Quasi-Detonation in Matrix of Cylinders

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Introduction

Quasi-detonation propagation, flame acceleration in duct with porous media or regular obstructions has been studied for many years. Main velocity propagation modes has been identified and classified depending on the gas mixture composition, stoichiometric ratio, initial pressure, porosity and pore size, or blockage ratio. Low-speed deflagration, high-speed deflagration, quasi-detonation and Chapman-Jouguet (CJ) detonation regimes has been found and described. Criterion to flame acceleration and transition from one regime to another were proposed [1-15].

But, in spite of the large amount of experimental and theoretical data, the physical mechanisms of wave propagation for different regimes still not clear. In a broad sense, these are local shock wave compression and adiabatic compression resulting in spontaneous ignitions of unburnt products at elevated thermodynamic conditions, usually referred to as turbulent mixing mechanisms. In the case of a shock adiabatic compression, the hot spots in the porous medium may be formed by single or multiple reflections of the leading shock wave front, shock wave diffractions and focusing effects within the porous matrix as well as interactions of shock headed transient gas jets from the adjacent pores.

Early was shown that normal shock reflection mechanism itself cannot 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 [16-17].

From experimental and theoretical point of view it is interesting to elucidate the dominating ignition mechanisms of quasi-detonation at different conditions. In this study we visualize fast deflagration and quasi-detonation in matrix of cylinders and measure mean and local inner pore velocity correlations.

Experimental design

To better understand the processes occurring in a single cell of porous structure we provide experiments in simple 2D geometry – matrix of cylinders in narrow gap. In such geometry the flame front can be considered roughly as a plane and also we can experimentally observe ignition phenomena inside a single pore. Experiments were conducted in test volume (cross-section of 8 × 107 mm and 500 mm long) equipped with a matrix of 8 mm cylinders (Figure 1a), situated chequerwise, with BR=0.73 (Figure 1b).

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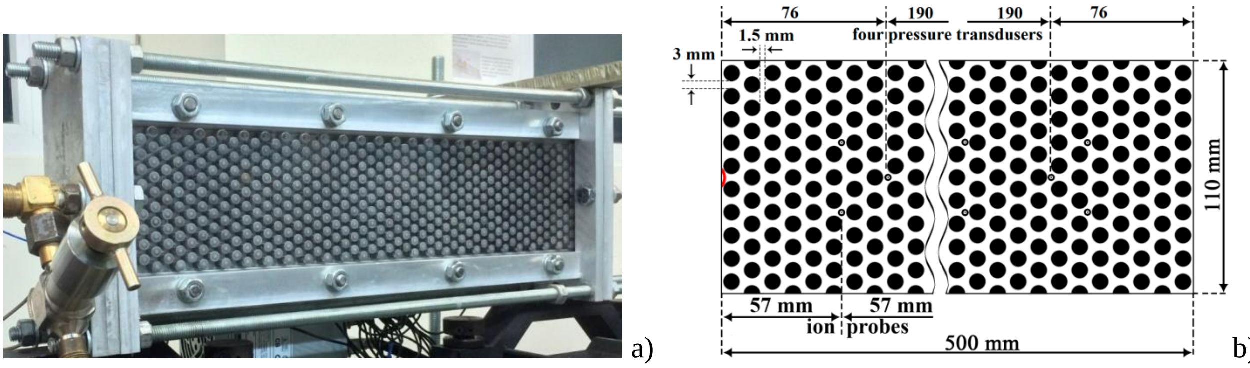

Figure 1. Photograph of the installation (a) and schematic of 8 mm cylinder pattern (b).

A flame was initiated in a small pre-chamber (ignited by standard spark plug) and transmitted to quasi-detonation mode in a porous layer. The propagation phenomena was observed through the transparent wall along the entire length of the test volume using two high speed cameras PHOTRON FASTCAM SA-X2 and PCO DICAM PRO equipped with dual narrowband filters λ_{max} = 430.4 nm, $\Delta\lambda_{0.5}$ = 2.6 nm and λ_{max} = 430.6 nm, $\Delta\lambda_{0.5}$ = 2.6 nm (photoluminescence of CH radical). Experiments were made in a stoichiometric oxy-acetylene mixture C_2H_2+2.5O_2, with 70 degrees of argon and nitrogen dilutions. Initial pressure was varied from 0.01 to 0.04 MPa. Commercial grade acetylene, oxygen and argon of 99.9 % purity were used for mixture preparations. A pressure meter controlled the initial pressure of the mixture with an accuracy of ± 0.4 mm Hg. 16 ion gauges and 3 pressure transducers measured the velocity and pressure of shock and reaction fronts. Two lines of ion sensors (8 each line) provided measurements of a quasi-detonation velocity in different parts of the test volume along the direction of wave propagation.

