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COMBUSTION, EXPLOSION, AND SHOCK WAVES

Thermal Tests of a Pulse-Detonation High-Speed Burner

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Abstract—The steady-state temperatures of the elements of a high-speed pulse-detonation burner (HSPDB) running on a natural gas–air mixture were measured in the course of long-term tests of the burner operating in the pulse-detonation mode without forced cooling at a frequency of 2 Hz. Knowledge of the steady-state temperatures is required for the development of an energy-efficient forced cooling system for the HSPDB. The experiments have shown that the maximum ~~the~~ steady-state temperature (~500°C) is reached after
1 approximately 200 s of operation at internal elements of the HSPDB, more specifically, turbulizing obstacles placed in that part of the burner duct through which the detonation wave travels periodically. The HSPDB wall in this part of the burner duct is heated to 420°C within ~1000 s. In the part of the burner duct through which the deflagration wave travels, the HSPDB walls and internal elements are heated to a steady-state temperature not exceeding 330°C. The results show that the forced cooling of the HSPDB is generally required only for those parts of the burner duct through which the detonation wave passes periodically.

Keywords: pulse-detonation burner, natural gas, thermal mode

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INTRODUCTION

During 2010–2013, at the Center for Pulse-Detonation Combustion of the Semenov Institute of Chemical Physics, RAS, research and development work has been conducted, aimed at creating a fundamentally new scientific and technical product: the world's first energy-saving high-speed pulse-detonation burner (HSPDB) with controlled pulse-detonation combustion of natural gas [1–7]. The work was carried out under the state contract with the Ministry of Education of the Russian Federation, according to which the HSPDB prototype must have the following performance characteristics:

—the thermal power, from 2000 to 2500 kW (corresponds to that of conventional high-speed burners);

—the maximum velocity of the detonation products at the outlet section, 400 to 1500 m/s;

—the operating frequency, from 0.04 to 2 Hz;

—the maximum temperature of the detonation products at the outlet section, from 1400 to 2500°C;

—the maximum pressure of the detonation products at the outlet section, from 2 to 14 atm;

—the ignition energy, within 1.0 J;

—the burner duct length, no more than 5–6 m.

These characteristics are to be achieved at a reduced natural gas consumption and a reduced emission of nitrogen oxides compared with the current high-speed burners of the same power. The burner is designed for heating furnaces of the steel, sheet metal, and other industries, as well as in various thermal power plants.

The aim of this work is to determine the maximum (steady-state) temperature of the HSPDB structural elements in long-term tests of the prototype in the pulse-detonation mode without forced cooling at a frequency of 2 Hz. Due to the peculiarities of HSPDB operation—periodic filling the burner duct with a cold air–fuel mixture portion, burning this portion in the running detonation wave, and empting the duct from the hot detonation products—it was expected that the temperature of the structural elements should reach a maximum steady-state value. Knowledge of this steady-state temperature is important for the development of an energy-efficient forced cooling system for the HSPDB.

TEST PROCEDURES

Figure 1 shows a schematic diagram of the prototype ~~HSPDB~~, indicating the positions of thermocouples *1–6* for measuring the temperature of the structural elements and the thermocouples mounted at heat target *7*, located at a distance of ~~400~~ mm from the open end of the HSPDB. The prototype ~~HSPDB~~ consists of four main components: a system of separate supply of natural gas and air (not shown in Fig. 4); mixing and ignition unit (MIU), which provides the

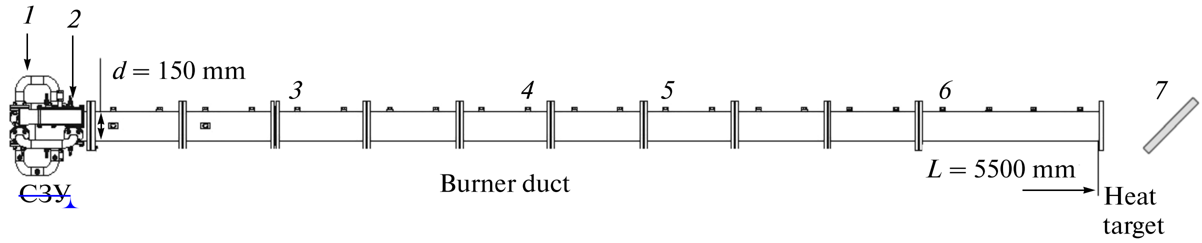

Fig. 1. Schematic diagram of the HSPDB prototype and the positions of the thermocouples (see the text).

