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Cyclic Deflagration-to-Detonation Transition in the Flow-Type Combustion Chamber of a Pulse-Detonation Burner

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Abstract—The possibility of realization of a rapid cyclic deflagration-to-detonation transition (DDT) with a frequency of up to 2 Hz under conditions of high-velocity flow (~10 m/s) and separate supply of the combustible mixture components (methane and air) in a tube, 5.5 m in length and 150 mm in diameter, with an open end at a low ignition energy (~1 J) is for the first time demonstrated. It is shown that such a tube with turbulizing obstacles of special shape and placement can ensure reliable DDT at a distance of 3–4 m from the ignition source within $\Delta\tau_{DDT} \le 20$ ms after ignition. The results will be used in the development of a new type of industrial burner—a pulse-detonation burner for high-rate heating and fragmentation, combining thermal and shock-wave (mechanical) impacts on the treated object.

Keywords: cyclic deflagration-to-detonation transition, natural gas–air mixture, pulse-detonation burner

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INTRODUCTION

In existing power plants and burners, the chemical energy of fuel is converted into heat and mechanical work through slow combustion, known as deflagration. In addition to deflagration, there is another mode of combustion—detonation. During detonation, the chemical oxidation of fuel occurs in the mode of self-ignition at high pressure and density behind a strong shock wave. So far, detonation has not been used in the energetics, largely because of the problem of the initiation of detonation waves: to initiate detonation, it is necessary to ensure a reliable and controlled deflagration-to-detonation transition (DDT) within the shortest possible distances at a possibly low ignition energy, while the detonability of practical fuel–air mixtures under normal conditions is known to be very poor.

In 2010, at the Center for Pulse-Detonation Combustion of the Semenov Institute of Chemical Physics RAS, an experimental model of a pulse-detonation burner (PDB) operating on natural gas was for the first time constructed, a prototype of industrial burners of new generation, combining shock wave (mechanical) and thermal impacts [1]. The important scientific result of [1] is the demonstration of a rapid cyclic DDT [2] over a predetonation distance of 2.5–3.0 m at a relatively low ignition energy (~1 J) in a near-limit-diameter (94 mm) tube with an open end and a separate supply of natural gas and air. The problem of detonation initiation was solved by a careful selection of the shape and placement of turbulizing obstacles, so as to provide an optimum balance between the rates of flame acceleration and shock wave (SW) amplification. Using the model PDB, the authors of [1] performed experimental studies of low-frequency (0.03 Hz) controlled cyclic DDT at relatively low flow velocities of natural gas and air (~0.5–1.0 m/s).

The present study experimentally demonstrates the possibility of realization of rapid cyclic DDT with separate supply of natural gas and air at much higher velocities (~10 m/s) than those used in [1]. The results of the work give ground to significantly increase the operation frequency and thermal power of promising PDBs.

EXPERIMENTAL SETUP

The experimental setup (Fig. 1) consists of two coupled sections: a mixing and ignition unit (MIU) with a spark ignition source (~1 J) and a straight detonation tube, 150 mm in diameter and 5.5 m in length, with obstacles of special shape and placement. The construction of the sections, the details of their coupling, and the shape and positioning of the obstacles, being subjects of patenting, are not discussed here. The end of the detonation tube was open. The tube section adjacent to the open end, 2-m long, was smooth, without obstacles in it.

