A PROTOTYPE OF PULSED DETONATION BURNER OPERATING ON NATURAL GAS

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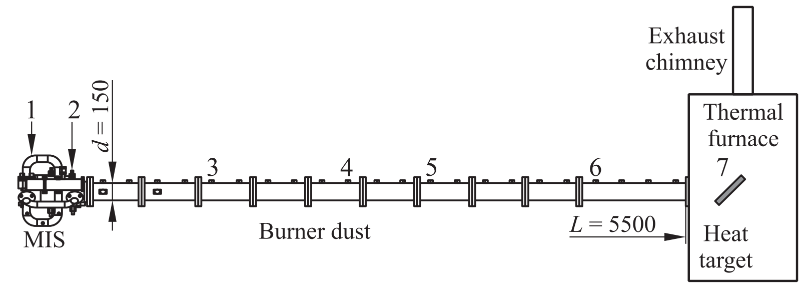
In power plants and industrial burners, fuel is converted into heat and mechanical work due to slow burning referred to as deflagration. Besides deflagration, there exists another combustion mode that is detonation. Upon detonation, chemical oxidation of fuel occurs in a mode of self-ignition at high pressure and density behind a strong shock wave [1]. Detonation was not used in power engineering so far. The main reason is the problem of detonation initiation and control: to obtain detonation, it is necessary to ensure a reliable and controlled deflagration-to-detonation transition (DDT) on the shortest distances with the minimum ignition energy, whereas detonability of practical fuels in air under normal conditions is very low. In the period from 2010 to 2014 the Center for Pulse Detonation Combustion at the ICP RAS performed research and development work on the creation of the world's first energy-saving pulse-detonation burner (PDB) with controlled pulse-detonation combustion of natural gas. The work was launched within the frame of the State Contract with the Ministry of Education and Science of the Russian Federation, according to which the PDB prototype should have met the following requirements:

- thermal power ranges from 2000 to 2500 kW (corresponding to the most common power of conventional burners);
- maximum speed of detonation products in the outlet section is adjustable and ranges from 400 to 1500 m/s;
- operation frequency is adjustable and ranges from 0.01 to at least 2 Hz;
- maximum temperature of detonation products in the outlet section is adjustable and ranges from 1400 to 2500 °C;
- maximum overpressure of detonation products in the outlet section is adjustable and ranges from 2 to 14 atm;
- ignition energy does not exceed 1.0 J; and
- the length of the burner duct does not exceed 5–6 m.

The objective of this paper is to briefly outline the accomplishments of the project and its recent follow-up.

1 Operation Principle

The PDB (Fig. 1) consists of two coupled sections: the mixing/ignition section (MIS) with a spark-ignition source (ignition energy less than 1 J; 2 to 4 standard automobile spark plugs) and the burner duct — a straight tube of 150 mm in diameter and 5.5 m long with obstacles of special shape and placement. The main principles of obstacle shaping and placement are discussed in [2] as well as disclosed in patents [3–5]. According to these references, the shape, pitch, and blockage ratio of obstacles should vary with distance from the ignition source. This variation first ensures the fastest possible flame acceleration for generating a sufficiently strong shock wave and then it ensures the fastest possible transition of this shock wave to a detonation due to its focusing at shaped obstacles of low hydrodynamic drag. The end of the burner duct is attached to the thermal furnace and is open to the atmosphere through the exhaust chimney. The last three sections of the tube of 2-meter total length, adjacent to the open end of the burner duct are made smooth, i. e., there are no obstacles inside.



(*a*)

(*b*)

Figure 1 Schematic (*a*) and photograph (*b*) of the PDB. Dimensions are in millimeters

The operation cycle of the PDB consists of several stages. Their duration is controlled by a digital controller. Both components of the mixture are delivered in MIS through separate lines equipped with check valves. Natural gas containing 98.9% methane (according to certificate) is fed into the burner through the receiver 200 l in volume at overpressure of 0.3 bar connected to the natural gas manifold via a control valve. Ambient air is fed into the PDB with a vortex blower, which provides airflow up to 0.5 m^3/s.