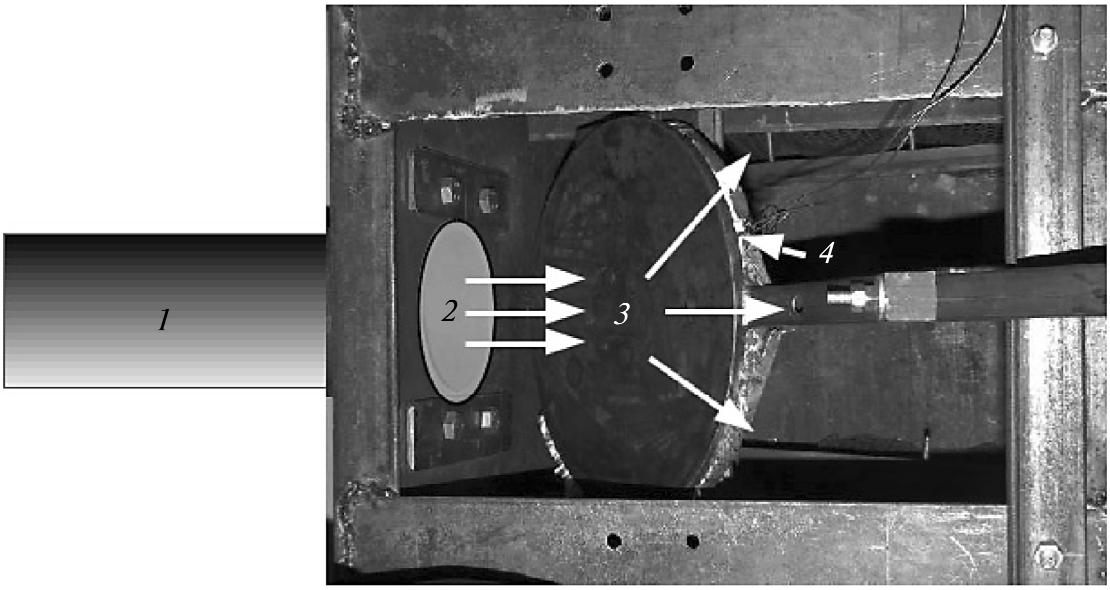

Fig. 2. Photograph of the heat target mounted in the noise-dampening chamber: (*1*) outlet segment of the HSPDB duct, (*2*) outlet section of the HSPDB, (*3*) heat target, and (*4*) thermocouples.

mixing of high-velocity flows of natural gas and air and reliable ignition of the resulting mixture; burner duct, a straight pipe with a diameter of d = 150 mm and 1 length L = 5.5 m containing special turbulizing obstacles for promoting deflagration-to-detonation transition [8]; and digital control system (not shown). The composition of the mixture at the MIU outlet before ignition was close to the stoichiometric, as confirmed by chromatographic analysis of the samples taken along the length of the burner duct. An 11-kg steel heat target had a shape of a massive disk turned to the burner duct axis at an angle of 45°. The heat target was fitted with two thermocouples and was mounted in noise-dampening chamber (Fig. 2). The duration of experiments with the HSPDB operating at a frequency of 2 Hz reached 300 s.

During the experiment, an analog-to-digital converter and a computer continuously recorded not only the signals from the thermocouples and thermistors, but also the signals from ionization probes placed along the burner duct to monitor the reaction front velocity. Figure 3 shows a photograph of one of the segments of the burner duct with mounted therein two pressure sensors *1*, ionization sensor *2*, thermistor *3*, and thermocouple *4*. In all operation cycles of the HSPDB, the reaction front velocity at a distance of more than 4.0 m from the MIU exceeded 1600–1700 m/s, which corresponds to the detonation velocity for a stoichiometric methane–air mixture near the propagation limit. In the HSPDB duct region where deflagration-to-detonation transition (DDT) occurred, the reaction front velocity was above 2000 m/s. This is consistent with the well-known fact that DDT involves overdriven detonation. At the end of the experiment, temperature control measurements at different parts of the HSPDB and heat target were additionally performed using a TESTO thermal imager.

