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Content of the reports is of interest for research and students specializing in physics and chemistry of the atmosphere and ionosphere.

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Applications of Pulsed and Continuous Detonations: In Search for Energy Efficient Solutions

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Introduction

A Pulsed Detonation Combustor (PDC), a tube of 150 mm diameter and 5.5 m length equipped with the mechanical valve and manifolds for separate delivery of natural gas and air (Fig. 1), as well as a continuous-detonation annular combustor (CDC) of 400 mm diameter and 300 mm height with the annular gap of 30 mm width equipped with the manifolds for separate delivery of hydrogen and air (Fig. 2) were designed, manufactured and tested within a research program aimed at experimental studies of energy efficiency of the thermodynamic cycle with detonation combustion (Zel'dovich cycle).

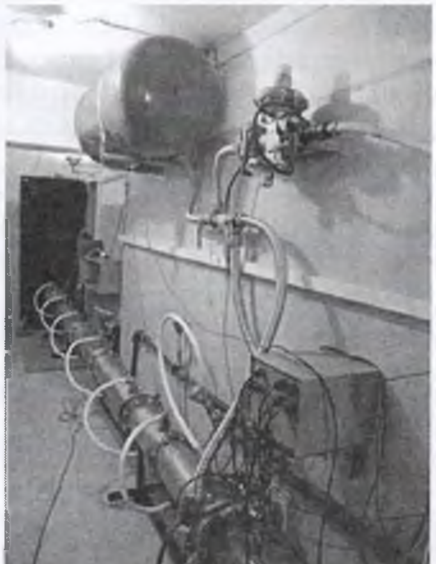


FIGURE 1. Pulsed detonation combustor operating on natural gas and air. The open end (far end) is immersed into a furnace.

FIGURE 2. Continuous detonation combustor operating on hydrogen and air.

The PDC consists of two coupled sections: the mixing/ignition section 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 with obstacles. The shape, pitch, and blockage ratio of obstacles vary with distance from the ignition source to facilitate deflagration-to-detonation transition (DDT). 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 immersed into the furnace.

The operation cycle of the PDC 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 liters in volume at overpressure of 0.3 bar connected to the natural gas manifold via a control valve. Ambient air is fed into the PDC with a vortex blower, which provides airflow up to 0.5 m^3/s.

In the first stage the PDC is filled with a mixture of natural gas and air. When filling the PDC 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 ± 0.3)%. To avoid leakage of fresh mixture through the open end of the burner duct the PDC 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) multi-point 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 ~ 3.5 m from the ignition source for ~20 ms after ignition.

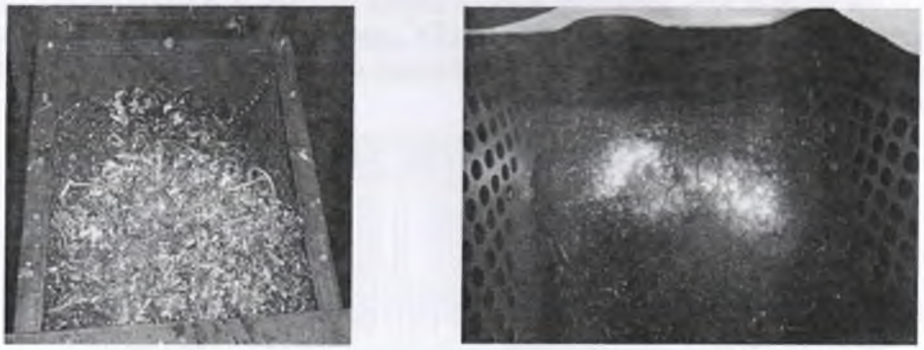
In the third stage, the shock wave exits from the duct open end followed by the outflow of the detonation products.

In the fourth stage, the PDC is first purged with air for a short time and then the supply of natural gas and air is resumed, thus the next cycle starts.

The (currently) maximum operation frequency of the PDC in the detonation mode is 5 Hz.

The PDC has several specific features as compared to conventional burners.

First, contrary to 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 ~1800°C, in the PDC combustion 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/м^3) at the outlet of the burner duct. Such jet allows heating different objects in a very short time. For example, Fig. 3 shows the photos of a bulk of metal shavings before and after the 100-second impact of pulsed jets generated by the PDC at operation frequency 4 Hz. Clearly, metal shavings got melted.



a *b*

FIGURE 3. Metal shavings before (a) and after (b) the 100-second impact of PDC jets.

