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PHYSICAL CHEMISTRY

Detonation Initiation in a Natural Gas–Air Mixture in a Tube with a Focusing Nozzle

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It was shown experimentally for the first time that, when an axisymmetric nozzle of special shape is placed in a tube, the shock-to-detonation transition in a stoichiometric natural gas–air mixture occurs under normal conditions at a shock wave (SW) velocity at the nozzle inlet exceeding 1150 ± 30 m/s, which corresponds approximately to a Mach number of 3.3. This finding is important for the development of new-generation burners using pulsed detonative (PD) combustion of natural gas, as well as for a better understanding of the dynamics of accidental gas explosions in mine working.

The available combustion chambers of industrial burners based on slow burning of natural gas at low overpressures have fundamental limitations on the heat deposition intensity. It is believed that using the PD combustion of natural gas will lift these limitations and considerably increase the power plant capacity and efficiency [1]. In PD burners, the working process will occur in the self-ignition mode at high pressures and temperatures in a travelling detonation wave. This will ensure a significant (by hundreds of times) increase in the heat release power, combustion temperature (by 30–50%), and maximal combustion product speed (by 15–20 times). In addition, it is expected that, due to an extremely short (~1 ms) combustion time of natural gas in a cyclic operation process, PD burners will ensure low emission indices of nitrogen oxides.

Controlled PD combustion of natural gas in air can be widely used only if the detonation initiation is achieved by means of weak igniters (with a power of ~1 J or lower). The fact is that the detonability of such mixtures is extremely low. The limiting tube diameter at which a methane–air mixture can detonate under normal conditions is close to 100 mm [2, 3]. The energy of direct detonation initiation in such tubes is as high as 10 MJ/m^2 [4]. Deflagration-to-detonation transition (DDT) run-up distances for a weak igniter are tens of meters even in tubes with special turbulizing devices (obstacles) [5]. It is evident that the use of direct detonation initiation in power engineering is impracticable and that the DDT run-up distances in channels with turbulizing devices are too large. Hence, new approaches should be developed to sharply decrease the DDT run-up distances in case of weakly initiated combustion.

One of the approaches is initiation of the fast DDT by means of flame acceleration up to the generation of a relatively weak SW followed by its gasdynamic focusing [6]. This concept was successfully used in [7] for realization of the fast shock-to-detonation transition in a straight tube filled with a stoichiometric propane–air mixture. In [7], the focusing element was an axisymmetric convergent-divergent nozzle of special shape. It was experimentally shown that installation of a focusing nozzle in a tube ensures the shock-to-detonation transition at an SW velocity at the nozzle inlet above 680 ± 20 m/s, which approximately corresponds to a Mach number of 2.

The purpose of this work was to experimentally investigate the fast transition of a weak shock wave to detonation in a stoichiometric natural gas–air mixture in a straight tube with a focusing nozzle.

The experiments were carried out in a straight round stainless steel tube 4500 mm in length and 94 mm in diameter (Fig. 1). The tube consisted of two chambers separated by a bursting diaphragm: a low-pressure chamber (LPC) 3400 mm in length and a high-pressure chamber (HPC) 1000 mm in length. One end of the LPC was sealed with a metallic bursting diaphragm, and the other end was open to atmosphere. Before the experiment, the LPC was purged with a fivefold volume of a stoichiometric explosive natural gas–air mixture, which was prepared by the method of partial pressures in a mixing vessel 40 L in volume with forced mixing. The natural gas used as motor fuel contained 98.9% of methane.

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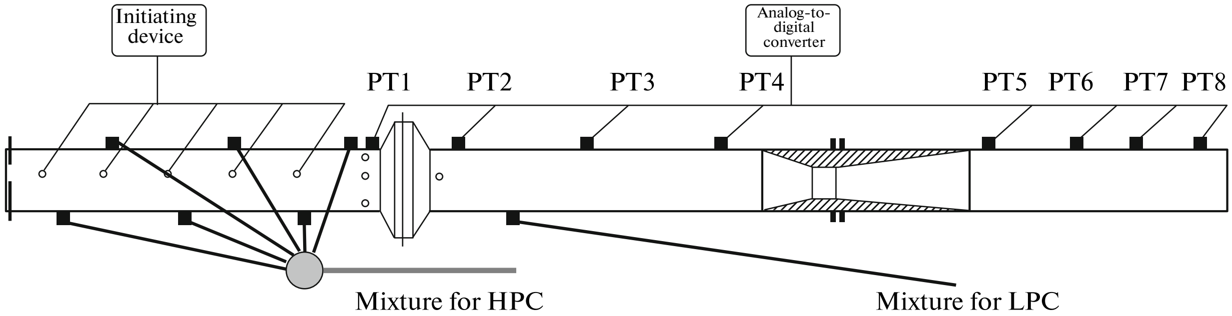