TEST RESULTS

Figure 4a shows the time dependences of the temperature of the outer walls of the different elements of the HSPDB measured in an experiment with a pulse-detonation mode duration of 300 s. To decrease the time required for the HSPDB to reach the steady-state thermal mode, all its elements were preliminary

Fig. 3. Photograph of one of the sections of the burner duct: (*1*) pressure sensor, (*2*) ionization sensor, (*3*) heat target, and (*4*) thermocouples.

heated before the experiment by operating the burner for a short time in the continuous deflagration mode (*0* mark at the timeline). Therefore, at $t = 0$, elements *1*, *2*, *4*, and *6* (curves *1*–*4* in Fig. 4a) had different temperatures. After 300 s of operation of the HSPDB in the pulse-detonation mode, fuel supply into the MIU was stopped, and the HSPDB elements were cooled with a high-velocity air stream continuously supplied into the MIU. For this reason, all the temperature curves in Fig. 4a pass through a maximum at $t > 300$ s due to the thermal inertia of the processes and due to heat exchange with the environment.

Figure 4a shows that the temperature curves for the different elements of the HSPDB differ greatly from each other. During the experiment, the temperatures of MIU elements 1 and *2* (Fig. 1) almost reach steady-state values of 150 and 200°C, respectively (curves *1* and *2* in Fig. 4a). As for elements *4* and *6* of the burner duct (Fig. 4a, curves *3* and *4*), their temperatures have no time to reach the steady-state level during the experiment. To assess the steady-state temperature of these elements, we extrapolated the experimental data to a longer duration of HSPDB operation (1200 s) by using exponential functions. The applicability of this extrapolation was tested based on the results of [9], where the thermal state of a detonation tube with cyclic DDT in a hydrogen–air mixture was studied experimentally and by numerical modeling. Typical dimensions of the experimental setup in [9] were relatively small (a tube 40 mm in diameter and 500 mm in length), while the frequency of detonation pulses was relatively high (60 Hz). Therefore, the steady-state thermal mode of operation was achieved in a relatively short time. Processing the results from [9] demonstrated that the exponential extrapolation of the experimental data gives an error in temperature within 10%.

The results of the extrapolation of the experimental data for the temperature of elements *4* and *6* of the burner duct (Fig. 1) are displayed in Fig. 4b. Figure 4b shows that elements *4* and *6* (curves *3* and *4* in Fig. 4b) can be heated up to 330 and 420°C, respectively. Note that element *4* is located in that part of the burner duct through which the deflagration wave travels periodically: a complex consisting of a head shock wave and a turbulent flame front, separated by a layer of shock-compressed explosive mixture of finite thickness (of the order of the duct diameter). Unlike element *4*, ele-

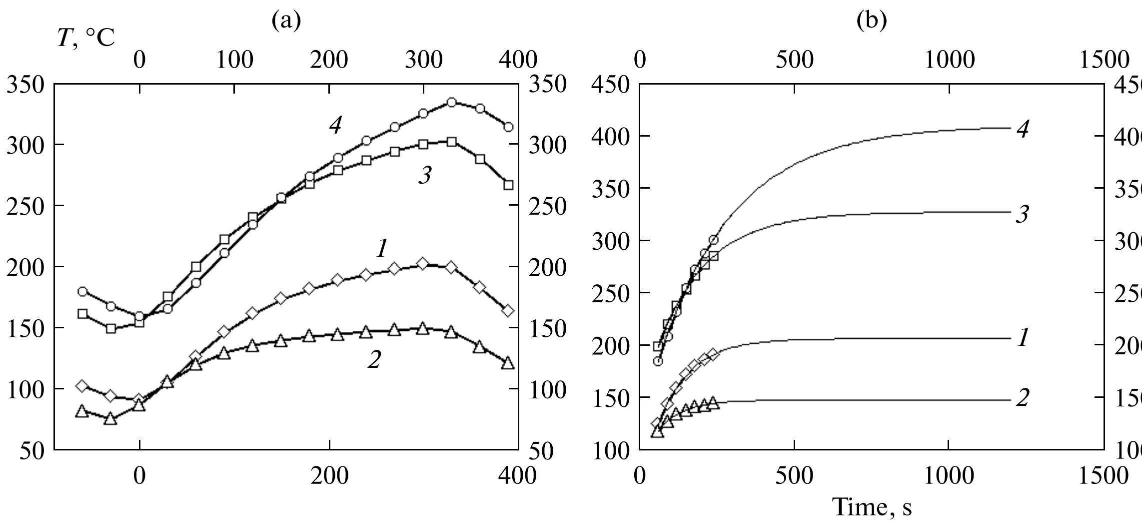

Fig. 4. (a) Time dependences of the temperatures of the outer elements of the HSPDB construction measured in a 300-s-long experiment and (b) extrapolation of these dependences to 1200 s: (*1*) MIU outer wall (position *1* in Fig. 1), (*2*) MIU outer wall (position *2* in Fig. 1); (*3*) outer wall of the burner duct (position *4*, Fig. 1); and (*4*) outer wall of the burner duct (position *6* in Fig. 1).

ment *6* is located in the part of the burner duct through which the detonation wave propagates periodically, a complex consisting of a ~~head~~ shock wave and an adjacent ignition front. That the temperature and velocity of the detonation products are higher than those the deflagration products explains the fact that the steady-state temperature of element *6* is higher than that of element *4*.

