ISSN 0012-5016, Doklady Physical Chemistry, 2017, Vol. 474, Part 2, pp. 93–98. © Pleiades Publishing, Ltd., 2017.
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PHYSICAL CHEMISTRY

Deflagration-to-Detonation Transition in the Gas–Liquid-Fuel Film System

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Presented by Academician A.A. Berlin May 30, 2016

Received October 24, 2016

Abstract—A deflagration-to-detonation transition was experimentally detected for the first time in a channel with a thin wall liquid-fuel film and a gaseous oxidizer using a weak ignition source, which generates no primary shock wave of any significant intensity. In a number of tests, a low-velocity quasi-stationary detonation-like combustion front traveling at an average velocity of 700–900 m/s was recorded; the structure of this front included a leading shock wave and a reaction zone following after a time delay of 80 to 150 μs.

DOI: 10.1134/S0012501617060021

In all the known experimental investigations of detonation in a gas–film system, detonation explosion was initiated by powerful sources. In 1952, Loison [1] observed detonation in such a system as a result of transmitting gas detonation to an air-filled tube with a thin film of a liquid fuel applied to the wall. In a large series of Troshin et al.'s works (see, e.g., [2]), "film" detonation was initiated by exploding lead azide charges, blasting caps, etc., in tubes 6 to 30 mm in diameter and 1.6 to 3.5 m in length. In these tubes, various liquid fuels (petroleum oils, viscous lubricants, individual hydrocarbons) and carbon in the form of carbon black were applied as films and layers onto the inner surface of the tubes, and various oxidizer gases (oxygen or oxygen-enriched air) were used at an initial pressure of 1 to 40 atm. It was shown that such a strong initiation always required a transition section equal to 20–30 tube diameters; along this section, an accelerating flame propagated, which then transitioned to detonation. Similar results were later obtained by Nicholls et al. [3, 4].

The gas–film heterogeneous system has a number of important advantages for using in continuous-detonation [5] and pulse-detonation [6] combustors (CDC and PDC, respectively) fueled by liquid fuel. First, in such a system, detonation is observed on films of virtually any thickness [2], which reduces the requirements for fuel metering accuracy and improves the operation reliability. Second, the gas–film system can be additionally used for active thermal protection of the walls of CDCs and PDCs during feeding a film to high-heat areas of the combustor. Noted in the literature, the necessity of using strong sources of detonation initiation could be assigned to disadvantages of the gas–film system. However, a thorough analysis of the literature demonstrated the absence of any mentions of attempts to perform a deflagration-to-detonation transition (DDT) in such a system using weak ignition sources, which generate no primary shock wave (SW) of any significant intensity.

The purpose of this work was to experimentally investigate the possibility of DDT in the liquid fuel film–oxygen system using a weak ignition source.

In this work, a DDT was experimentally detected for the first time in the gas (oxygen)–liquid-fuel (*n*-heptane) film system in a straight smooth channel with a thin wall film of liquid-fuel and a gaseous oxidizer using a weak ignition source. It was shown that a DDT in the gas–film system can result in the propagation of both the high-velocity (1800–2000 m/s) and low-velocity (700–900 m/s) detonation wave in the channel. The obtained results are pioneering and essential for developing new jet propulsion systems based on controlled detonation combustion of regular motor fuels and also for improving fire and explosion safety systems.

