. The measurements of induction time behind the reflected shock wave at these conditions provide the direct tool to determine the role of auto-ignitions of the mixture via normal SW reflections in the propagation mechanism of quasi-detonations at the low velocity ranges.

The pressure transducer installed at the reflecting wall was used to determine the chemical induction time of the mixtures. The induction period was measured as the time interval between the beginning of a normal reflection of incident SW and the second pressure spike, initiated by the self-ignition of a shock-compressed gaseous mixture in a detachment zone. The induction zone length was defined by using a simple relation $L_{ind} = \tau_{ind} \cdot V$. Where, τ_{ind} is the chemical induction time corresponding to stagnation temperature and pressure of the gas flow behind the leading shock front, V is a shock velocity. Figure 4 shows the induction length versus velocity of the transmitted shock wave as it value approaches to quasi-detonations velocity in a porous bed. The experiments

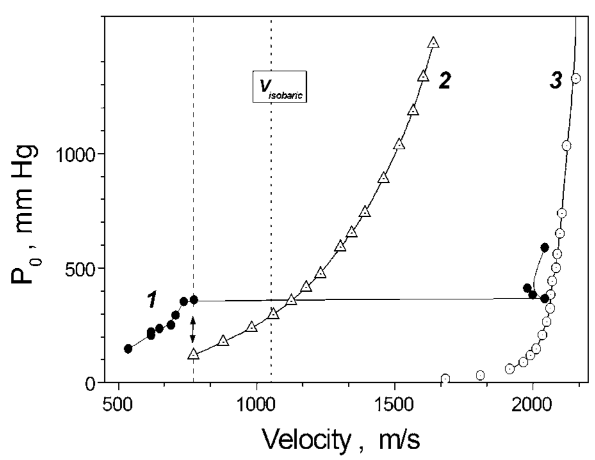


Fig. 3. The velocity of leading shock wave after transmission of quasi-detonations into a test section (1), the speed of quasi-detonation in porous bed (2), and detonation velocity in hollow tube (3) vs. initial pressure in $C_2H_2 + 2.5O_2 + 3.5\ N_2$ mixture.

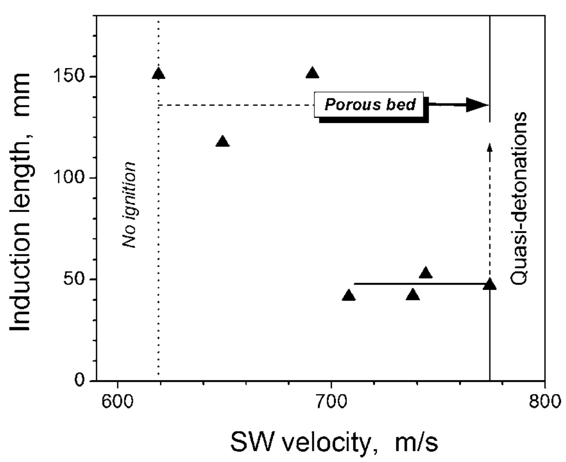


Fig. 4. Induction length vs. velocity of the leading shock wave after transmission of quasi-detonation from a porous medium in $C_2H_2 + 2.5O_2 + 3.5\ N_2$ mixture. Width of the tube is *35 mm*.

demonstrate that, at 3 times higher initial pressure of the mixture in the hollow tube than in porous bed and the same SW velocities (Fig. 3), the normal reflection of incident shock wave produces the induction zone of $\approx$ *48 мм* long (Fig.4). The extrapolation of this value to post-shock conditions of quasi-detonation using the pressure dependence of ignition time gives the induction length of $L_{ind} \approx$ *136 mm* in the porous body (Fig. 4). It means that during the time between initial shock compression and auto-ignition of the mixture in porous bed the leading shock front should travel the distance approximately equal to 4 channel widths, or 80 pore sizes. The measurements in oxyacetylene mixture with a *25 %* of nitrogen dilution exhibited nearly the similar behavior.

At the same time, pressure and ion current profiles of quasi-detonations show that the length scale between shock and reaction fronts does not exceed the value of *1.5 – 3 mm*, i.e. *1 – 2* pore sizes, within the scatter of experimental data. Thus, it evidences that the normal reflection of leading shock wave itself is not sufficient to ensure propagation mechanism of quasi-detonation at low velocities, and 3D interactions of shock waves and transient flows in porous matrix should be taken into account to achieve the necessary level of thermal excitation of the mixture, create hot spots, and switch on the self-sustained mechanism of quasi-detonation propagation.

Conclusions

The propagation of quasi-detonations in a porous packed bed, comprised of *5.5*-mm steel balls, and a subsequent transmission into smooth tubes has been studied experimentally. The necessary requirements for direct detonation initiation behind a regular porous bed comprised of spherical particles was obtained. It was established that a necessary quasi-detonation velocity required for re-ignition of detonation downstream of the porous bed is equal to the adiabatic sound speed of combustion products with an accuracy ± *40* m/sec.

It was observed that the normal shock reflection mechanism itself can not produce the successive auto-ignition of the mixture at real length scale in a porous bed and ensure the self-sustained propagation of quasi-detonation near the limits.

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References

1. Kauffman, C. W., Y. Chuanjun, and J. A. Nicholls.1982. Gaseous detonations in porous media. *Proc. Combustion Institute* 19:591-97.
2. Pinaev A.V., and G.A. Lyamin. 1989. Fundamental laws governing subsonic and detonating gas combustion in inert porous media. *Combustion Explosion Shock Waves* 25:75-85.
3. Babkin, V.S., A.A.Korzhavin, and V.A. Bunev. 1991. Propagation of premixed gaseous explosion flames in porous media. *Combustion and Flame* 87:182-90.
4. Zel'dovich, Ya.B. 1944. Theory of Combustion and Detonation in Gases. Moscow- Leningrad, Russia: Izd. Acad. Nauk SSSR, 71 p.
5. Makris, A., H. Shafique, J.H.S. Lee, and R. Knystautas. 1995. Influence of mixture sensitivity and pore size on detonation velocities in porous media, *Shock Waves* 5: 89-95.
6. Achasov, O.V., P.N. Krivosheev, O.G. Penyazkov, K.L. Sevruk, and S.A. Zhdanok. 2002. Ignition of an explosive gas mixture by a detonation wave formed in a porous medium. In: *Advances in Confined Detonations*. Eds. G. Roy, S. Frolov, R. Santoro, and S. Tsyganov. Moscow, Russia: TORUS PRES.109-112.
7. Achasov, O.V., Krivosheyev, P.N., Penyazkov, O.G., and S.A.Zhdanok. Flame-jets initiation of detonation in large volumes. Proceedings of 19th International Colloquium on Dynamics of Explosions and Reactive Systems, July 27 – August 1, 2003 Hakone, Japan, paper 1.