Fig. 1. Schematic of the experimental setup.

The bursting diaphragms were made of annealed copper 0.2 and 0.4 mm thick. Before the experiment, the diaphragm was incised using special instrument to control the pressure of its rupture. The diaphragm rupture overpressure in the HPC was achieved by burning the stoichiometric natural gas–air explosive mixture at an initial temperature of 293 ± 2 K and elevated initial pressure P_i. To this end, before the experiment, the HPC was evacuated and then filled with the mixture made by the method of partial pressures. To improve the mixing uniformity and increase the pressure rise rate in the HPC, the chamber was equipped with six inlet orifices for feeding the mixture components and six auto spark plugs located at regular intervals along the chamber length.

At a distance of 1600 mm from the diaphragm, a shaped obstacle—a nozzle consisting of a 40-mm-long convergent conical section, a 100-mm-long cylindrical sleeve, and 430-mm-long divergent conical section—was installed. The minimal cross-sectional diameter of the nozzle and sleeve was 47 mm. The profile of the convergent conical section destined for gas-dynamic focusing of the SW corresponded to the parabolic profile used in [7] with scaling to another tube diameter. The cylindrical sleeve ensured heat release behind the SW front with retention of a high density of the reaction mixture [8]. The divergent conical section was a right cone with an apex angle of 6°.

The pressure and SW velocity profiles were recorded with LKh604 piezoelectric pressure transducers PT1–PT8. The distances from the orifice exit section of the bursting diaphragm to the pressure transducers are presented below:

PT	PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8
Distance, mm	–100	593	994	1386	2188	2600	3000	3400

The signals of all the transducers were recorded with a PC using repeaters and a USB 3000 analog-to-digital converter.

The experimental procedure was as follows. First, calibration tests were performed for determining the SW characteristics in an experimental setup with and without a focusing nozzle. In these runs, the LPC was purged with neat air. We found that, to generate an SW with a Mach number of 2.6–3.5, the initial pressure of the natural gas–air explosive mixture in the HPC should be increased to P_i = 6.5–8.3 atm. As expected, after passing the nozzle, the SW became somewhat weaker.

Then, a series of runs were carried out in which the LPC was purged with the stoichiometric natural gas–air mixture, other conditions being the same. These experiments were carried out without a focusing nozzle. They demonstrated that the generated SWs were not able to initiate detonation of the mixture, at least, in the LPC of selected length.

Finally, a series of runs were carried out in which the LPC was purged with the stoichiometric natural gas–air mixture and a focusing nozzle was used. In these experiments, the shock-to-detonation transition was observed.

The table lists the results of 11 representative experiments as the average leading SW front velocities at seven measuring segments PT1–PT2, PT2–PT3, PT3–PT4, PT4–PT5, PT5–PT6, PT6–PT7, and PT7–PT8. The average leading SW velocity in each measuring segment was determined from the distance between the pressure transducers and the time interval between the SW front arrivals at the corresponding pressure transducers in the oscillogram. The error in determining the average SW velocity did not exceed 3%. The focusing nozzle was placed in the PT4–PT5 measuring segment.

