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Initiation of Gas Detonation in a Tube with a Shaped Obstacle

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In this work, for the first time, we have experimentally shown that installation of an axisymmetric obstacle of special shape (nozzle) in a tube ensures shock wave-to-detonation transition in a stoichiometric propane–air mixture under normal conditions at very low minimal shock-wave velocity at the nozzle inlet, namely, 680 ± 20 m/s, which approximately corresponds to a Mach number of 2. This result is important for novel jet propulsion systems with detonative burning of fuel.

To ensure fast deflagration-to-detonation transition in hydrocarbon–air mixtures at minimal ignition energy is a most important basic challenge, solving which opens a way for practical use of detonation in promising power plants of flying vehicles—pulse detonation engines [1, 2]. In 2003–2008, at the Semenov Institute of Chemical Physics, RAS, a series of experimental and theoretical studies was performed to reduce the deflagration-to-detonation transition run-up distance and time in tubes for mixtures of gaseous and liquid hydrocarbon fuels with air [3]. One of the simplest and most promising solutions is to install a set of regular obstacles of particular shape within the detonation tube [4].

The purpose of this work was to experimentally investigate the fact transition of a weak shock wave to detonation in diffraction by a single obstacle of particular shape—convergent–divergent nozzle.

The experiments were carried out in a 4500-mm-long straight round tube 52 mm in diameter (Fig. 1) with a stoichiometric propane–air mixture. Before each experiment, the tube was evacuated and then filled with the mixture until normal initial conditions (temperature 293 ± 2 K, pressure 1 atm). A shock wave was produced by a solid-propellant gas generator, which was a cylindrical combustion chamber with a volume of 22 cm^3 equipped with a changeable bursting diaphragm with an outlet orifice diameter of 6 mm and a T6000 piezoelectric pressure transducer (Fig. 1, transducer PT1). At a distance of 2100 mm from the orifice exit section of the shock-wave generator, a shaped obstacle—a nozzle consisting of a 17-mm-long convergent conical section and 450-mm-long divergent conical section—was installed. The minimal cross-sectional diameter of the nozzle was 27 mm. The profile of the convergent conical section corresponded to calculated parabolic profile no. 2 [5]. The divergent conical section had the shape of a right cone and the length that was much larger than that calculated previously [5] for preventing rapid attenuation of secondary blast waves forming in the vicinity of the minimal cross section of the nozzle. The pressure and shock-wave velocity profiles were recorded with LKh600 piezoelectric pressure transducers PT2–PT9. The distances (mm) from the orifice exit section of the shock-wave generator to the pressure transducers are presented below.

PT2—877	PT6—3066
PT3—1691	PT7—3366
PT4—1991	PT8—3774
PT5—2776	PT9—4174

The signals of all the transducers were recorded with a PC using repeaters and an L-card L-783 analog-to-digital converter. The diagnostic system in all the experiments was triggered after reaching a certain given voltage at transducer PT1.

The experimental procedure was as follows [6, 7]. A weighed (2–3 g) charge of 12/7 CA cotton powder was placed in the gas generator. The charge was ignited by a weighed sample of porous cotton powder. The cotton powder burning time was about 10 ms, and the maximal pressure in the chamber of the shock-wave generator ranged from 500 to 1500 atm. The solid-propellant gas generator produced a shock wave with a long compression phase duration: the time of outflow of propellant gases exceeded 1 ms. Diaphragms of various thicknesses from different materials allowed us to vary the maximal pressure in the gas generator and, hence, the initial velocity of the primary shock wave.

