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COMBUSTION, EXPLOSION, AND SHOCK WAVES

Pulse-Detonation Burner Unit Operating on Natural Gas

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Abstract—The possibility of controlled cyclic deflagration-to-detonation transition within a length of 2.5–3.0 m in an open-end tube (94 mm in diameter) with separate continuous supply of natural gas and air was demonstrated for the first time. Based on experimental studies, a workable pulse detonation burner, a prototype of new generation of industrial burners, was developed. It can produce a combined effect on the objects blown on with combustion products—shock-wave (mechanical) and thermal.

Keywords: deflagration-to-detonation transition, natural gas–air mixture, experimental model of a pulse detonation burner.

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In the existing power installations and burner units, chemical energy of fuel is converted into heat and mechanical work through slow combustion (deflagration). In addition to deflagration, there is another mode of combustion—detonation. During detonation, the chemical reaction of fuel oxidation occurs in the mode of ignition at high pressure behind a strong shock wave (SW). While deflagration of hydrocarbon fuel–air mixtures provides a heat release per unit surface area of reaction front of ~1 MW/m^2, the heat release in the detonation front is by about 4 orders of magnitude higher, ~ 10000 MW/m^2. In addition, unlike the products of slow combustion, detonation products have an enormous kinetic energy: the velocity of the detonation products is ~20–25 times greater than that of the slow combustion products. Replacing, for example, a conventional combustion chamber by a pulse detonation combustor with periodic supply of combustible mixture could offer big energy benefits due to a combination of shock-wave (mechanical) and thermal effects on objects blown on with detonation products [1].

Until now, pulse detonation combustion has not been used in the energy industry. The main reason for this lies in the problem of cyclic initiation of detonation, either by using a very powerful energy source that generates a strong SW or by ensuring deflagration-to-detonation transition (DDT) in very long smooth tubes or tubes with regular obstacles. In view of safety concerns, direct initiation of detonation should be immediately excluded from consideration. As regards the second method, it is promising only if the problem of ensuring reliable and controllable DDT within a short distance at a small ignition energy can be solved. Unfortunately, the detonability of practical fuel–air mixtures under normal conditions is very low, and this problem has remained unsolved until now.

According to the available literature data, the sizes of tubes required to realize DDT mixtures of practical fuels with air are, indeed, unacceptably large. For example, in [2, 3], a series of experiments on DDT in methane–air mixtures of different compositions in straight closed tubes of different diameter equipped with regular annular obstacles with a blockage ratio of 0.3–0.6 installed at regular intervals equal to the tube diameter was performed. Under normal conditions, DDT was observed only in tubes of diameter 520 and 174 mm, with the minimum distances from the ignition source to the point of detonation onset being 15–17 m and 6–8 m, respectively [2]. It is noteworthy that, in a tube with a diameter of 121 mm, DDT was observed only at an increased pressure (2 atm or higher) at a distance of $L_{DDT} > 4$–5 m [3]. However, the results of [3] contradict the data from [4], where DDT was observed to occur within a very short distance, $L_{DDT} = 2.5$–3 m, in a stoichiometric methane–air mixture under normal conditions in a closed tube of diameter 100 mm encumbered with special-shape obstacles (protected by a patent). In addition, the results of [3] contradict the known fact that the limiting diameter of a smooth tube in which a methanem-dashair mixture can detonate under normal conditions is close to 100 mm. For example, recently [5], detonation was successfully initiated in a stoichiometric methane–air mixture under normal conditions in a tube with a diameter of 94 mm at a relatively low Mach number, $M = 3.3$, of the SW during its diffraction on a single obstacle of special shape, a convergent-divergent nozzle.

The results of [4] and [5] suggest that the reason for this contradiction lies in the different influences of

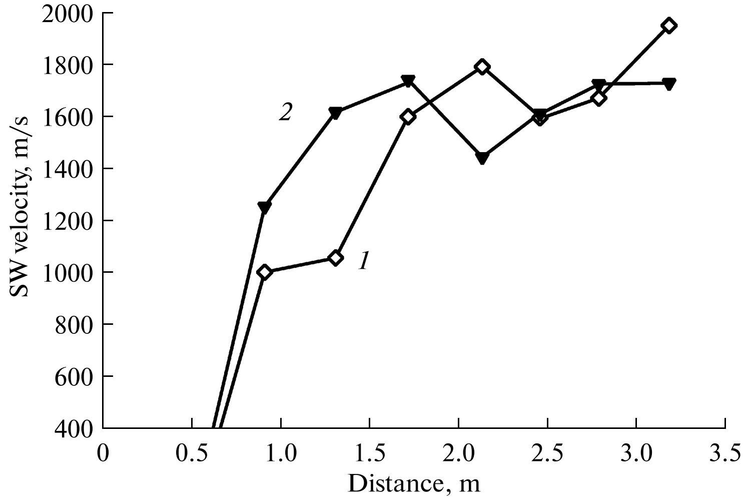

Fig. 1. Deflagration-to-detonation transition in a natural gas–air mixture in two (of the ten) cycles (*1*, *2*) during the operation of PDBU at a repetition frequency of 0.03 Hz.

obstacles on a flame and a SW, two major components of the DDT process. A cascade of regular obstacles, which facilitates the rapid acceleration of the flame due to a strong turbulization of the flow, may hinder the spread of the SW due to significant losses of the momentum and thereby impede or preclude the occurrence of DDT. This means that the solution of the above-mentioned problem of detonation initiation through controllable DDT should be sought in a careful selection of the shape and placement of obstacles, providing an optimal tradeoff between the rate of acceleration of the flame and the strengthening of the SW. This idea constitutes the basis of the concept of rapid DDT, which has been successfully pilot-tested for various gas and spray explosive mixtures [6].