Results

Figure 2 shows the video storyboard (324000 frames per second) of a small zone where the wave velocity is already stationary (Figure 3). The arrows indicate the direction and distance traveled by the brightest region in the flame front. Based on this, local reaction zone velocities around cylinders were determined (Figure 4). As can be seen from the figure 4 and table 1 the velocity is varied from 400 m/s to 1500 m/s.

If we determine the average quasi-detonation velocity V = 675 m/s (Figure 3) as the velocity of the leading shock wave heading a quasi-detonation structure, the post-reflected shock wave pressure and temperature behind normally reflected leading shock at initial pressure 0.02 MPa are P_5 = 0,35 MPa and T_5 = 907 K respectively. Based on these values, we can find ignition time and induction zone length using a detailed kinetic mechanism from [18]: τ_{ind} = 1,17 ms, $L_{ind} = \tau_{ind}$ V = 790 mm, where V - the leading shock wave velocity. This means that during the time between initial shock compression and auto-ignition of the mixture in porous layer the leading shock front should travel the distance approximately equal to 158 pore size. At the same time the pressure and ion current measurements show that induction zone length is less than one pore size (Figure 3a). This result is evidence that the self-ignition of the mixture due to the normal shock reflection mechanism is not sufficient to maintain the propagation of quasi-detonation in a porous medium [16, 17]. If we assume that the leading shock wave velocity is close to maximal measured in experiments (Figure 2, Frame 4) V = 1516 m/s. For such wave intensity, for post-shock conditions behind leading shock wave we immediately obtain values of P_2 = 0,56 MPa and T_2 = 1770 K, τ_{ind} = 0,5 µs and L_{ind} = 0,76 mm for ignition time and induction zone length correspondingly. This value for induction zone length correlates well with the pore size (Figure 2 , frame 1).