Figure 5 shows a photograph of the outlet section of the burner duct with element *6* (Fig. 5a) and a typical thermal image of this section (Fig. 5b) after 60 s of operation of the HSPDB in pulse-detonation mode. Temperature measurements taken with the thermal imager and thermocouples are in good agreement with each other.

In addition to measuring the temperature of the outer walls of the HSPDB, we measured the tempera-
1 ture of the turbulizing obstacles installed in the burner duct (elements *3* and *5* in Fig. 1) and temperature of the heat target (element *7* in Fig. 1). The results of these measurements are shown in Figs. 6a and 6b, respectively.

Figure 6a demonstrates that, in contrast to the outer walls of the burner, internal elements *3* and *5* of the HSPDB reach the steady-state temperatures, 300 and 500°C, much faster, after 100 and 200 s of operation of the HSPDB in the pulse-detonation mode, respectively. The fact that the internal elements of the HSPDB are heated to these temperatures indirectly confirms the validity of the results of extrapolating the temperature curves in Fig. 4b. Note that element *3* is located where the deflagration wave propagates periodically, whereas element *5* is position where the detonation wave travels periodically. It is known that the components of burners and combustion chambers can withstand for a long time temperatures up to ~400°C without forced cooling. For practical devices, the temperature of 500°C appears to be excessively high, not so much because of the problem of thermal stability of the metal, but due to the fact that, at such a temperature, the air–natural gas mixture entering the HSPDB can spontaneously ignite after a short induction period. Consequently, forced cooling of the internal components of the HSPDB should be provided. As can be seen from Fig. 6a, such cooling is required only in those parts of the burner duct through which the detonation travels periodically.

Figure 6b shows the temperature curves for the heating of the target blown on by the pulse-detonation products (curve *1*) and ~~deflagration pulse~~ products (curve *2*) in two different 40-s-long experiments. Both experiments were performed at the same settings of the fuel-supply system and MIU, at a partial filling of the burner duct with fresh mixture to ensure its complete combustion in each cycle. The experiment with pulse-detonation was conducted on the same HSPDB as that described above. The experiment with pulse-deflagration was performed on a HSPDB in which the burner duct section with obstacles was replaced by a smooth section. For the HSPDB of this design, DDT was observed in none of the cycles, with the average velocity of the deflagration wave at the end of the burner duct being 900–1000 m/s. Figure 6b shows that the rates of heating of the heat target by pulse-detonation and deflagration products are approximately constant and equal to 1.1 and 0.7 K/s, respectively. Note that these experiments were purely demonstrative, with no task of enhancing heat transfer from the deflagration and detonation products. Nevertheless, this comparison shows that the heating of the heat target by the pulse-detonation products is more efficient.