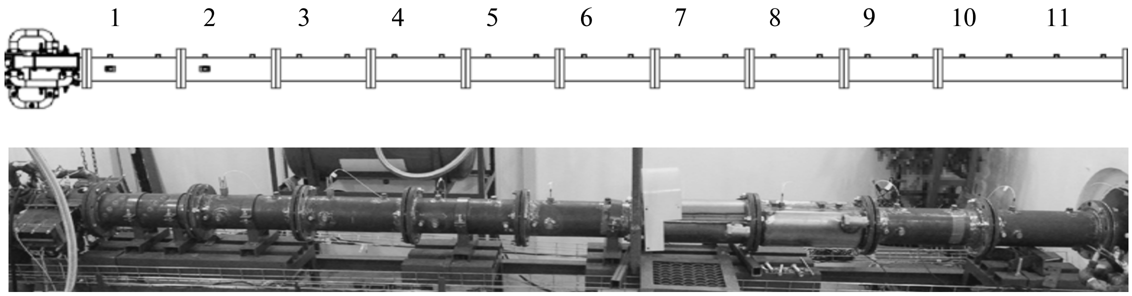

Fig. 1. Schematic diagram and photograph of the experimental setup.

The operation cycle of the installation consisted of several stages, the durations of which were controlled by a digital controller. In the first stage, the installation was filled with a natural gas–air mixture, with both the mixture components being fed into the MIU through separate pipelines equipped with check valves. The velocity of admission of the fuel–air mixture (FAM) was ~10 m/s. Natural gas, containing 98.9% methane, was fed into the detonation tube through the MIU from a 200-L container at an excess pressure of 0.3 atm. Atmospheric air was supplied into the installation by a SCL-K11TS vortex blower. The blower provided an air flow rate of up to 500 L/s. During filling the installation with combustible gas mixture, the flow rate was adjusted so as to ensure the stoichiometric composition of the mixture. In addition, the mixture composition was analyzed by chromatography. To prevent fresh mixture from outflowing through the open end of the detonation tube, it was filled with mixture incompletely. A digital controller enabled to set up the time of tube filling accurately to provide its safe cyclic operation even in the absence of DDT: the mixture burned out completely in both the detonation and deflagration modes.

In the second stage, after natural gas shutoff (with a fast-response shutoff valve), multipoint ignition of the combustible mixture in the MIU was produced and the air flow was cut off, followed by the processes of flame acceleration and rapid DDT at a distance of L_{DDT} = 3–4 m from the ignition source within $\Delta\tau_{DDT} \leq$ 20 ms after ignition.

In the third stage, the discharge of the shock wave and the outflow of the detonation products through the open end of the tube occurred. If we assume that the average velocity of the bulk of the combustion products flowing through the open end of the tube into the atmosphere is close to the characteristic speed of sound in the combustion products (~1000 m/s), the time of evacuating the combustion and detonation products will be a few tens of milliseconds, i.e., comparable to the total time of mixture combustion.

In the fourth stage, the entire installation, containing residual gases, was first purged with air for $\Delta\tau_p$ = 50–100 ms, after which the supply of natural gas and air was switched on, and the cycle repeated itself.

The maximum frequency of operation of the experimental setup in the pulse-detonation mode was evaluated based on the total cycle time: $\Delta\tau_c = \Delta\tau_f + \Delta\tau_{DDT} + \Delta\tau_e + \Delta\tau_p \approx$ 450–550 ms. Since the filling of the detonation tube takes a significantly longer time $\Delta\tau_f$ as compared to the total time of mixture combustion $\Delta\tau_{DDT}$ and the time of tube emptying, it is clear that the maximum frequency of operation of the setup is determined by the time of gas mixture filling and the time of purge with air $\Delta\tau_p$. Therefore, the maximum pulse frequency in our case is $f_{max} \approx 2$ Hz.

We recorded the following parameters of the process: the pressure in the MIU (using CARAT-DI frequency pressure sensors), the pressures at different measurement cross sections of the detonation tube (with PCB113A23 high-frequency piezoelectric pressure sensors) and the luminescence of the combustion products at different measurement cross sections of the detonation tube (with photodetectors based on FD-256 photodiodes). The signals from the sensors and photodiodes were fed into amplifiers and analog-to-digital converters, into a personal computer.

