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Deflagration-to-Detonation Transition in a High-Velocity Flow with Separate Delivery of Fuel and Oxidizer

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In [1], we have reported the design of an experimental model of a pulsed detonation burner (PDB) operating on natural gas, which is a prototype of new-generation industrial burners with no analogues in the world. For this PDB, the low-frequency (0.03 Hz) cyclic controlled deflagration-to-detonation transition (DDT) have been studied upon separate continuous delivery of natural gas and air at a relatively low velocity (~0.5–1.0 m/s) [1]. The most important achievement of [1] is realization of the “fast” DDT [2] in a straight tube 94 mm in diameter owing to the careful selection of the shape and arrangement of turbulizing obstacles that provide optimal matching between the flame acceleration and shock wave amplification.

In the present work, we have experimentally demonstrated for the first time that the fast DDT can be realized under the conditions of separate delivery of fuel and oxidizer—natural gas and air–at considerably higher velocities (~10 m/s) as compared with those in [1], which makes it possible to considerably increase the operating frequency and thermal power of promising PDBs.

The experimental setup (Fig. 1) consisted of two connected sections of a mixing and ignition device (MID) with a spark ignition source (ignition energy, ~1 J) and a straight detonation tube 150 mm in diameter and 5500 mm long with specially arranged obstacles of special shape. The construction of the sections and their connection, as well as the obstacle shape and arrangement are subjects of patenting and are not discussed here.

The detonation tube has an open end. The tube segment 2000 mm long adjacent to the open end was smooth; i.e., it had no obstacles. Natural gas and atmospheric air were continuously delivered to the setup through different pipes: natural gas was fed from a receiver 200 L in volume with an overpressure of 0.3 atm, and air was delivered by means of an SCL-K11TS vortex air compressor. The latter provided air flow rates up to 500 L/s. The gas flow rates were adjusted in a way to obtain a stoichiometric mixture. The natural gas contained 98.9% of methane (motor gas).

The following process parameters were recorded in the experiment: the pressure in the MID (by means of KARAT-DI60 low-frequency pressure transducers), the pressure in different measuring sections of the detonation tube (by means of PCB 113A23 high-frequency piezoelectric pressure transducers), and the glow of combustion products in different measuring sections of the detonation tube (by means of photo gauges based on FD-256 photodiodes). The signals of the transducers and photodiodes were recorded by a personal computer by means of amplifiers and analogue-to-digital converters.

The table presents the distances (*X*) of transducers 1–12 from the beginning of the detonation tube. Transducers 9–12 were located in the smooth segment of the tube. The average velocity of the pressure wave or the shock wave (SW) in each segment between neighboring transducers in the detonation tube was determined from the distance between the transducers and the time interval between the arrivals of the SW front at the corresponding transducer on the oscillogram. The error of determination of the average SW velocity was no more than 2%. Detonation was mainly identified by three criteria: (1) the quasi-stationary SW velocity between the neighboring transducers in the smooth tube segment (1600 m/s or higher), (2) the pressure recorded by a transducer (30 atm or higher), and (3) characteristic soot tracks on the foil (spin pitch, 400–500 mm) introduced through the open end into the detonation tube. In some cases, the records of photo gauges mounted in the same section with pressure transducers were used for identification of detonation. In these cases, simultaneous sharp deviations

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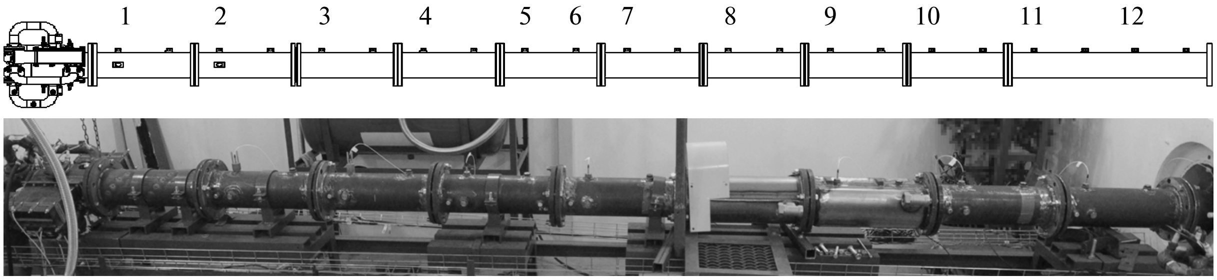

Fig. 1. Schematic and photograph of the experimental setup. 1–12 are pressure transducers.

of photo gauge and transducer signals corresponded to detonation.