In the first stage, the PDB is filled with a mixture of natural gas and air at a fill rate up to about 30–40 m/s (fill time 130–180 ms). The fill rate is measured by the diaphragm-type flowmeter. When filling the PDB with a combustible mixture, the mass flow rates of components are adjusted to ensure that mixture composition is close to stoichiometric (mixture composition is checked by chromatographic analysis of probes taken in several tube sections), i. e., the volume concentration of methane is $9.5\% \pm 0.3\%$. To avoid leakage of fresh mixture through the open end of the burner duct, the PDB is filled only partly with the mixture. The digital controller sets the time of filling the burner duct to avoid leakage through its open end even for the most undesired condition of DDT failure: a mixture is completely burned in both the detonation and deflagration modes.

In the second stage, after shutoff of natural gas supply (with a fast-acting valve), multipoint fuel–air mixture ignition is triggered in MIS followed by automatic stopping of air supply, fast flame acceleration in the burner duct, and DDT at a distance of $\sim$ 3.5 m from the ignition source for $\sim$ 20 ms after ignition.

In the third stage, the shock wave exits from the duct open end followed by the outflow of the detonation products. If one assumes that the average velocity of the bulk of the combustion products through the open end of the burner duct in the atmosphere is close to the characteristic sound velocity in the combustion products ($\sim$ 1000 m/s), the duration of emptying the duct from the products will be several tens of milliseconds, i. e., the time interval comparable to the total time of mixture burnout via DDT.

In the fourth stage, the PDB is first purged with air over $\sim$ 50–100 ms and then the supply of natural gas and air is resumed; thus, the next cycle starts.

The operation frequency of the PDB in the detonation mode can be readily estimated from the total cycle time. Since the filling of the burner duct is significantly longer than the total time of mixture combustion and duct emptying time, it is evident that the maximum operation frequency is mostly determined by the rate of PDB filling with a combustible mixture and the time of purging the duct with air. Therefore, the maximum pulse frequency in the considered conditions is about 5 Hz. Duration of experiments while working with detonation frequency of (1.8 ± 0.1) Hz reached 300 s without water cooling. With water cooling, the maximum duration of experiments with detonation frequency of (5.0 ± 0.1) Hz reached 100 s. Note that in the latter case, there was no physical limitation of PDB operation, because the temperature of cooling water did not exceed 40 °C.

2 Diagnostic Tools and Measuring Procedures

In general, the following parameters of the process are recorded in the course of experiment: pressure in MIS (using low-frequency KARAT-DI60 pressure sensors); pressure in 11 sections of burner duct (using high-frequency PCB113A23 pressure sensors referred below as P1 to P11); ionization current between the electrodes of ionization probes installed in the same duct sections; optical pyrometers KM2st-TermiksK and thermocouples (type K) for temperature measurement of PDB structural elements and heat targets installed in the thermal furnace; NOx emission in detonation products (using special gas probes and TESTO-335 gas analyzer); and noise level at different locations in the test room and outside (using certified sound-level meters Algorithm-03). In the experiments, different types of heat targets are used including solid bodies of different shape or loose metal shavings. Signals from the sensors, probes, thermocouples, etc. come through amplifiers and analog-to-digital converter (sampling frequency of 1 MHz) to a personal computer. During long-duration experiments, only signals of thermocouples and signals of ionization probes used to monitor the speed of the reaction front were recorded. After the termination of long-duration experiments, a thermal imaging camera (TESTO) was used to additionally control the final temperature of different parts of PDB. Also, pyrometers were used to measure the temperature of different objects in the thermal furnace.

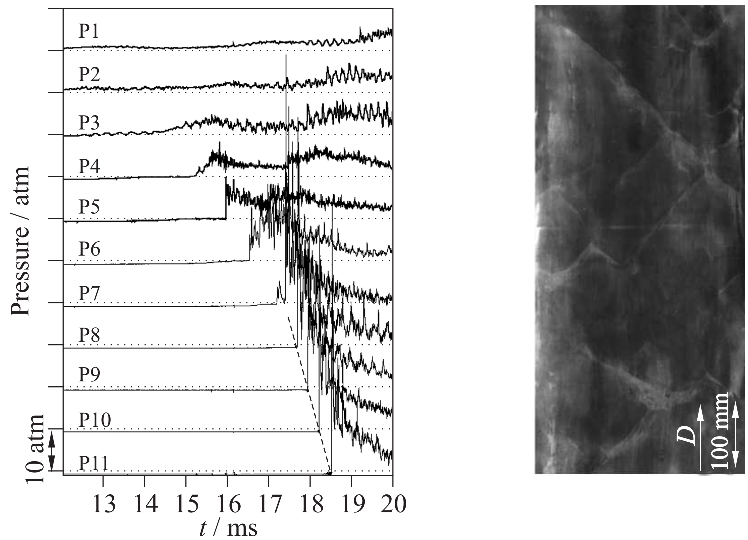
The average velocity of the shock wave front at each measuring segment between adjacent pressure sensors in the burner duct is determined by the distance between the sensors and the time interval between the arrival of the shock wave at the sensors in the pressure records. The relative error in the average detonation velocity is estimated as a sum of relative measuring errors of distance between the pressure sensors (0.4%) and shock arrival times at neighboring sensors (1.6%) and is equal to 2%.