The table and Fig. 2 present the results of ten representative experiments as the average velocity of the leading front of a shock wave at eight measuring segments 0–PT2, PT2–PT3, PT3–PT4, PT4–PT5, PT5–

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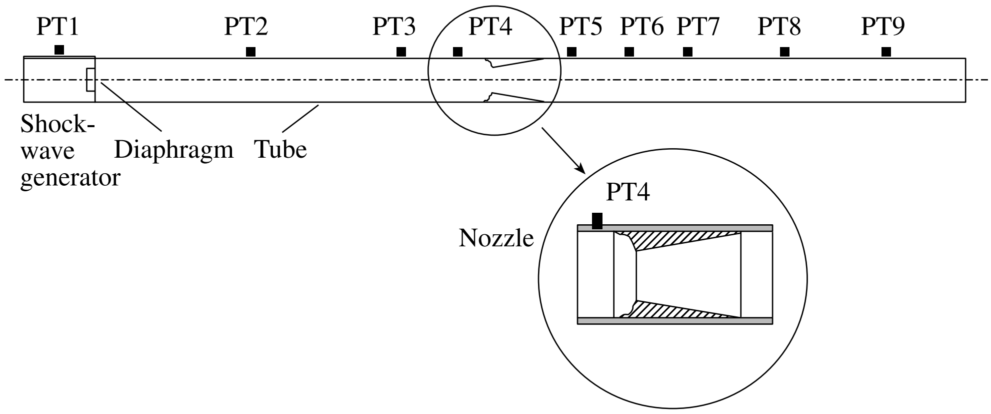

Fig. 1. Schematic of the experimental setup.

PT6, PT6–PT7, PT7–PT8, and PT8–PT9. The measuring segment 0–PT2 extended for 877 mm from the orifice exit section of the shock-wave generator to pressure transducers PT2. The moment of diaphragm rupture was determined from the record of transducer PT1.

In Fig. 2, the vertical dashed line (at 2130 mm) shows the position of the minimal nozzle cross section. The lower dotted line represents the Chapman–Jouguet detonation velocity (~1804 m/s). The average shock-wave velocity in each measuring segment was found from the distance between the neighboring pressure transducers and the time interval between the shock-wave front arrivals at the corresponding pressure transducers in the oscillogram. The error in determining the average shock-wave velocity did not exceed 3%. Figure 2 shows that there is a certain minimal (critical) value of the average velocity of the primary shock wave at the nozzle inlet at which detonation is initiated in the tube; i.e., the shock wave-to-detonation transition is a threshold phenomenon. The critical value for the 4500-mm-long tube 52 mm in diameter is 680 ± 20 m/s. For the stoichiometric propane–air mixture under normal conditions, this velocity corresponds to a Mach number of approximately 2.

If the average shock-wave velocity at the nozzle inlet is below this critical value, there is no detonation (table, experiment 5). If the average shock-wave velocity at the nozzle inlet is above this critical value, there is shock wave-to-detonation transition (table, experiments 2–10).

Figure 3 presents the pressures at pressure transducers PT2–PT9 with identification of wave phenomena in one of the experiments with detonation initiation (table, experiment 9). The pressure measurement error is estimated at 30%. The vertical dashed line indicates the moment of rupture of the diaphragm in the shock-wave generator. The record of transducer PT2 shows that the overpressure in the primary shock wave is constant for about 1 ms and then gradually decreases in a rarefaction wave. The intensity of the primary shock wave as it propagates along the tube decreases, which follows from the decrease in the amplitude (records PT4–PT6) and velocity (table). The average shock-wave velocity at the nozzle inlet in experiment 9 is 890 ± 30 m/s. In

Table 1. Average shock-wave velocity (km/s) in various measuring segments in ten representative experiments

No.	0–PT2	PT2–PT3	PT3–PT4	PT4–PT5	PT5–PT6	PT6–PT7	PT7–PT8	PT8–PT9
1	0.8002	0.7216	0.6667	0.6076	0.5009	0.5319	0.4964	0.4825
2	0.9164	0.9065	0.9934	**1.5096**	1.7365	1.7647	1.6790	1.6736
3	0.9193	0.7622	0.6993	0.7003	0.6017	0.6667	1.2107	**1.6667**
4	0.9410	0.7687	0.7500	0.8423	0.9206	1.2048	1.3645	**1.9802**
5	0.9533	0.9271	0.8197	0.8450	0.9295	1.2048	**1.6190**	1.8692
6	0.9606	0.8965	0.8287	0.8561	0.9416	1.1583	**1.4891**	1.9608
7	0.9659	0.8706	0.8065	0.7666	0.8951	0.9709	1.2326	**1.9608**
8	1.0057	0.9903	0.9524	**1.4564**	1.7683	1.7647	1.6585	1.7167
9	1.0198	0.9432	0.8902	0.9334	1.0247	1.3393	**1.9336**	1.8100
10	1.0465	1.0503	1.0033	1.2520	**1.7683**	1.7341	1.7739	1.6461

Note: The velocities from which the detonation run-up distance was determined (Fig. 4) are written in boldface.