Second, due to periodic filling of PDC 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 furnace interior, the temperature of PDC structural elements achieves a certain maximum steady state value. The steady-state temperatures of PDC structural elements were measured in the course of long-duration testing in a pulse-detonation mode with a frequency of 2 Hz without forced cooling. Experiments showed that the maximum steady-state temperature (~ 500°C) is reached after approximately 200 s of PDC operation in DDT-enhancing obstacles located in a part of the burner duct periodically traversed by the detonation wave. The walls of the PDC in this part of the burner duct were estimated to heat up to ~ 400—430 °C during the time on the order of 1000 s. In the part of the burner duct periodically traversed by the deflagration wave the walls and interior elements were heated to a steady-state temperature of no more than ~ 300—330 °C. Thus, the results show that the forced cooling is generally required only in the parts of the burner duct traversed by the detonation wave.

Third, the PDC produces low NOx emission as compared to conventional burners. As a matter of fact, the characteristic time of high-temperature processes in the PDC is considerably shorter than in conventional burners and therefore the NOx emission index is considerably (by a factor of 3) lower despite the detonation temperature is about 700°C higher than the typical combustion temperature of methane — air mixture.

Fourth, despite the PDC is considered as a noisy device, our measurements showed that the use of proper noise reduction techniques allows reducing noise level to acceptable values. As an example, Fig. 4 shows the time dependence of the noise level measured by a precise sound level meter outside the furnace chimney equipped with noise suppression elements. The numbers in Fig. 4 mark the characteristic portions of the curve: 1 is the background noise, 2 is the noise of air blower, 3 is the noise at PDC operation with frequency of 1 Hz, 4 is the noise at PDC operation at 2 Hz, and 5 is the noise at PDC operation at 4 Hz. It is seen that the maximum noise level at the outlet of furnace chimney is about 105 dB which is below the allowable standard value.

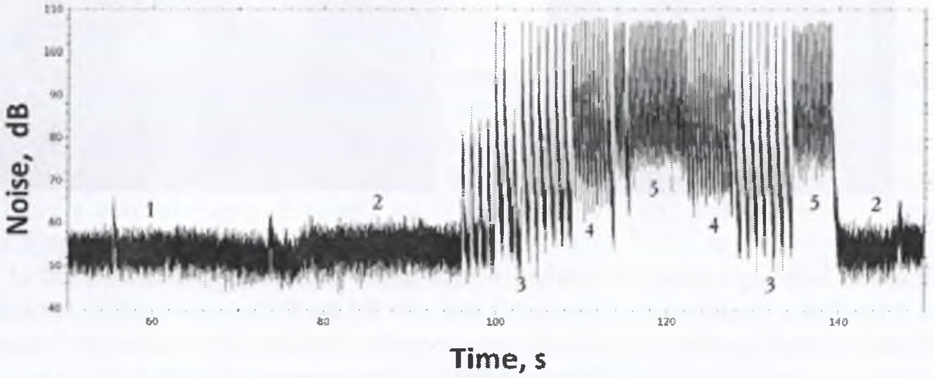


FIGURE 4. PDC noise level at the outlet of furnace chimney.

Continuous Detonation Combustor

To understand how the CDC operates, consider an annular channel formed by the walls of two coaxial cylinders. Mounting an injector head at the bottom of the cylinders to provide supply of fuel components into the annular channel and a nozzle at the other end of the channel makes an annular flow reactor. Combustion in such a reactor can be realized in different ways: either as in an ordinary burner or according to a Voitsekhovskii scheme, when the mixture is burned in detonation waves traveling in tangential direction over the bottom of the annular channel. The detonation wave burns fuel mixture injected into the CDC during one wave revolution in the annular channel (in the case of a single wave). The angular frequency of rotation of the detonation wave in a medium-size chamber is of the order of 10^5 rpm and higher. The oxidation of fuel in the wave occurs in the mode of self-ignition at high pressures and temperatures. Therefore, the efficiency of the combustion process in the CDC, ceteris paribus, will be higher than in the conventional burner (the process occurs at higher pressures behind the shock wave). Use of the CDC promises great benefits, at least theoretically, for the aerospace and energy industries. In particular, because the fuel burns in the CDC continuously, a turbine can be installed at the nozzle exit, on a common shaft with the compressor driving air into the annular combustion chamber. Given that the speed of the turbine is on the order of 10^4 rpm, during one revolution of the turbine, the detonation wave makes ten or more turns, i. e., the exhaust gas flow through the turbine can be considered nearly steady with some pulsations. In this configuration, a gas turbine with a CDC is very similar to a conventional gas turbine, but instead of continuous combustion, a detonation wave continuously circulates in the CDC.