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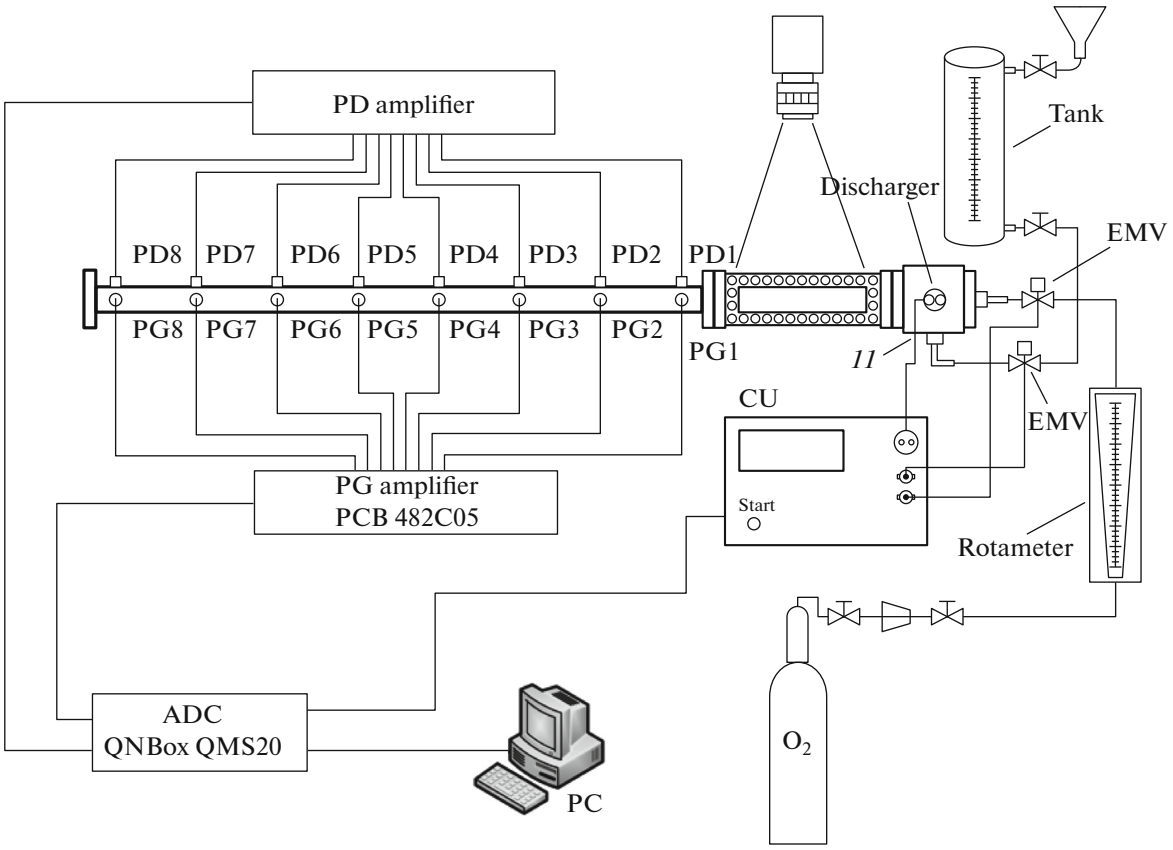

Fig. 1. Scheme of experimental setup with optical section.

Tests were carried out on an experimental setup a scheme of which is shown in Fig. 1. The test section was a 3-m-long 54 × 24-mm rectangular-sectioned straight channel with polished inner walls. Waves of pressure and luminosity caused by combustion were recorded with PCB 113B24 pressure gauges (PG1–PG8) and FD265A photodiodes (PD1–PD8), respectively, which were installed in holes at the same cross sections of the channel on two adjacent side walls along the central longitudinal axes of the walls at an interval of 400 mm. A liquid-fuel film always laid on the lower wall of the channel. As a rule, photodiodes PD1–PD8 were mounted on the upper wall of the channel, and pressure gauges PG1–PG8 were attached to the side wall at a height of 27 mm above the liquid-fuel film. The positions of the pressure gauges and photodiodes are X^* = (1) 170, (2) 570, (3) 970, (4) 1370, (5) 1770, (6) 2170, (7) 2570, and (8) 2970 mm from the closed end of the channel.

To the optical section, a 60-mm-long fuel feed section with a 22 × 50-mm internal channel was connected. The opposite end of the section was closed with a blind flange. In the middle of the section, an electric discharger was placed. Between two parallel electrodes of the discharger, which were spaced 10 mm from each other, a copper wire 150 μm in diameter was fastened. The wire was placed parallel to the channel axis at a distance of 13 mm from the liquid-fuel film.

The liquid fuel was fed to the channel from a fuel tank via a fuel feed line with a electromagnetic valve (EMV) through five openings on the channel bottom at a distance of 25 mm from the closed end. Oxygen was fed to the channel from a cylinder through a pressure reducer and a rotameter via an oxygen feed line with a solenoid valve through an opening 3 mm in diameter at the center of the closed end of the channel. The operation of the EMVs and the blasting of the copper wire were controlled by a control unit (CU) (Fig. 1).

Before a test, the channel was installed at an angle of 3.5° to the horizon line so that the liquid fuel fed to it spread over the bottom to form a thin film. The fuel flow rate was calculated from the change in the liquid level in the tank for a known time interval. The oxygen flow rate was adjusted according to the rotameter readings. The control unit was programmed in time intervals. During the first time interval 60 to 120 s long, the bulk of the channel was blown three times with oxygen. During the second time interval 80 s long, the channel was blown with oxygen simultaneously with feeding the fuel so that a liquid-fuel film was produced in the channel. Then, the oxygen and