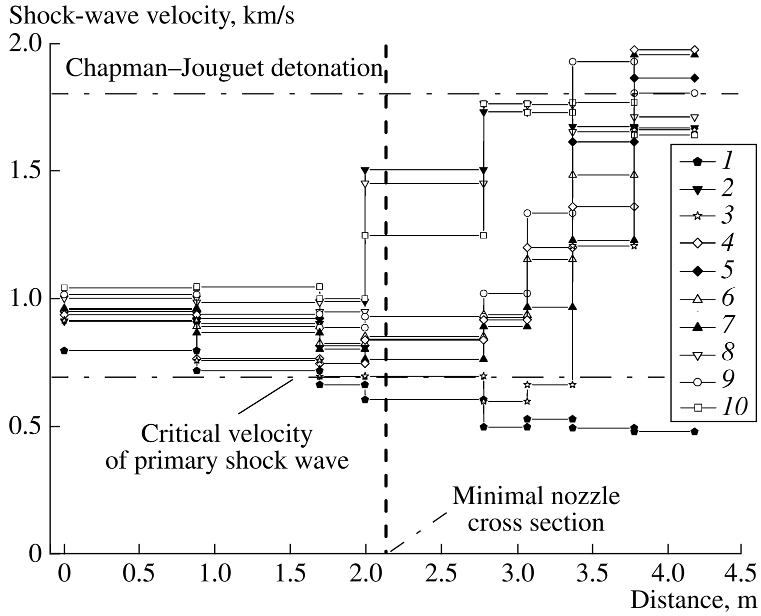

Fig. 2. Average velocity of the leading shock front versus travelled distance in various measuring segments in 10 representative experiments.

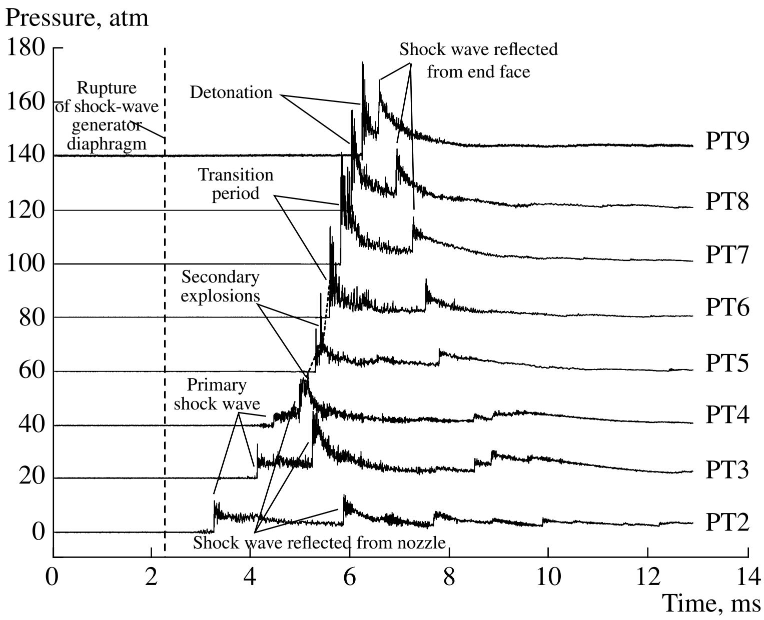

Fig. 3. Pressure records of transducers PT2–PT9 in experiment 9 with identification of wave phenomena.

