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PHYSICAL CHEMISTRY

Deflagration-to-Detonation Transition in Crossed-Flow Fast Jets of Propellant Components

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Abstract—It was experimentally proven for the first time that the turbulence produced by crossed-flow supersonic jets of a fuel (natural gas) and an oxidizer (oxygen), which are injected at a pressure of 25 to 150 atm into a smooth detonation tube 74 mm in diameter, causes a fast deflagration-to-detonation transition at distances as short as 300 mm (up to 4 tube diameters) in times of tenths of a millisecond (~0.4 ms). The obtained results can be used for designing compact predetonators for detonation combustors of promising energy-converting devices.

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All the existing concepts of transport and power engineering equipment using the chemical energy of various fossil or synthetic fuels are based on either direct or indirect conversion of the chemical energy of controlled fuel combustion into useful work, with the combustion being always considered slow (essentially subsonic). An alternative solution attractive from the energy point of view, which promises a qualitative leap in energy saving, is a transition to (essentially supersonic) controlled detonation combustion [1].

Numerous designs of controlled detonation combustion, including pulse-detonation [2] and continuous-detonation [3] combustion, have been proposed to date. An important challenge of controlled detonation combustion is to initiate detonation in the working medium (a mixture of a standard motor fuel and an oxidizer) over the shortest distances at the minimum ignition energy. One of the known methods for initiating detonation is to transmit a detonation wave from the highly detonable donor propellant mixture into the combustion chamber being filled with the working medium. In pulse-detonation combustors, detonation wave transmission is repeated in each cycle, whereas in continuous-detonation combustors, it is performed once; however, initiating pulses can be repeated in the case of blowout.

Predetonators (detonation tubes filled with a donor propellant mixture) typically include weak ignition sources (spark plugs), turbulizing obstacles ensuring fast deflagration-to-detonation transition [4], and oxygen as an oxidizer. Along with the requirement of reliable operation in a high-frequency mode, predetonators are also imposed with requirements of high survivability and compactness (minimum overall sizes guaranteeing detonation wave generation at a minimum amount of the donor propellant mixture). Meanwhile, the products of detonation of oxygen mixtures have very high temperature (above 3000 K), and uncooled turbulizing obstacles are rapidly destroyed, whereas refusing to use turbulizing obstacles leads to a significant (by a factor of tens [5]) increase in the overall sizes of predetonators. The published (see, e.g., [6, 7]) methods for designing a fast deflagration-to-detonation transition in smooth tubes require relatively strong ignition sources.

The purpose of this work was to experimentally explore the possibility of performing a fast cyclic deflagration-to-detonation transition over short distances in a smooth tube into which gaseous propellant components are supplied separately without any turbulizing obstacles. The idea underlying this work was to create conditions for fast flame acceleration in a smooth tube using crossed-flow supersonic gas jets providing high turbulence.

Figure 1 presents a schematic of an experimental setup. The setup consists of a 1-m-long steel detonation tube of diameter $d = 74$ mm with 4.5-mm-thick

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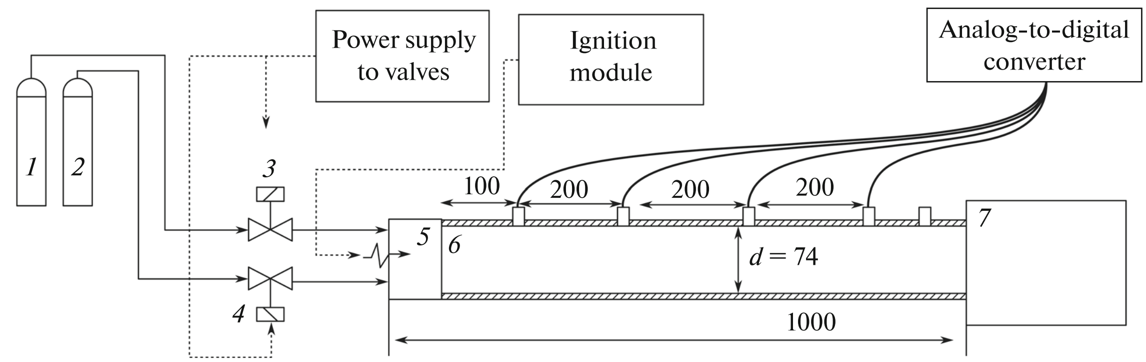

Fig. 1. Schematic of experimental setup: (*1*, *2*) oxygen and natural gas cylinders, (*3*, *4*) controlled valves, (*5*) spark plugs, (*6*) detonation tube, and (*7*) buffer tank. Dimensions are in millimeters.

smooth walls; a system of supply of gaseous propellant components (commercial oxygen and natural gas containing 98% methane); and ignition, control, and diagnostics systems. One end of the detonation tube is closed and has holes for interchangeable nozzles for supplying propellant components with a cross-section area of 0.5 to 10 mm^2 and for two spark plugs (standard automotive spark plugs with an ignition energy of ~0.2 J). The other end of the detonation tube is connected to a large buffer tank about 2 m^3 in volume, which is vented to the atmosphere through a permeable flame arrester.