Figure 5 shows high-speed video frames of the CDC exhaust plume and the luminosity of the detonation continuously rotating in the annular CDC gap.

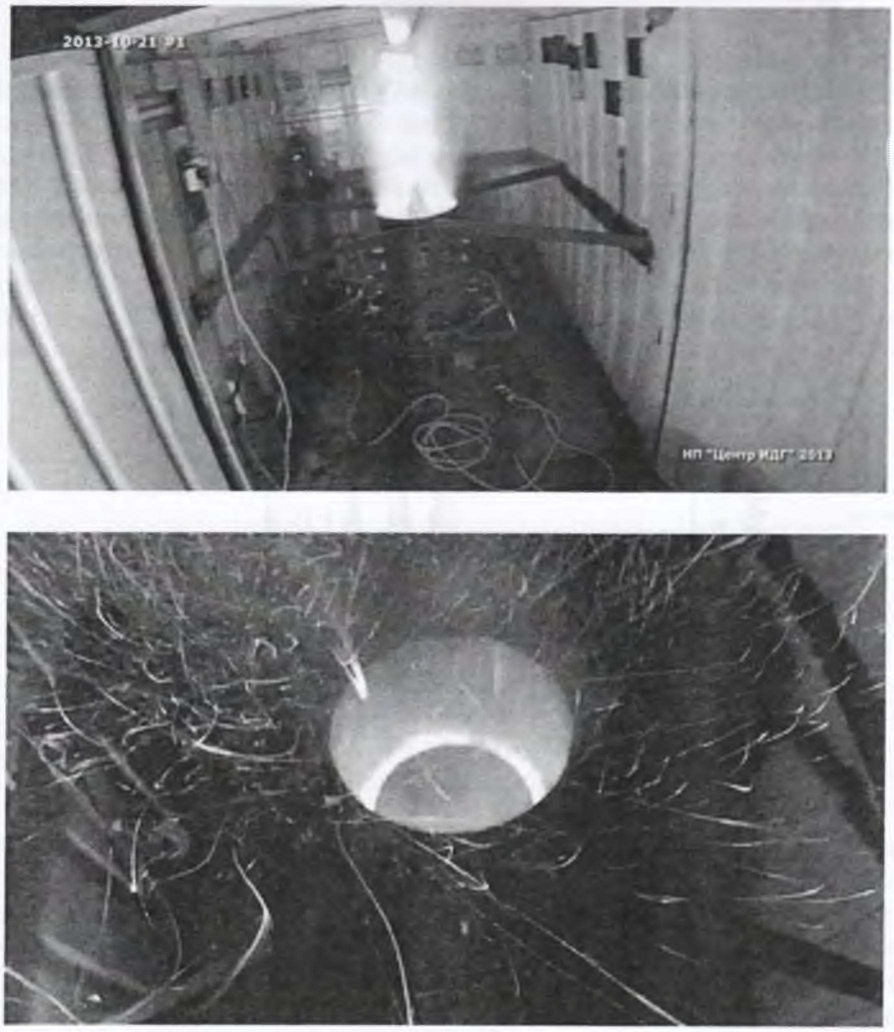


FIGURE 5. High-speed video frames of the CDC exhaust plume (top) and detonation luminosity in the annular gap (bottom).