approximately 5 ms, transducer PT4 installed at a distance of 139 mm from the minimal nozzle cross section detects a strong shock front corresponding to a shock wave reflected from the wall of the convergent nozzle section. The reflected wave is followed by a pressure peak caused by local explosions of the shock-compressed mixture in the nozzle. The record of transducer PT5 placed at a distance of 196 mm from the nozzle outlet shows that secondary explosions give rise to an intense shock front propagating in the divergent nozzle section, although the measured average velocity of the leading shock wave within the nozzle increases only by 50 m/s. Behind this shock front, there are additional secondary explosions. Shock waves catch up with one another and virtually merge in the record of transducer PT6, causing a sharp increase in the amplitude and velocity of the leading shock front. In the measuring segment PT6–PT7, the transition period still continues

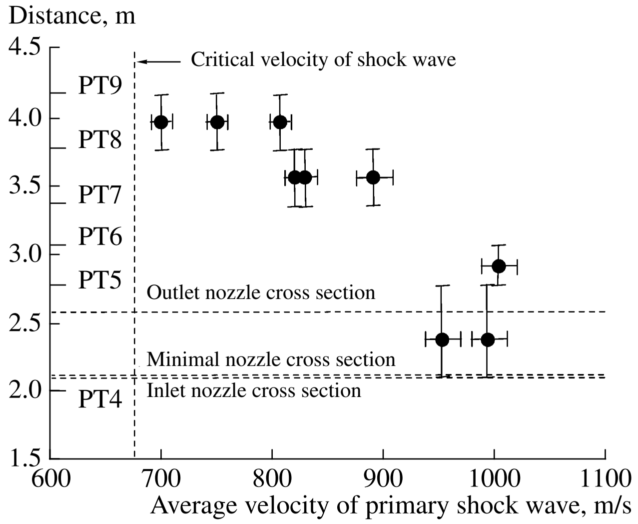

Fig. 4. Detonation run-up distance versus average velocity of the primary shock wave at the nozzle inlet.

(the average shock-wave velocity is 1340 ± 40 m/s). Finally, transducers PT8 and PT9 detect detonation propagating at velocities 1930 ± 60 and 1810 ± 50 m/s in the measuring segments PT7–PT8 and PT8–PT9, respectively. The average shock-wave velocity in the measuring segment PT8–PT9 is very close to the Chapman–Jouguet detonation velocity. Further, the detonation wave is reflected from the closed end of the tube and propagates through the combustion products upstream as an attenuating shock wave. Thus, in the experiment considered, the shock wave-to-detonation transition occurred at a distance of approximately 3570 ± 204 mm from the orifice exit section of the shock-wave generator, or at a distance of 1440 ± 204 nm from the minimal nozzle section and 990 ± 204 nm from the outlet nozzle cross section.

Figure 4 presents the detonation run-up distance as a function of the average velocity of the primary shock wave at the nozzle inlet according to the data of the table. While drawing Fig. 4, it was assumed that the detonation run-up distance is the distance to the point where the velocity of the leading shock-wave front reaches at least 1500 ± 45 m/s. With an increase in the average velocity of the primary shock wave, the detonation run-up distance is seen to decrease. At an average velocity of the primary shock wave above 950–1000 m/s, detonation occurs within the nozzle.

This fact seems important for designing the process in pulse detonation engines. Unlike conventional notions that a nozzle is intended for increasing the time of outflow of detonation products and, hence, for enhancing the specific impulse of jet thrust of pulse detonation engines, in this case, the nozzle is designed for both initiating detonation and controlling the outflow of explosion products.

Thus, in this work, it has experimentally been shown that, for initiating detonation by a shock wave in a stoichiometric propane–air mixture in a tube with an obstacle of special shape, the shock-wave velocity must exceed 680 ± 20 m/s. Such a shock wave is easy to produce, e.g., by replacing the solid-propellant shock-wave generator and a portion of the tube upstream the nozzle in the experimental setup by a tube section with a Shchelkin spiral. After ignition of the explosive mixture by a weak heat source, the flame acceleration in the section with the Shchelkin spiral gives rise to a shock wave propagating at a velocity of 900–1000 m/s [8].

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