The gases are fed to the nozzles by two supply lines 8 mm i.d. from standard 40-L cylinders at a pressure of 25 to 150 atm. In the supply lines 100 mm upstream of the nozzles, controlled solenoid valves are installed. The volumes of the sections of the oxygen and natural gas supply lines from the cylinders to the valves are ~300 and ~280 mL, respectively. The volumes of the sections of the oxygen and natural gas supply lines from the valves to the nozzles are ~5 mL in each case.

The ignition system is based on a standard automotive ignition module belonging to the control system. The control system includes a TEMP-1m4 four-channel time relay controlling two solenoid valves and the ignition module. The minimum discrete time of change in the state of the channels is 10 ms. The channel change time error is within 5 ms. The diagnostics system comprises four ionization probes mounted along the detonation tube, a low-frequency pressure transducer in the buffer tank, two low-frequency pressure transducers in the propellant component supply lines, a USB-3000 analog-to-digital converter, and a PC. The ionization probes record the propagation of the reaction front along the tube. The recording of slow combustion fronts and detonation fronts with ionization probes was successfully used previously and has proven its reliability and efficiency [8]. From the ionization probe readings, the reaction front velocity was determined as the ratio of the distance between probes to the time it takes for the front to travel this distance. The front velocity determination error is estimated at 5%. The pressure transducer in the buffer tank is used for determining the time of flow of the detonation products from acoustic vibrations. The pressure transducers in the propellant component supply lines monitor the pressure in the supply lines. From the pressure drop rate in the supply lines, the flow rates of the propellant components and the average composition of the mixture in the detonation tube were found. The error of determining the average fuel–oxidizer equivalence ratio in the detonation tube is estimated at 20% at most.

The experiment was carried out in a single-pulse mode or in a high-frequency mode according to the following procedure. Before the experiment, the sections of the propellant component supply lines between the cylinders and the valves were filled with the gases to a certain given pressure level, after which the cylinder valves were closed. Then the control system sent a signal to open the valves and, in a given delay time, signals to ignite the propellant mixture and close the valves. If the experiment was performed in the high-frequency mode, then, after a certain time interval, which depended on the operation frequency, signals to open or close the valves or to ignite the mixture were sent again. The experiment was conducted until the pressure in the supply lines decreased to a certain lower limiting value. Thus, the maximum amount of the propellant mixture that participated in the experiment is the sum of the amounts of the propellant components in the sections of the supply lines between the cylinders and the valves.

The main result of this work was an experimental proof of the possibility of performing a fast cyclic deflagration-to-detonation transition over short distances in a smooth tube into which gaseous propellant components are supplied separately without any turbulizing obstacles. Such a proof was obtained both in the single-pulse mode and in the high-frequency mode. In the single-pulse mode, an ignition signal was sent at a frequency less than 0.1 Hz, and in the high-frequency mode, the ignition frequency was 1 to 10 Hz.

Figures 2 and 3 give examples of the ionization probe readings and, calculated from these readings,

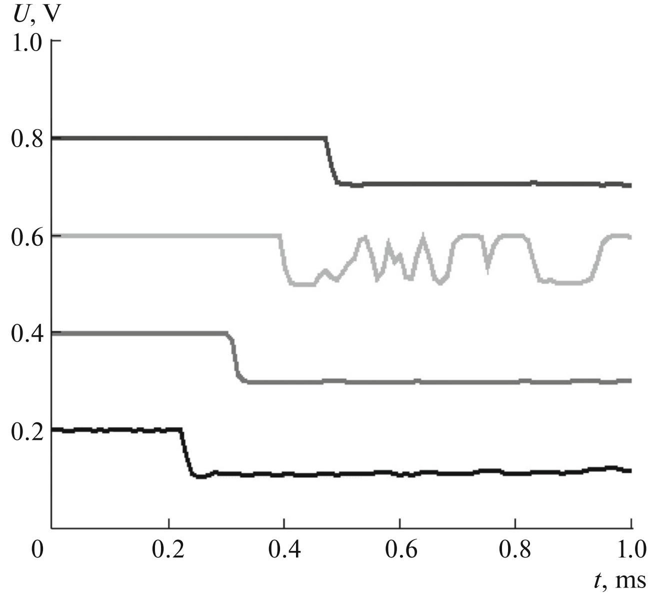

Fig. 2. Example of the ionization probe signal readings in a single pulse.