Detonation in the experiments was identified by four characteristics: (i) highest speed (1600 m/s and above) of a quasi-stationary shock wave in a smooth section of the burner duct; (ii) the level of pressure (30 atm and above) registered by a PCB sensor (the relative measuring error of PCB sensor is 5% at 100 °C); (iii) characteristic footprints on 1-meter long smoked foil (spin pitch 400–500 mm) inserted into the open end of the burner duct; and ($i\nu$) matching records of pressure sensors and ionization probes installed in one section of the duct ("simultaneous" sharp deviation of both records).

3 Pulse Detonation Mode of Operation

Figure 2 shows the pressure records in a single PDB cycle with the fast cyclic DDT with cycle frequency of (1.8 ± 0.1) Hz and a photograph of the smoked foil footprint in a single shot with the fast DDT. It is seen that the "explosion in the explosion" (in the terminology of Oppenheim [6]) occurs between sensors P6 and P7 at ~ 17.2 ms after ignition. Explosion occurs between shock precursor and flame and leads to overdriven detonation wave running toward the open end of the burner duct and retonation wave traveling toward MIS. In the vicinity of sensor P8, the overdriven detonation catches up with the shock precursor and the wave of self-sustaining detonation forms which propagates in a quasi-stationary mode towards the end of a smooth section of the duct with a speed of 1600–1700 m/s.

Detonation mode observed in the smooth section of the burner duct should be considered as a near-limit (spinning) regime of self-sustaining detonation. First, the deficit of average detonation velocity of 100–200 m/s relative to the thermodynamic Chapman–Jouguet (CJ) value in a stoichiometric methane–air mixture ($D_{\mathrm{CJ}} \approx 1800$ m/s) is consistent with the maximum allowable deficit of the detonation velocity on



(*a*) (*b*)

Figure 2 Pressure records by sensors P1 to P11 in one of PDC operation cycles in an experiment with fast cyclic DDT at (1.8 ± 0.1) Hz (dashed line shows the detonation wave trajectory) (*a*) and the photograph of the smoked foil footprint of the detonation in a single shot (*b*)

the limit of propagation in a smooth tube. Second, the structure of the wave corresponds well to the structure of spinning detonation with characteristic weakly damped oscillations of the pressure signal. The oscillation frequency of the signal on the records of pressure sensor P11 is approximately 3.7 kHz (see Fig. 2*a*). 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. Third, the smoked foil footprint of the wave in the smooth section of the burner duct in Fig. 2*b* shows clearly how the overdriven detonation formed by the DDT (with multiple heads in the front) is converted into a spin (inclined blurred line in the upper part of the photo). Pressure peaks in Fig. 2 greatly exceeding the peak value calculated for a plane wave with the CJ parameters also indicate that the detonation propagates in the conventional pulsing mode (multiheaded in the overdriven mode and single-head in the spin mode). In

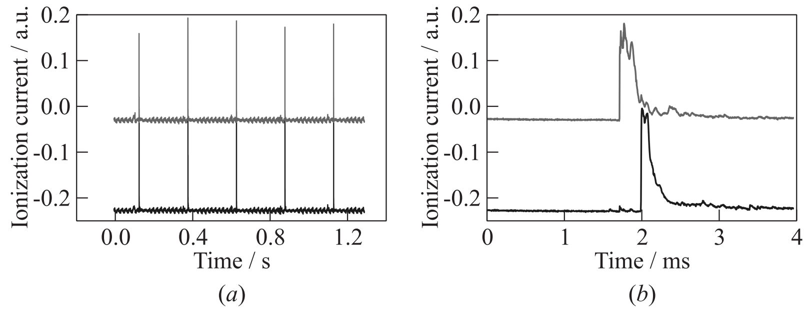


Figure 3 Records of two ionization probes located at a distance of 0.5 m from each other in the part of PDB duct with periodic passage of detonations: (*a*) original records; and (*b*) resolution of the peaks of ionization current in the millisecond range

both cases, due to the presence of transverse waves in the reaction zone of the lead shock front, the recorded peak pressures are much higher than the CJ pressure.