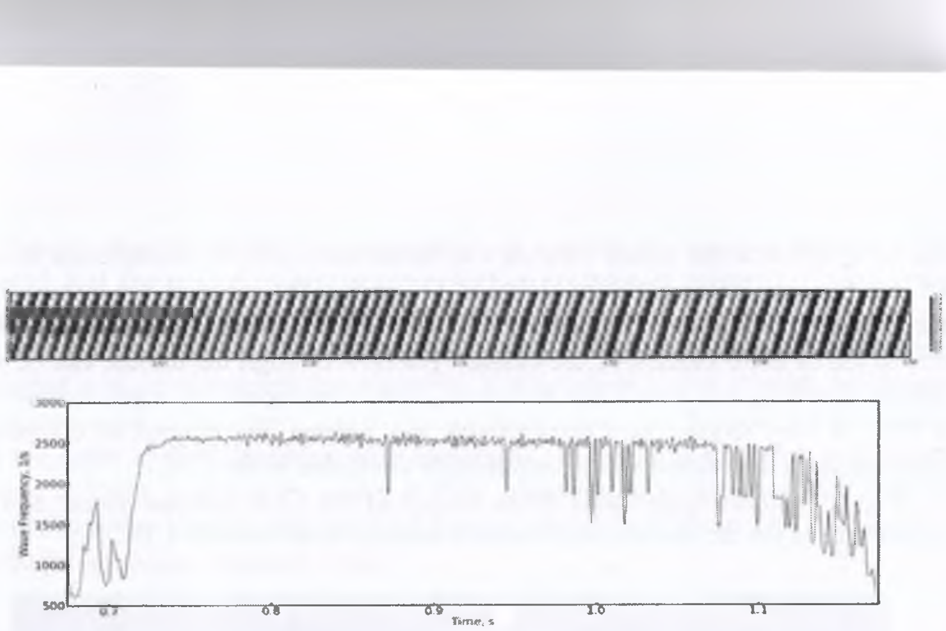


FIGURE 6. Distance — time diagram for the wave process in the CDC (top) and detonation rotation frequency vs. time (bottom).

Fig. 6 shows the records of 8 ionization probes arranged equidistantly in a single circumferential section of the CDC (top) and the measured dependence of the detonation rotation frequency on time (bottom). The X-axis in the records corresponds to time and the Y-axis corresponds to the probe number (from 1 to 8).

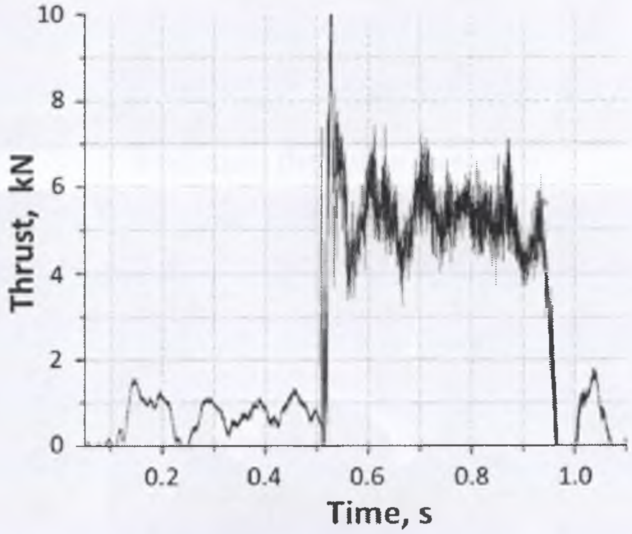


FIGURE 7. Measured thrust of the CDC.

The maximum brightness in the records corresponds to the maximum ionization current attained in the detonation front. As a matter of fact, these records represent the distance — time diagram for the wave process in the CDC and the slopes of bright lines represent the detonation propagation velocity. According to these records the average detonation propagation velocity is 1950 m/s, which is very close to the thermodynamic detonation velocity in the stoichiometric hydrogen — air mixture. According to the lower diagram in Fig. 6 during most of the operation time the rotation frequency is about 2.5 kHz, which corresponds to the mode with two detonation waves simultaneously propagating in one direction (rotation of a single detonation wave at a given velocity would result in the frequency of ~1.3 Hz).

Figure 7 shows the measured thrust of the CDC in the mode with two detonation waves. In this figure, ignition starts at 0.51 s and fuel supply is terminated at 0.94 s. The fuel-based specific impulse in this experiment is equal to 3200 s indicating high energy efficiency of the thermodynamic cycle with detonation combustion.

Conclusions

Two large-scale devices utilizing the thermodynamic cycle with pulsed and continuous detonation combustion (Zel'dovich cycle) have been designed, manufactured and tested, namely the PDC and CDC. These devices can be considered as prototypes of industrial burners of new generation which are capable of producing lengthy and energetic pulsed or continuous supersonic plumes of high-temperature combustion products at essentially decreased fuel consumption and NOx emission as compared to conventional burners in metallurgy, chemical engineering, waste incineration, etc.

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PL-11

Radiochemical Physics of the Upper Earth Atmosphere

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The splash of large scale studies of physicochemical processes in the atmosphere observed during last three decades is explained by growing interest to the propagation processes of electromagnetic signals from satellites and RLS. It became clear that collision and radiation processes involving the Rydberg complexes play a fundamental role in the shaping of the radio signals. The influence of highly excited molecular states, where a weakly bounded electron occupies a remote orbit (with the radius much exceeding the size of the residual ion) is appreciable and should be thoroughly investigated for the correct interpretation of the information carrying by the electromagnetic waves [1—3].