Given below are the distances to pressure sensors 1–11 from the beginning of the detonation tube:

No.	1	2	3	4	5	6	7	8	9	10	11
X, mm	124	624	1123	1623	2122	2623	3123	3622	4120	4620	5122

Sensors 8–11 were positioned over the smooth section of the tube. The mean velocity of the pressure or shock wave at each measurement distance between neighboring pressure sensors in the detonation tube was calculated by dividing this distance by the time it took for the shock wave front to traverse it, as determined from the oscillogram. The error in determining *D* was less than 3%. The onset of detonation was mainly identified by three criteria: (1) the velocity of (1600 m/s and above) the quasi-steady shock in the

smooth section of the tube, (2) the pressure amplitude (30 atm and higher) registered by the sensor, and (3) the characteristic pattern on a smoked foil (spin pitch 400–500 mm) inserted through the open end of the detonation tube. In some experiments, detonation was identified using photosensors positioned at the same cross sections with the pressure sensors. In this case, detonation manifested itself through simultaneous sharp signals of the photosensor and pressure sensor.

EXPERIMENTAL RESULTS AND DISCUSSION

The most important new result of the present work is the demonstration of the possibility of realization of a rapid cyclic DDT (with a frequency of cycles of up to 2 Hz) under high-velocity flow conditions (~10 m/s) with separate supply of the combustible mixture components. We have experimentally shown that, in such a tube with turbulizing obstacles of special shape and placement, it is possible to ensure a reliable cyclic DDT at a distance of 3–4 m from the ignition source within a time $\Delta\tau_{DDT} \leq 20$ ms after ignition.

Figure 2 shows pressure oscillograms and a photograph of a smoked-foil pattern for one of the cycles of an experiment with fast cyclic DDT. The numbering in the figure corresponds to the numbering of sensors (see above). It is evident that the explosion in explosion (in the terminology of [3]) occurs ~17.2 ms after ignition between sensors 6 and 7, located at distances of 2623 and 3123 mm from the ignition source. The explosion occurs between the SW precursor and the flame and results in an overdriven detonation wave propagating in the direction of the open end of the tube and a retonation wave traveling towards the source of ignition. In the vicinity of sensor 8 (at a distance of ~3622 mm), the overdriven detonation wave overtakes the SW precursor, and the resultant self-sustaining detonation wave begins to propagate towards the end of the smooth section of the tube in the steady-state mode at an average velocity of 1670 m/s.

Figure 3 shows oscillograms of the pressure signals from four sensors (8–11) in the smooth section of the tube for ten consecutive cycles of operation of the PDB at a frequency of ~1 Hz. In this experiment, the filling of the tube with fresh fuel–air mixture took $\Delta\tau_f \approx 425$ ms. The gradual downward bias of the baselines of all the sensors is due to the heating of the sensors by detonation products. Nevertheless, Fig. 3 shows a good reproducibility of the signals from all the sensors, especially the pressure peaks corresponding to the arrival of the detonation wave.

The closed circles in Fig. 4 show the detonation wave viscosity measured between sensors 8–9, 9–10, and 10–11 in the ten consecutive cycles ($N = 10$) presented in Fig. 3. The solid line represents the arithmetic mean of the detonation velocity $\overline{D}$ for the specified measurement distances in the ten cycles, whereas the horizontal dotted line represents the thermodynamic Chapman–Jouguet detonation velocity for a stoichiometric methane–air mixture ($D_{CJ} \approx 1800$ m/s). As can be seen, detonation propagates in the smooth tube section first (between sensors 8–10) in the overdriven (on average) mode, with a degree of overdrive of