Figure 2 shows the results of runs 1–9 presented in the table. The vertical dashed line (at 1600 mm) shows the position of the inlet cross section of the convergent nozzle portion. The upper horizontal dashed line represents the Chapman–Jouguet detonation velocity (~1800 m/s). Figure 2 shows that there is a certain minimal (critical) value of the average leading SW velocity at the nozzle inlet (the lower horizontal dashed line) at which detonation is initiated in the tube; i.e., the shock-to-detonation transition is a threshold phenomenon. The critical velocity value for the HPC 3400 mm in length and 94 mm in diameter is 1150 ± 30 m/s. For the stoichiometric methane–air

Average shock-wave velocity (m/s) in various measuring segments in 11 representative experiments

Run	Measuring segment							Notes
	PT1–PT2	PT2–PT3	PT3–PT4	**PT4–PT5**	PT5–PT6	PT6–PT7	PT7–PT8	
1	1226	1122	1150	**1709**	1661	2000	1744	Detonation
2	1192	1114	1162	**1680**	1884	1744	1898	The same
3	1238	1193	1278	**1769**	1884	1808	1852	″
4	1176	1082	1146	**1661**	1471	1328	1200	Secondary explosions
5	1255	1175	1131	**1566**	1343	1261	1172	The same
6	1255	1059	1097	**1617**	1379	1402	1200	″
7	1209	1090	1122	**1600**	1486	1402	1220	″
8	797	895	992	**993**	984	1027	1042	SV diffraction
9	716	737	907	**973**	1066	993	980	The same
10	670	787	868	**752**	883	1389	1282	Secondary explosions
11	1048	934	1000	**708**	1932	1613	1415	The same

Note: The average leading SW velocities inside the nozzle are written in boldface.

mixture under normal conditions, this velocity corresponds to a Mach number of ~3.3.

If the average SW velocity at the nozzle inlet was significantly below this critical value, no detonation was observed (table, experiments 8 and 9). In this case, upon SW diffraction in the nozzle, secondary explosions were observed neither inside nor outside the nozzle.

If the average SW velocity at the nozzle inlet exceeded this critical value, the shock-to-detonation transition occurred into the nozzle (table, experiments 1–3).

In the experiments where the SW velocity at the nozzle inlet was slightly lower than the critical value, secondary explosions occurred in the nozzle but did not lead to detonation (table, experiments 4–7). In this case, secondary waves merged with the leading SW front inside the nozzle, generating a rather strong blast wave. However, such a wave was attenuated after leaving the nozzle. In addition, under these conditions, regimes with delayed secondary explosion were observed. This was exemplified in the table by the results of two runs (experiments 10 and 11) in which the average velocity of the leading SW increased jump-

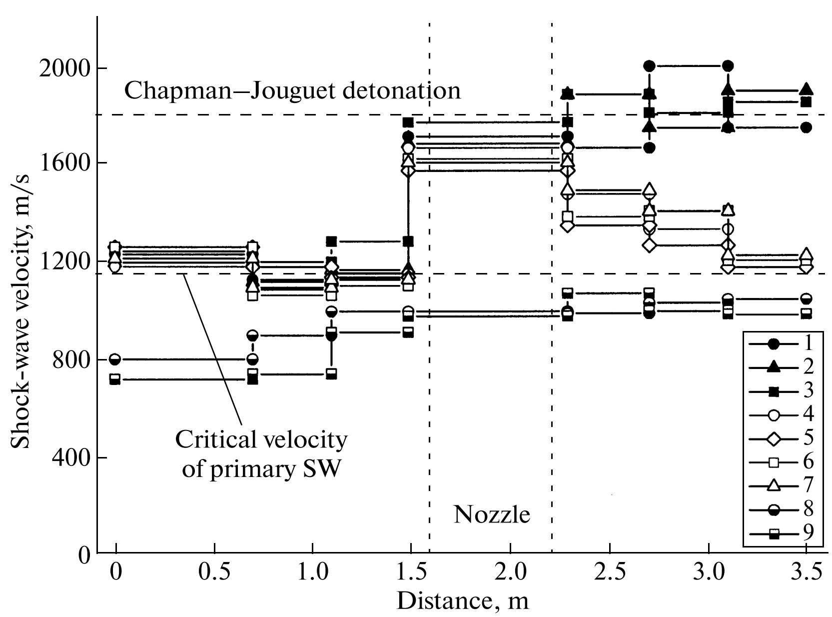

Fig. 2. Average velocity of the leading shock front versus travelled distance in various measuring segments in representative experiments 1–9 (table). Distance is measured from PT1.