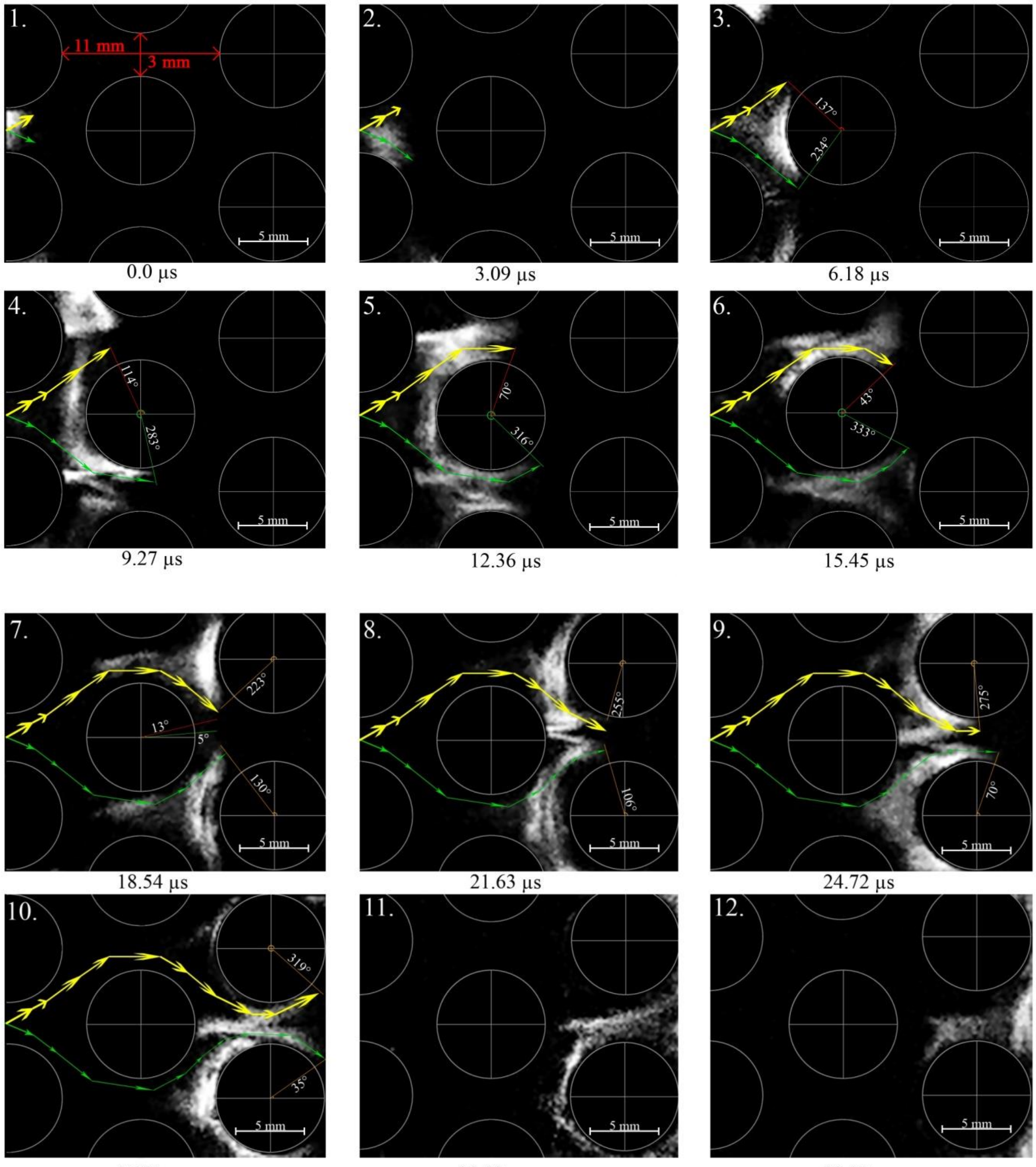

Figure 2. The video storyboard (*324000* frames per second) of quasi-detonation propagation along the pores.

Table 1: Reaction zone velocities of deduced from the photos

Frame number	Velocity above obstacles (m/s)	Velocity below obstacles (m/s)	Frame number	Velocity above obstacles (m/s)	Velocity below obstacles (m/s)
2	397	750	7	978	652
3	1110	1145	8	987	626
4	851	1516	9	546	1031
5	1236	881	10	1172	969
6	775	579			

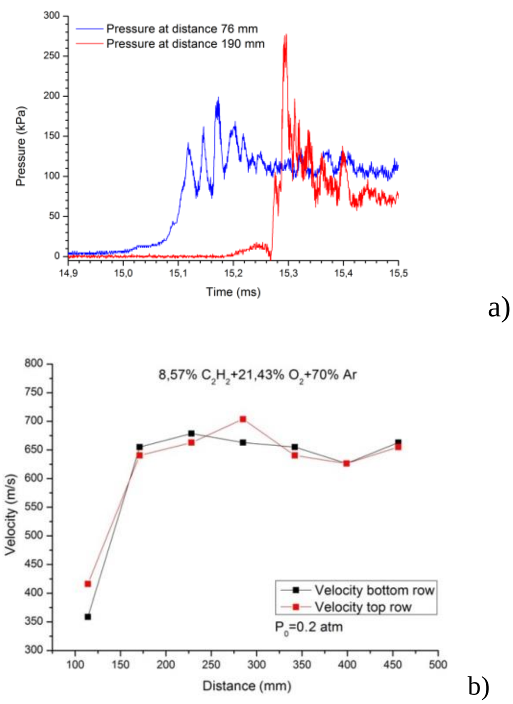

Figure 3. Pressure (a) and mean front velocity measured by ion probes (b).

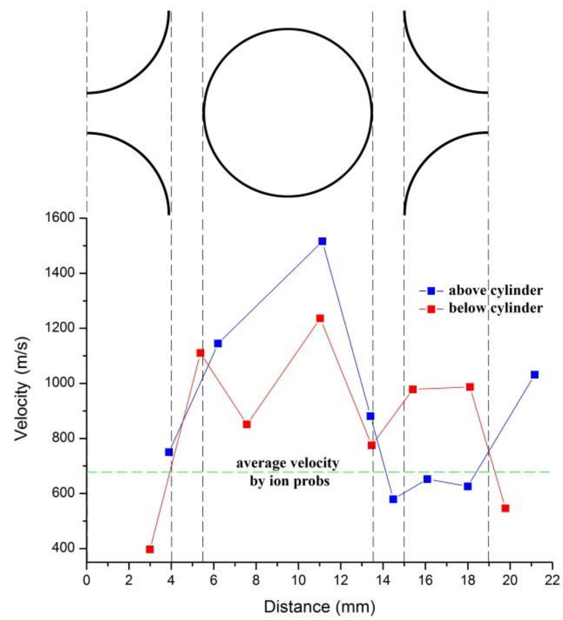

Figure 4. Local wave velocities around cylinders.