Figure 3 shows an example of records of two ionization probes located at a distance of 500 mm from each other in that part of the PDB duct which is traversed periodically (at 4 Hz) by a detonation wave (i. e., at a distance larger than 4.0 m from the igniter). In all operation cycles, the reaction front velocity at this measuring segment exceeds 1600–1700 m/s, which is close to the detonation velocity in the methane–air mixture of near-stoichiometric composition. In the vicinity of the burner sections where DDT occurs, the recorded speed of the reaction front attains 2000 m/s and even higher. Figure 3 shows a good repeatability of signals of two probes. Note that repeatability of signals was good not only within a given run but also from run to run with the fixed controller settings.

4 Thermal Regime

Due to specific features of PDB operation, namely, periodic filling of burner duct with a portion of cold fuel–air mixture, followed by burning of this portion in the traveling detonation wave and outflow of hot detonation products into the atmosphere, the temperature of PDB structural elements achieves a certain maximum steady-state value. Knowledge of such steady-state temperature is required for the development of energy-efficient forced cooling system for PDB.

Figure 4 shows the measured temperature histories of internal structural elements (obstacles) *3* and *5* (see Fig. 1) of the PDB in the experiment with the operation frequency of (1.8 ± 0.1) Hz and with the duration of 300 s. To shorten the time of achieving the steady-state condition, the PDB was first operated in the continuous deflagration mode and then (at time zero in Fig. 4) was switched to the pulse detonation mode. Clearly, the steady-state temperatures of internal elements *3* and *5* (300 and 500 °C, respectively) are reached in 100 and 200 s of PDB operation in pulse detonation mode, respectively. Note that element *3* is located in a part of the burner duct which is cyclically traversed by a deflagration wave, whereas element *5* is located in a part of the duct which is cyclically traversed by a detonation wave. It is known that the structural elements of burners made of stainless steel can readily withstand temperatures of up to $\sim$ 400 °C without forced cooling. However, temperature of 500 °C could be too high for a practical device and therefore, the internal elements of the PDB could require forced cooling. Thus, at operation frequency of (1.8 ± 0.1) Hz cooling is required only to those areas of the burner duct which are cyclically traversed by a detonation wave. Measured heat fluxes to tube walls were 49 ± 2 kW/m^2 at 1 Hz and 138 ± 12 kW/m^2 at 4 Hz at PDE operation with water cooling.

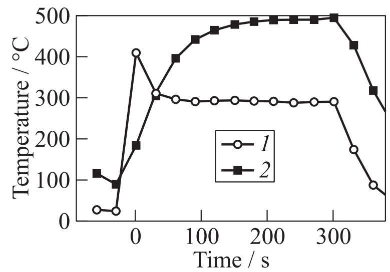


Figure 4 The measured temperature histories of different structural elements of the PDB in the experiment with the operation frequency of (1.8 ± 0.1) Hz and with the duration of 300 s: *1* — interior obstacle in the burner duct (position *3* in Fig. 1); and *2* — interior obstacle (position *5*)

5 Emissions of Nitrogen Oxides

Since the characteristic time of high-temperature processes in the PDB is considerably shorter than in conventional burners, it could be expected that the PDB produces lower NOx emission as compared to conventional burners, despite the detonation temperature is about 700 °C higher than the typical combustion temperature of methane–air mixture. Sampling of detonation products was carried out using a probe with a check valve and a flute for dispersing the directed motion of the products. The probe was coaxially inserted into the PDB at a depth of 500 mm from the exit section. The concentration of nitrogen oxides in the detonation products was measured by Testo 335 gas analyzer (Testo AG, Germany). For a detonation wave propagating in a stoichiometric natural gas–air mixture at 0.1 MPa and 293 K, the mean (based on a series of experiments) concentration of nitrogen oxides was found to be [NOx] ≈ 210 ppm, including [NO] ≈ 203 ppm.