The most important result of this work is the demonstration of the possibility of the fast DDT at high flow velocities (~10 m/s) upon separate delivery of fuel and oxidant. It has been shown that the use of specially arranged turbulizing obstacles of special shape in such a tube can provide a reliable DDT at a distance of 3–4 m from the ignition source within 15–16 ms after the ignition.

Figure 2 shows the oscillograms of pressure (*p*) and the photograph of the soot print in one of the runs with fast DDT. The numbering of transducers corresponds to the numbering in the table. As seen, the explosion in explosion (by the terminology of Oppenheim [3]) occurs between transducers 6 and 7 located at a distance of 2372 and 2623 mm from the ignition source within ~14.5 ms after the ignition. The explosion occurs between the SW precursor and flame and leads to the formation of a overdriven detonation wave propagating in the direction to the open end of the tube and a retonation wave traveling toward the ignition source. Near transducer 9 (at a distance of ~3622 mm), the overdriven detonation wave overtakes the SW precursor so that a self-sustained detonation wave is formed, which propagates in a quasi-stationary mode in the smooth segment of the tube (of ~1900 mm in length) at an average velocity of 1600–1700 m/s. Figure 3 shows the evolution of the average SW velocity along the detonation tube length (*X*) in three experiments at identical initial conditions. The points in the curves correspond to the positions of transducers (2–12).

The observed detonation regime should be treated as a near-limit one. First, the average velocity deficit of 100–200 m/s as compared with the thermodynamic value for the stoichiometric methane–air mixture (~1800 m/s, Fig. 3) is consistent with the allowable deficit of the detonation velocity for the propagation limit in the smooth tube. Second, the wave structure in the smooth tube segment (Fig. 2) corresponds to the structure of spinning detonation with characteristic slowly damped oscillations of the signal. In particular, the oscillation frequency behind the wave front is approximately 3.7 kHz. This frequency is consistent with the known heuristic rule $s/d \approx 3$, where s is the spin pitch, and d is the tube diameter. Indeed, according to this rule, the spin pitch in a tube 150 mm in diameter should be $s \approx 450$ mm, and at the average velocity of spinning detonation $D \approx 1600-1700$ m/s, the characteristic frequency should be $D/s \approx 3.6$–3.8 kHz.

The possible operation frequency of the experimental setup in the pulsed detonation mode can be estimated from the following considerations. Inasmuch as the velocity of filling of the detonation tube with the fuel–air mixture is ~10 m/s, the filling time will be ~550 ms. It is seen from the oscillogram in Fig. 2 that the total combustion time for the mixture in the experimental setup (upstream of transducer 12) is ~16–17 ms. If the average speed of the outflow of the major portion of the combustion products through the open end of the tube into the atmosphere is taken to be close to the characteristic speed of sound in the combustion products (~1000 m/s), then it takes several tens of milliseconds for these combustion and detonation products to leave the setup; i.e., this time is comparable with the total combustion time of the mixture. Inasmuch as the detonation tube filling time is considerably longer than the total combustion time and the tube emptying time, it is evident that the filling process determines the operation frequency of the setup in the pulsed model. Hence, under our conditions, the pulse frequency of ~1.5–2.0 Hz can be obtained.

Thus, we have experimentally demonstrated for the first time that the fast DDT can be realized under the high-velocity flow conditions (~10 m/s) with separate delivery of fuel and oxidizer—natural gas (98.9%

Distances of pressure transducers from the beginning of the detonation tube

Transducer	1	2	3	4	5	6	7	8	9	10	11	12
X, mm	124	624	1123	1623	2122	2372	2623	3123	3622	4120	4620	5122