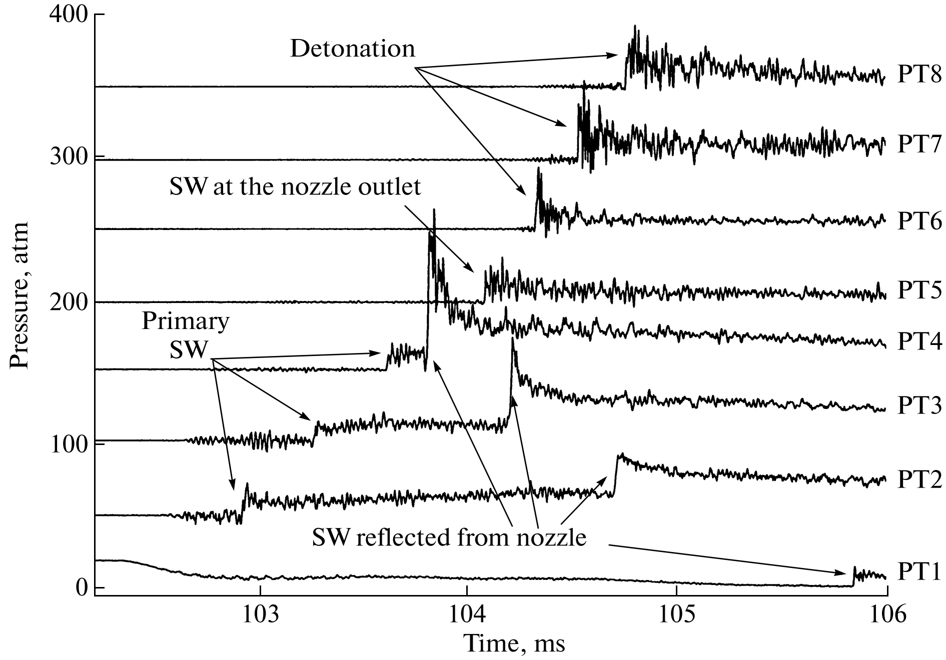

Fig. 3. Pressure records of transducers PT1–PT8 in experiment 1 with identification of wave phenomena.

wise after it left the nozzle. The jumpwise increase in the leading SW velocity was due to merging with the secondary blast wave generated into the nozzle.

Figure 3 presents the pressures recorded by pressure transducers PT1–PT8 in one of the runs with detonation initiation (experiment 1, table) with identification of wave phenomena. The pressure measurement error was estimated at 30%. The records of transducers PT1–PT3 showed that the overpressure in the primary SW was approximately constant and the compression phase in it lasted at least 1.7 ms (in the cross section of PT2).The average velocity of the primary SW at the nozzle inlet in experiment 1 was 1150 ± 30 m/s. At the instant of time of 103.8 ms, pressure transducer PT4 installed at a distance of 214 mm from the nozzle inlet detected a strong shock front corresponding to the SW reflected from the walls of the convergent nozzle section. Transducer PT5 placed at a distance of 18 mm from the nozzle outlet detected a detonation wave. The average wave velocity inside the nozzle was somewhat lower than the Chapman–Jouguet detonation velocity (1709 ± 50 m/s). In measuring segments PT5–PT6, PT6–PT7, and PT7–PT8, detonation propagating in a quasi-stationary mode at average velocities of 1600 ± 50, 2000 ± 60, and 1740 ± 50 m/s, respectively, was also observed. The small detonation velocity deficit observed (~100–150 m/s) as compared with the thermodynamic value was due to the fact that the tube diameter was close to the limiting diameter at which detonation propagation is still possible.

Thus, in this work, it has experimentally been shown for the first time that, for initiating detonation by a shock wave in a stoichiometric natural gas–air mixture in a tube with a focusing obstacle, the SW velocity must exceed 1150 ± 30 m/s. Such an SW can be generated, e.g., by replacing the HPC and a portion of the tube upstream the nozzle in the experimental setup by a tube section with turbulizing obstacles [9]. This result is of importance for the development of new-generation burners using PD combustion of natural gas, as well as for a better understanding of the dynamics of accidental gas explosions in mine working. In the latter case, hardware parts can serve as turbulizing obstacles, and the kinks, forks, and narrow spots of mine galleries can function as focusing devices.

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