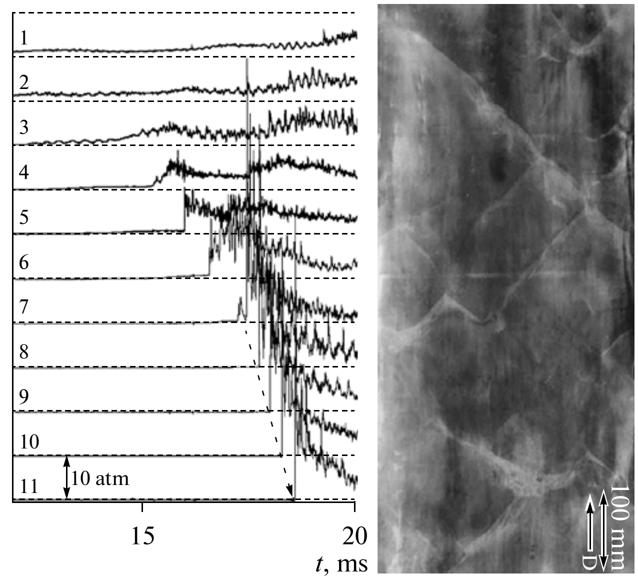

Fig. 2. Oscillograms of the pressure measured by sensors 1–11 during one of the cycles of an experiment with rapid cyclic deflagration-to-detonation transition (left) and a photograph of the smoked-foil pattern of the detonation wave (right). The dashed line shows the trajectory of the detonation wave.

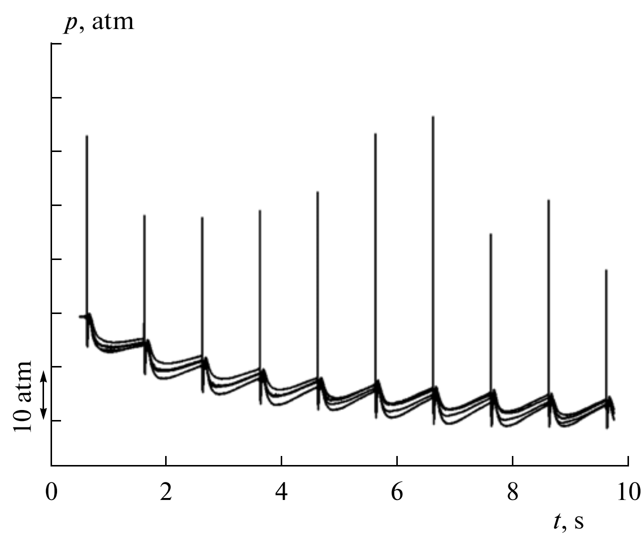

Fig. 3. Oscillograms of the pressure measured by sensors 8–11 in the smooth section of the tube during ten consecutive cycles of PDG operation at a frequency of ~1 Hz for 10 s in an experiment with a time of tube filling with fresh FAM of 425 ms.

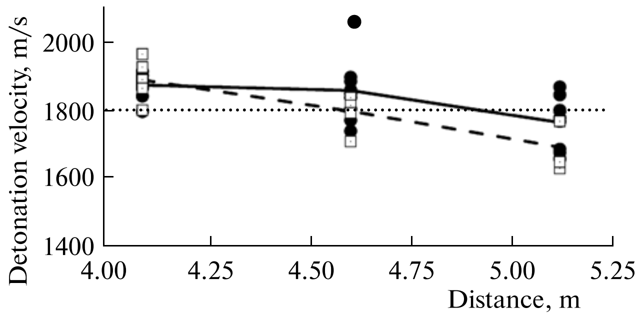

Fig. 4. Experimental value of the velocity D at the measurement distances between sensors 8–9, 9–10, and 10–11 in ten consecutive cycles ($N = 10$) in two experiments: in the experiment specified in Fig. 3 (closed circles, $\Delta\tau_f \approx 425$ ms) and in experiment with $\Delta\tau_f \approx 375$ ms (open squares). The solid and dashed lines represent the arithmetic mean of the detonation velocity in the respective experiments. The dotted line is the Chapman–Jouguet detonation velocity.

3–4% ($\bar{D} = (1.03 \div 1.04)D_{CJ}$), and then, over the last measurement distance (between sensors 10 and 11), at an average velocity somewhat lower than D_{CJ} ($\bar{D} \approx 0.98D_{CJ}$). As known [4], overdriven detonation arises during DDT. That the average velocity over the last measurement distance is low can be explained by two factors. First, a natural attenuation of the overdriven detonation wave is caused by the rarefaction wave arriving from the combustion products zone. Secondly, due to an incomplete filling of the detonation tube with combustible mixture, its composition near the open end differs from that in the rest of the tube (mixture was diluted with purge air), with the outer boundary of the FAM being smeared due to turbulent mixing with purge air.