Experimental results

No. of test	E_i, J	u_{O_2}, cm/s	δ_f, mm	M_0	L_*, cm	T_*, ms	D, m/s	Detonation mode
1	14 ± 1	0	0.5	1.1	100	4.5	1800/980	+/–
2	27 ± 1	0	0.5	1.2	96	3.8	1810	+
3		2	0.4	1.1	122	7.5	2060	+
4		13	0.4	1.0	176	22.5	1875	+
5		13	0.7	1.2	–	–	760	–
6	52 ± 3	2	0.4	1.0	196	10.1	1920	+
7		13	0.4	1.0	–	–	740	–
8		13	0.4	1.0	190	30.7	1700	+
9		13	0.7	1.2	103	3.8	1925	+
10		13	0.7	1.4	100	2.6	1890	+
11	210 ± 10	2	0.4	1.4	104	3.5	1970	+
12		13	0.3	1.2	108	4.3	1815	+
13		13	0.4	1.2	210	7.2	2030	+
14		13	0.4	1.2	110	4.6	1850	+
15		13	0.7	1.4	152	3.5	1930	+
16	480 ± 10	13	0.4	1.4	112	3.6	1870	+

fuel supply was rapidly cut off, and a command was issued to blast the wire by discharging a capacitor with a capacitance of $C = 6800$ μF, which was precharged to voltage U. The discharge energy was found as $E_i = CU^2/2$.

The average velocity of the liquid fuel within the channel was estimated from the instant of time at which the fuel began to flow from the open end of the channel. At the given angle of inclination of the channel, the average velocity of the liquid-fuel film was 6 ± 1 cm/s. The average fuel flow rate in each of the tests was determined from the height of the liquid column before and after the test; from the fuel flow rate, the average film thickness δ_f was calculated.

The tests were carried out at five different values of the ignition energy E_i (from 14 to 480 J) and three values of the rate u_{O_2} of oxygen blowing through the channel of 0, 2, and 13 cm/s.

In the tests, a DDT was detected for the first time in the gas–film system using a weak ignition source, which generates no primary shock wave of any significant intensity.

The table presents the results of 16 tests: the predetonation distance L_* and time T_*, and the average detonation wave (DW) velocity D and average Mach number M_0 of the SW generated by the ignition source in the first measurement section at given values of the ignition energy E_i, the rate u_{O_2} of oxygen blowing through the channel, and the n-heptane film thickness δ_f. The plus sign (+) denotes the modes of propagation of the reaction fronts at velocities close to the detonation velocity ($D > 1500$ m/s) for which there is coincidence of the instants of time of sharp deviation of the signals of the pressure gages and photodiodes installed at the same cross section of the channel. The minus sign (–) indicates the low-velocity modes of propagation of the reaction front for which there is a significant (but steady) lag of the luminosity front from the shock front. The predetonation distance L_* and time T_* were determined as the coordinates of the point of intersection of extrapolated straight lines in the experimental x–t (distance–time) diagram, which describe the propagation of the DW and the retonation wave, the latter being produced by a secondary explosion ("an explosion in an explosion" in Oppenheim's terminology). The DW velocity D was determined as the average of the values over two or three measurement segments at various predetonation distances L_*.

Figure 2 gives an example of the readings of pressure gauges PG1–PG8 (continuous curves) and photodiodes PD2–PD8 (dashed curves) in test 2 at an ignition energy of 27 J without oxygen blowing past the film. The readings of pressure gauges PG1–PG4 show that the explosion of the wire produces a weak (quasi-acoustic) shock wave, which propagates at a velocity of about 380 m/s ($M_0 = 1.17$). An insignificant pressure increase in this wave is hardly noticeable from the readings of PG1–PG4 at the instants of time 0.6, 1.7, 2.7, and 3.8 ms. The first signs of a luminosity appear at the instant of time 3 ms at cross section 2 at photodiode PD2 without significant pressure increase, and the luminosity persists for 10 ms, indicating combustion in this section. An abrupt (by ~3.5 MPa) pressure