In the present work, based on the concept of rapid DDT, we for the first time created a workable experimental model of a pulse detonation burner unit (PDBU) operating on natural gas, a prototype of industrial burner units of new generation. The model PDBU was used to perform experimental tests of managed cyclic DDT with separate continuous supply of natural gas and air.

The PDBU model consisted of three adjoined sections: a precombustion chamber with an ignition source (two standard automotive spark plugs), a flame-acceleration unit with a total length of 1200 mm, and a detonation tube, 94 mm in diameter and 3600 mm in length, encumbered with obstacles of special shape and placement. The construction of sections and details of their joining, as well as the shape and placement of obstacles, being subject to patent, are not discussed here.

The end of the detonation tube was opened. A 900-mm-long segment of the tube adjacent to the open end was smooth, i.e., contained no obstacles. Natural gas and air were continuously fed into the PDBU through separate gas lines from pressurized vessels at a slight overpressure. The gas flow rate was such as to prepare a mixture of stoichiometric composition. Natural gas contained 98.9% methane (engine gas).

In the experiment, we recorded the following parameters: the pressure in the precombustion chamber and in the flame-acceleration unit (with CARAT-DI60 low-frequency pressure sensors), the pressure in different sections of the detonation tube (LKh604 and PCB113A23 high-frequency piezoelectric pressure sensors), and emission from combustion products in various sections of the detonation tube (FD-256 photodiodes). After passing through amplifiers and analog-to-digital converters, the signals from the pressure sensors and photodiodes were recorded using a personal computer. The mean SW velocity at each measurement distance between pressure sensors was calculated from its length and the time it took for the SW to traverse it. The error in determining the mean SW velocity did not exceed 3%. The mean visible flame speed was calculated from the distance between the photosensors and the time intervals between the arrivals of the flame to the corresponding photodiodes. Detonation was identified based on two characteristics: (l) the steady-state SW velocity in the smooth section of the tube and (2) the coincidence of the arrival of the shock front and flame front to a particular section of the tube.

The most important new result of the work is the demonstration of the possibility of rapid cyclic DDT in a near-limit-diameter tube with an open end and separate continuous supply of natural gas and air. Figure 1 shows the measured dependence of the SW velocity on the distance traveled in the detonation tube for two (of the ten) cycles of operation at a frequency of 0.03 Hz (~two cycles per minute). The origin of the distance corresponds to the inlet section of the detonation tube. It is evident that DDT in the tube occurs

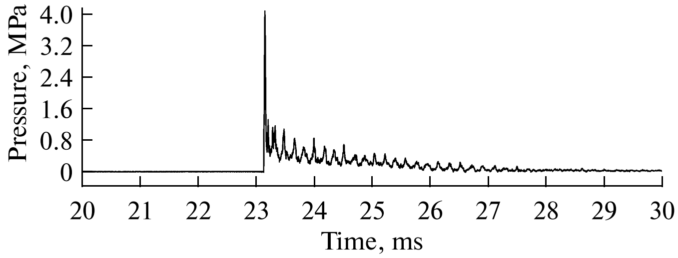

Fig. 2. Oscillogram of the pressure time profile in the detonation wave.

at a distance of about 1.5 m, and then the resulting detonation wave propagates over a distance of 1.5 m in the steady-state mode at a mean velocity of 1600–1700 m/s, including the smooth section.

The observed detonation regime should be deemed as a near-limit one. First, the mean velocity deficit of 100–200 m/s relative to the thermodynamic value for stoichiometric methane–air mixture (≈1800 m/s) is consistent with the permissible detonation velocity deficit near the propagation limit in a smooth tube. Secondly, the wave structure within the smooth section of the tube (Fig. 2) corresponds to the structure of spin detonation with typical weakly damped oscillations of the signal. Indeed, the oscillation frequency behind the shock wave front is ~6 kHz (6 oscillations in 1 ms). This frequency agrees well with the heuristic 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 for a 94-mm-diameter tube must be $s \approx 280$ mm, so that, at a mean spinning detonation velocity of $D \approx$ 1600–1700 m/s, the characteristic frequency of pulsations should be $D/s \approx 5.7$–6.1 kHz. The oscillogram displayed in Fig. 2 shows that the total time of burnout of the mixture in the experimental PDBU in one working cycle was ~23 ms. Note that almost all this time is taken to accelerate the flame and reach DDT, since detonation combustion lasted a very short time, ~1 ms, i.e., 4% of the total burning time. Given that the mean velocity of the bulk of the combustion products through the open end of the tube into the atmosphere is presumably close to the speed of sound (1000 m/s), the characteristic time of emptying the PDBU can be estimated as 4 ms. Consequently, the combustion of the mixture in the PDBU with subsequent emptying the burner duct took ~30 ms. This means that the rate of detonation cycles in the given PDBU cannot exceed ~30 Hz. Such a frequency of cycles can be obtained by instantaneously filling the tube with combustible mixture. With using high-pressure compressors, the filling velocity can reach 100 m/s, and the experimental PDBU can operate at a repetition frequency of 15 Hz.

Thus, the present work for the first time experimentally demonstrated the possibility of controlled cyclic DDT in a 94-mm-diameter tube with an open end and separate continuous supply of natural gas and air within a length of ~2.5–3.0 m (with account of the sizes of the precombustion chamber and flame acceleration unit). Based on experimental studies, we designed, constructed, and tested a workable PDBU, a prototype of industrial burners of new generation, which produces a combined shock-wave (mechanical) and thermal effect on objects blown on with combustion products.

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