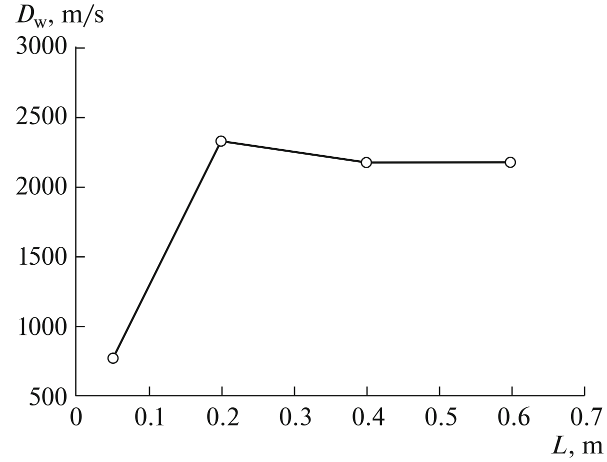

Fig. 3. Example of the measured dependence of the detonation wave velocity on the traveled distance in a single pulse.

the dependence of the reaction front velocity on the traveled distance, respectively, in an experiment performed at initial pressures in the oxygen and natural gas supply lines of 150 atm with cross-section areas of the nozzles of 9 and 4 mm^2, respectively. The estimated average fuel–oxidizer equivalence ratio in this experiment is $\Phi \approx 1.5$. Based on the ionization probe signal rise rate (in Fig. 2, the signals are recorded from top downward), it can be said that the ionization probes detect the change in the ionization current in the detonation tube (see [8]). The reaction front velocity at the first measurement segment (see Fig. 3) was calculated from the time interval from the beginning of ignition to the arrival of the front at the first probe. Figure 3 shows that the detonation wave velocity at a distance of as short as ~300 mm reaches 2300 m/s, and then the detonation wave front propagates quasi-steadily at a velocity of 2200 m/s. In other words, in this single-pulse experiment, a fast deflagration-to-detonation transition was detected at the predetonation distance $L \approx 4d$ in a time of about 0.4 ms after ignition. Although the detonation wave velocity values measured in our experiments generally agree with the published experimental results [9] over a wide range of fuel–oxidizer equivalence ratios, the former are, on the average, somewhat (by several percent) higher than the latter. This indicates that, because of the short length of the measurement section, the detonation waves observed in our experiments propagate in an overdriven, rather than self-sustained mode.

The high-frequency mode of setup operation with simultaneous opening and closing of the propellant component supply valves turned out to be the most stable and ensure a fast cyclic deflagration-to-detonation transition up to a frequency of 10 Hz. Figure 4 presents an example of the measured dependence of the reaction front velocity on the traveled distance in an experiment conducted at initial pressures in the oxygen and natural gas supply lines of 96 and 109 atm with cross-section areas of the nozzles of 9 and 1 mm^2, respectively, in four successive pulses at a frequency of 10 Hz. The estimated average fuel–oxidizer equivalence ratio in this experiment varied from $\Phi \approx 0.75$ in the first pulse to $\Phi \approx 1.48$ in the fourth pulse. As previously, the reaction front velocity at the first measurement segment was calculated from the time interval from the beginning of ignition to the arrival of the front at the first probe. In the high-frequency mode, as well as in the single-pulse mode, the detonation wave velocity at a distance of as short as ~300 mm reaches 2300–2400 m/s, and then the detonation wave front propagates quasi-steadily at a velocity of 2200 to 2500 m/s. In other words, in this experiment, a fast cyclic deflagration-to-detonation transition was detected at the predetonation distance $L \approx 4d$ in a time of about 0.4 ms after ignition.

Thus, we, for the first time, experimentally proven the possibility of performing a fast cyclic deflagration-to-detonation transition over very short distances in a smooth tube into which gaseous propellant components (oxygen and natural gas) are supplied separately without any turbulizing obstacles. The idea underlying this work was to create conditions for fast flame acceleration in a smooth tube using crossed-flow supersonic gas jets providing high turbulence. The obtained results can be used for designing compact predetonators for continuous- and pulse-detonation combustors of promising energy-converting devices. Such predetonators, which are sections of a smooth tube 4–5 diameters long, can generate successive detonation pulses at a frequency up to ~10 Hz even at very weak

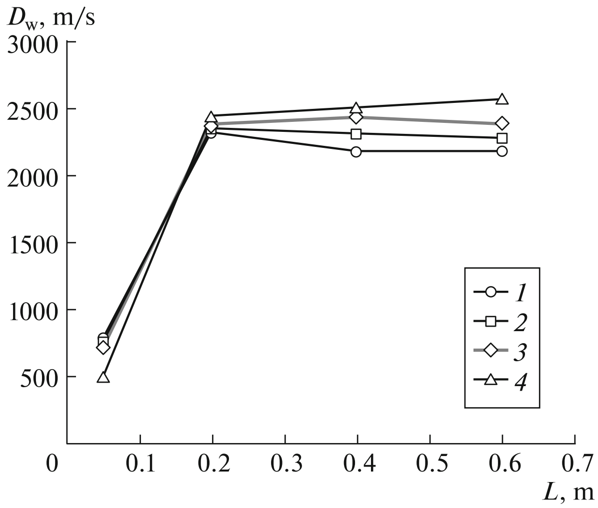

Fig. 4. Example of the measured dependences of the detonation wave velocity on the traveled distance in four successive pulses at an operating frequency of the setup of 10 Hz.

(~0.2 J) ignition. Important distinguishing features of such a predetonator are the absence of turbulizing obstacles (complicating strongly the cooling system) and the repeated generation of overdriven detonation waves, which have higher initiating ability than self-sustained detonation waves.

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