6 Noise

Despite the PDB is considered as a noisy device, the presented measurements showed that the use of proper noise reduction techniques allows reducing noise level to acceptable values. As an example, Fig. 5 shows the time dependence of the noise level measured by a precise sound-level meter (Algorithm-03) outside the exhaust chimney (see Fig. 1*a*)

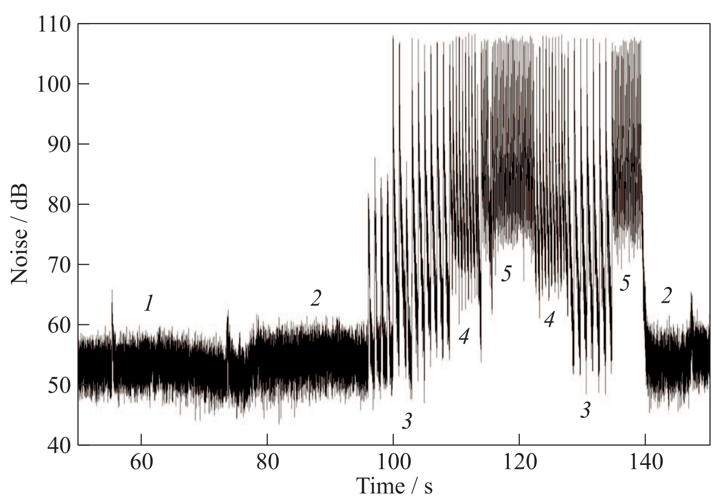
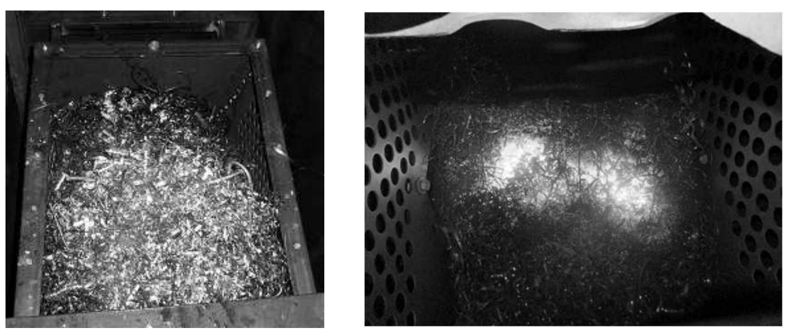


Figure 5 The PDB noise level at the outlet of furnace chimney

equipped with noise-suppression elements. The numbers in Fig. 5 mark the characteristic portions of the curve: *1* is the background noise; *2* is the noise of air blower; *3* is the noise at PDB operation with frequency of 1 Hz; *4* is the noise at PDB operation at 2 Hz; and *5* is the noise at PDB operation at 4 Hz. It is seen that the maximum noise level at the outlet of exhaust chimney is about 105 dB which is below the allowable standard value.

7 Example of Application

Contrary to most conventional burners with combustion taking place in the flame outside the burner producing a low-density jet with the maximum velocity of ~ 200 m/s and maximum temperature of ~ 1600–1700 °C, combustion in the PDB is completed inside the burner duct producing a long-penetrating and highly energetic pulsed jet of detonation products possessing a very large flow velocity (above 1000 m/s), high temperature (about 2500 °C), and high density (about 2 kg/m^3) at the outlet of the burner duct. Such jet allows heating of different objects in a very short time. For example, Fig. 6 shows the photos of a bulk of metal shavings before and after the 100-second impact of pulsed jets generated by the PDB at operation frequency 4 Hz. Clearly, metal shavings got melted.



(*a*) (*b*)

Figure 6 Metal shavings before (*a*) and after (*b*) the 100-second impact of PDB jets

8 Concluding Remarks

A large-scale device utilizing the thermodynamic cycle with pulsed detonation combustion (Zel'dovich cycle) has been designed, manufactured, and tested, namely, the PDB operating on natural gas–air mixture. This device is considered as prototype of industrial burner of new generation which is capable of producing lengthy and energetic pulsed supersonic plume of high-temperature combustion products at essentially decreased NOx emission as compared to conventional burners in metallurgy, chemical engineering, waste incineration, etc.

Acknowledgments

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