For comparison, the squares in Fig. 4 show the values of the detonation velocity $\bar{D}$ measured at the spacings between sensors 8–9, 9–10, and 10–11 in another experiment with ten consecutive cycles ($N = 10$), but with a time of tube filling with fresh FAM of $\Delta\tau_f \approx 375$ ms. The reduction of the tube filling time by ~50 ms compared to the experiment represented by the solid curve in Fig. 4 led to the overdriven detonation mode being observed only between sensors 8 and 9, after which the detonation velocity decreased to $\bar{D} \approx 1800$ m/s (between sensors 9 and 10) and then to $\bar{D} \approx 1700$ m/s (between sensors 10 and 11).

As a quantitative criterion of reproducibility of signals in N consecutive operation cycles, we used the cyclic instability coefficient defined as

$$\eta = \max_N \left| \frac{D - \bar{D}}{\bar{D}} \right| \cdot 100\%.$$

According to Fig. 4, the cyclic instability coefficient determined at three measurement segments in two experiments (solid and dashed curves) does not exceed 10%. The maximum deviation of the detonation velocity, $D - \bar{D} \approx 180$ m/s, was observed only in one cycle between sensors 9 and 10, with the rest of the cycles being characterized by $\eta < 5\%$. Such a low value of the cyclic instability coefficient means that the DDT process is well reproduced from cycle to cycle, and, therefore, it can be implemented in industrial pulse-detonation burners.

The detonation mode observed at the end of the smooth section of the tube in the experiments with an incomplete filling of the tube with fresh FAM should be considered a near-limit (spin) one. First, the mean velocity 100–200 m/s lower than the thermodynamic value D_{CJ} is consistent with the admissible detonation velocity deficit at the detonation propagation limit in smooth tubes. Second, the structure of the wave corresponds to the structure of spin detonation, with characteristic weakly damped oscillations of the signal. The oscillation frequency of the wave front in the signal from pressure sensor 11 was approximately equal to 3.7 kHz. This frequency is consistent with the known empirical 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 with a diameter of 150 mm should be $s \approx 450$ mm, so that at the average velocity of spin detonation of $D \approx 1600$–1700 m/s, the characteristic frequency of oscillations must be $D/s \approx 3.6$–3.8 kHz. In addition, the smoked-foil pattern in the smooth section of the tube clearly shows how slightly overdriven detonation wave formed during DDT (with multiple heads in the front) transforms into spin detonation (inclined blurry line in the upper part of the photo of the smoked-foil pattern in Fig. 2. The pressure peaks, significantly higher than the Chapman–Jouguet pressure, also indicate that the detonation propagates in the traditional pulse mode (multiheaded in the overdriven region and single-head in the spin mode). In both cases, due to the presence of transverse waves in the reaction zone behind the leading shock front, the recorded peak pressures are substantially higher than the Chapman–Jouguet pressure.

CONCLUSIONS

Thus, the present study for the first time experimentally demonstrated the possibility of realization of a rapid cyclic DDT under conditions of high-velocity flow (~10 m/s) and separate supply of the combustible mixture components, natural gas (98.9% methane) and air, in a 50-mm-diameter tube with an open end at a low ignition energy (~1 J). It was shown that the use of such a tube with turbulizing obstacles of special shape and placement can ensure reliable cyclic DDT at a distance of 3–4 m from the ignition source within $\Delta\tau_{DDT} \leq 20$ ms after ignition. The maximum frequency of cycles reached at the experimental setup was 2 Hz. The results will be used in developing a new type of industrial burners, a pulse-detonation burner for heating and fragmentation combining thermal and shock wave (mechanical) impacts.

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