Conclusions

The propagation of fast deflagration and quasi-detonations in a layer comprised of matrix of 8-mm steel cylinders has been studied experimentally using high speed self-luminous observations. It was shown that inside the pore velocity can vary from 500 up 1600 m/s, while the average velocity of quasi-detonation is 650-700 m/s. Assuming that the velocity of leading shock wave heading the reaction zone is close to the maximal velocity of reaction zone 1600 ms we can obtain the realistic value for induction zone length of quasi-detonation correlating with the size of the pore.

References

[1] Kauffman CW, Chuanjun Y, Nicholls JA. (1982). Gaseous detonations in porous media. Proc. Combust. Inst. 19:591.
[2] Pinaev AV, Lyamin GA. (1989). Fundamental laws governing subsonic and detonating gas combustion in inert porous media. Combustion Explosion Shock Waves. 25:75.
[3] Babkin VS, Korzhavin AA, Bunev VA. (1991). Propagation of premixed gaseous explosion flames in porous media. Combustion and Flame. 87:182.
[4] Makris A, Shafique H, Lee JHS, Knystautas R. (1995). Influence of mixture sensitivity and pore size on detonation velocities in porous media. Shock Waves. 5: 89.
[5] Mihalik TA, Lee JH, Continillo G, Marra FS. (2001). Quenching Mechanisms of Gaseous Hydrocarbon-Air Flames in Packed Beds. Proc. 18th ICDERS.
[6] Achasov OV, Krivosheyev PN, Penyazkov OG, Sevrouk KL, Zhdanok SA. (2002). Ignition of an explosive gas mixture by a detonation wave formed in a porous medium. Advances in Confined Detonations: 109 (ISBN 5-94588-008-6)
[7] Zhdanok SA, Krivosheyev PN, Mbarawa M, Penyaz'kov OG. (2005). Ranges of Rates of Supersonic Combustion in a Porous Medium. Journal of Engineering Physics and Thermophysics. 78-4: 625.
[8] Achasov OV, Krivosheyev PN, Penyazkov OG, Zhdanok SA. (2004). Propagation and transmission of high-speed deflagration formed in porous media. Fire and explosion hazards: 829.
[9] Lee JHS, Knystautas R, Chan CK. (1985). Turbulent flame propagation in obstacle-filled tubes. Proc. Combust Inst. 20:1663.
[10] Teodorczyk A, Lee JHS, Knystautas R. (1988). Propagation mechanism of quasi detonations. Proc. of 22nd international symposium on combustion: 1723.
[11] Teodorczyk A. (1995). Fast deflagrations and detonations in obstacle-filled channels. Biuletyn Instytutu Techniki Cieplnej Politechniki Warszawskiej. 79: 145.
[12] Kuznetsov M, Matsukov I, Alekseev V, Dorofeev S. (1999). Photographic study of unstable turbulent flames in obstructed channels. Proc. 17th ICDERS.
[13] Rogg B, Hermnann D, Adomeit G. (1985). Shock-induced flow in regular arrays of cylinders and packed beds. Int. J. Heat Mass Transfer. 28-12: 2285.
[14] Ciccarelli G, Johansen C, Parravani M. (2011). Transition in the propagation mechanism during flame acceleration in porous media. Proc. Combust. Inst. 33: 2273.
[15] Thomas P, Ciccarelli G. (2015). Combustion wave propagation through a bank of cross-flow cylinders. Combustion and Flame. 162: 3254.
[16] Krivosheyev PN, Penyazkov OG, Zhdanok SA. (2005). Propagation mechanism and transmission of quasi-detonations. Proc. 20th ICDERS.
[17] Zhdanok SA, Krivosheyev PN, Penyazkov OG. (2005). Investigations of propagation and transition of detonation from porous medium to volume. Russian Journal of Physical Chemistry. 24: 27 (In russian) (С.А.Жданок, П.Н.Кривошеев, О.Г.Пенязьков . (2005). Исследования распространения и перехода детонации из пористой среды в объем. Химическая Физика. 2005. том 24. № 7. С. 27-36.)
[18] Alexander Konnov's combustion mechanisms (version 0.5). Available at: http://homepages.vub.ac.be/~akonnov/. (accessed 15.11.2011).