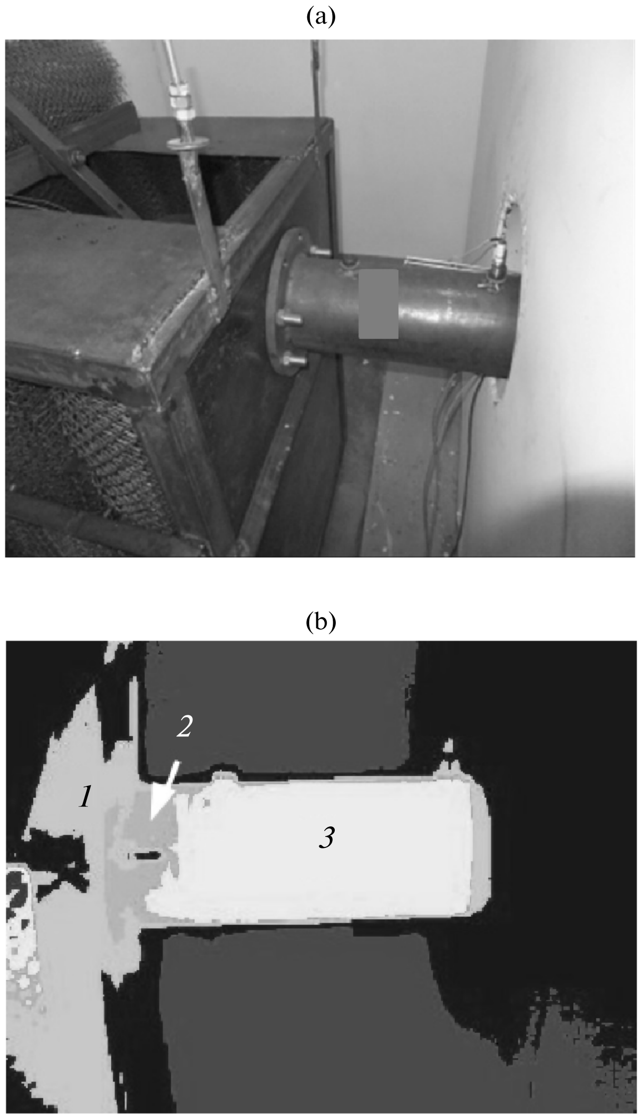

Fig. 5. (a) Photograph of the outlet segment of the burner duct adjacent to the noise-dampening chamber and (b) an example of a thermal image of this segment after 60 s of operation of the HSPDB in the pulse-detonation mode. The numerals indicate various temperature zones: (*1*) 50, (*2*) 100, and (*3*) 180°C.

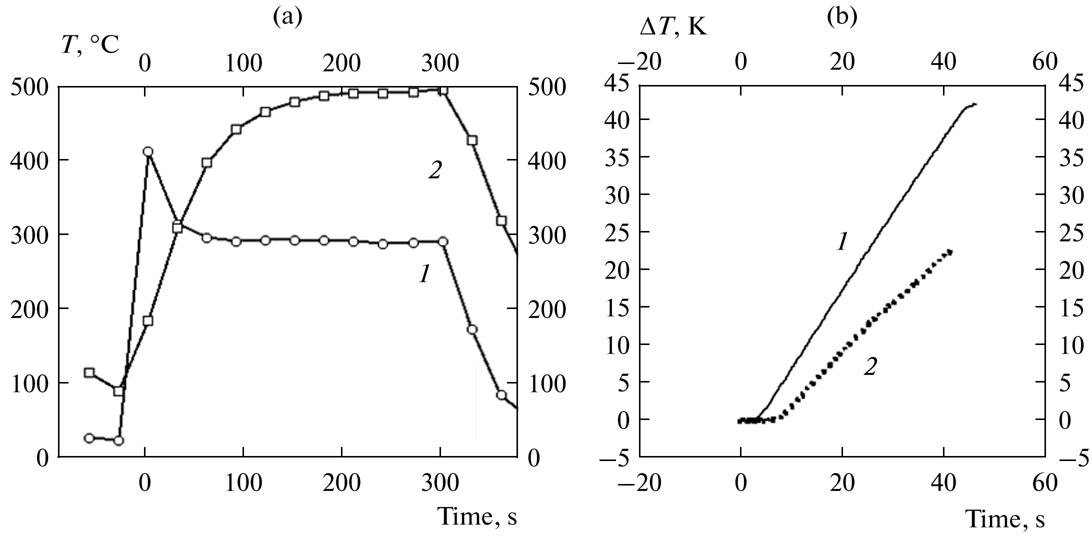

Fig. 6. (a) Measured time histories of the internal elements of the HSPDB construction for a 300-s operation in the pulse-deto-
1 1 nation mode: (*1*) turbulizing obstacle (position *3* in Fig. 1) and (*2*) turbulizing obstacle (position *5* in Fig. 1); (b) temperature
curves for the heating of the heat target by the (*1*) pulse-detonation and (*2*) pulse-deflagration products.

CONCLUSIONS

Thus, we measured steady-state temperature of the constructional elements of a HSPDB running on a natural gas–air mixture in long-term tests of the prototype operating in the pulse-detonation mode without forced cooling at a frequency of 2 Hz. Knowledge of the steady-state temperatures is required for the development of an energy-efficient forced-cooling system for the HSPDB. The experiments have shown that the maximum steady-state temperature (~500°C) is reached after ~200 s of operation at the inner ele-
1 ments of the HSPDB, more specifically turbulizing obstacles, positioned in the burner duct region through which the detonation wave passes periodically. The walls in this part of the burner duct are heated to ~420°C within ~~~1000s~~. In the burner duct region through which the deflagration wave periodically travels are heated to a steady-state temperature not exceeding ~330°C. The results obtained show that the forced cooling of the HSPDB is required only in those parts of the burner duct through which the detonation wave periodically travels.

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SPELL: 1. turbulizing