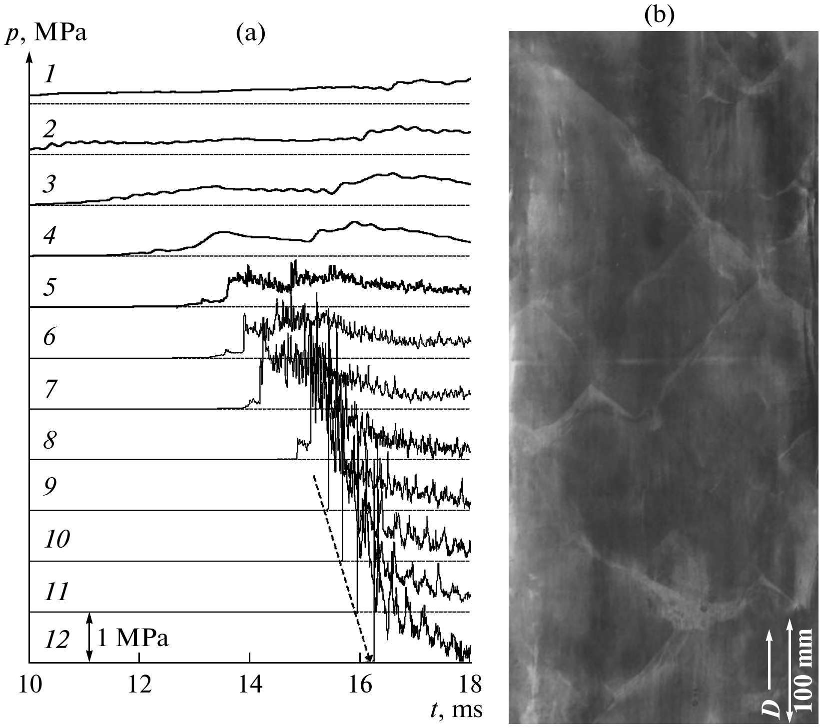

Fig. 2. (a) Oscillograms of pressure on transducers in the experiment with the fast DDT and (b) the photograph of the soot track of the detonation wave. The detonation wave trajectory is shown by a dashed line.

methane) and air—in a tube 150 mm in diameter with an open end and a weak ignition source with an ignition energy of ~1 J. It has been shown that the use of specially arranged turbulizing obstacles of special shape in such a tube can provide a reliable DDT at a distance of 3–4 m from the ignition source within 15–16 ms after the ignition. The results of this study will be used in development of an industrial burner of a new type, namely, a pulsed detonation burner for fast heating and fragmentation of various materials, which provides a combined impact, thermal and shock wave (mechanical), on the objects blown with combustion products.

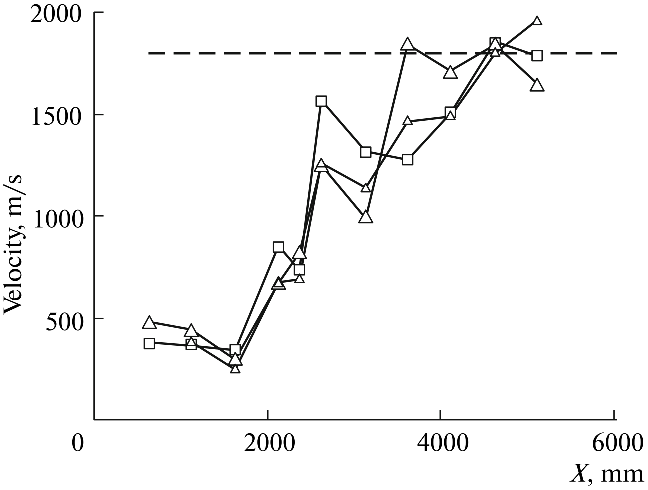

Fig. 3. Measured dependence of the velocity of the leading pressure wave or SW on the travelled distance *X* obtained from the pressure oscillograms in three experiments (△, □, ▵) under identical initial conditions.

ACKNOWLEDGMENTS

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REFERENCES

1. Frolov, S.M., Aksenov, V.S., Ivanov, V.S., et al., *Khim. Fiz.*, 2011, vol. 30, no. 7, pp. 77–80.
2. Frolov, S.M., *Khim. Fiz.*, 2008, vol. 27, no. 6, pp. 31–44.
3. Oppenheim, A.K., *Introduction to Gasdynamics of Explosions*, Wien; New York: Springer, 1972.

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