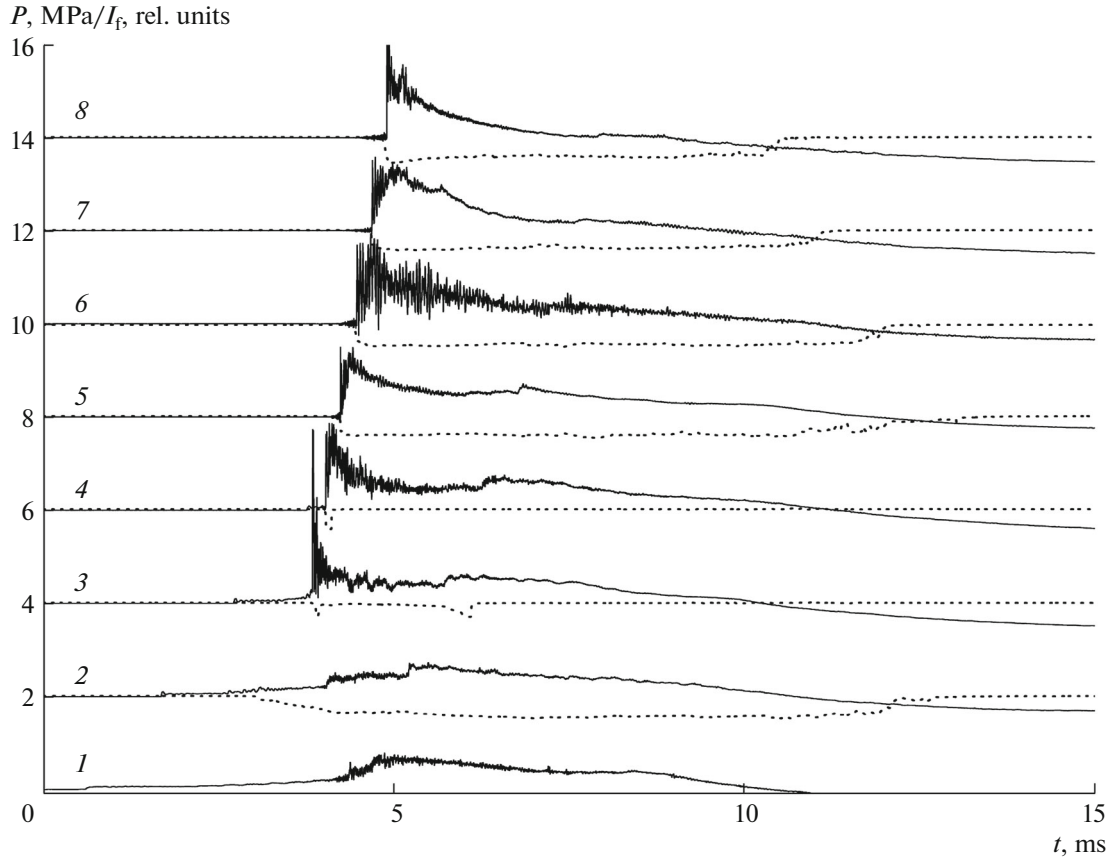

Fig. 2. Readings of pressure gauges (continuous curves) and photodiodes (dashed curves) in test 2.

increase in phase with the luminosity occurs at cross section 3 at a distance of 0.97 m from the closed end of the channel. At pressure gauges PG4–PG8, the amplitude of the pressure wave traveling toward the open end of the channel is approximately constant and reaches 1.5–1.7 MPa, and the beginning of the deviation of the signals of photodiodes PD4–PD8 from the zero line coincides with the arrival of the pressure wave at these cross sections; i.e., the reaction is initiated by a powerful SW.

The pressure wave (reaction front) velocities D_{4-5}, D_{5-6}, D_{6-7}, and D_{7-8} in respective measurement segments PG4–PG5 (PD4–PD5), PG5–PG6 (PD5–PD6), PG6–PG7 (PD6–PD7), and PG7–PG8 (PD7–PD8) are roughly the same and close to ~1810 m/s. The coincidence of the instants of time of the beginning of the pressure and luminosity signals at cross sections 3–8, as well as the pressure wave and reaction front velocities, suggests the propagation of a DW with rapid oxygen–fuel mixing behind the front of the leading SW and the self-ignition of the formed combustible mixture. A DDT occurs at a distance of $L_* \sim 1$ m from the ignition point at time $T_* = 3.8$ ms after the ignition. Note the fact that the luminosity signal at the point of DDT is much shorter than that in the produced detonation wave (compare the signals of photodiodes PD4 and PD5). Probably, at the point of DDT, there is fast and complete local combustion of one of the components of the combustible mixture—oxygen or fuel vapor.

Taking into account the positions of the pressure gauges and the photodiodes, one can state that the detonation wave front is virtually plane, at least, up to a height of ~27 mm above the film. Thermodynamic calculation of the parameters of detonation of a stoichiometric mixture of *n*-heptane with oxygen without regard for dissociation gave the following values of the Chapman–Jouguet detonation parameters (CJ index): velocity $D_{CJ} = 2340$ m/s, pressure $P_{CJ} = 3.9$ MPa, temperature $T_{CJ} = 3860$ K, and speed of sound $a_{CJ} = 1260$ m/s. Based on the calculated speed of sound in the detonation products, one can estimate the frequency of transverse waves along the width (~26 kHz) and height (~12 kHz) of the channel. In Fig. 2, the frequency of pressure pulsations behind the detonation front is 24–38 kHz, i.e., agrees with the estimate from above. However, the maximum and average pressures in the detonation wave in Fig. 2 (~1.5 and ~1 MPa, respectively) turned out to be noticeably lower than the calculated pressure. In the considered case, the entire wave process of combustion of the combustible mixture occurs very rapidly (within ~5 ms).

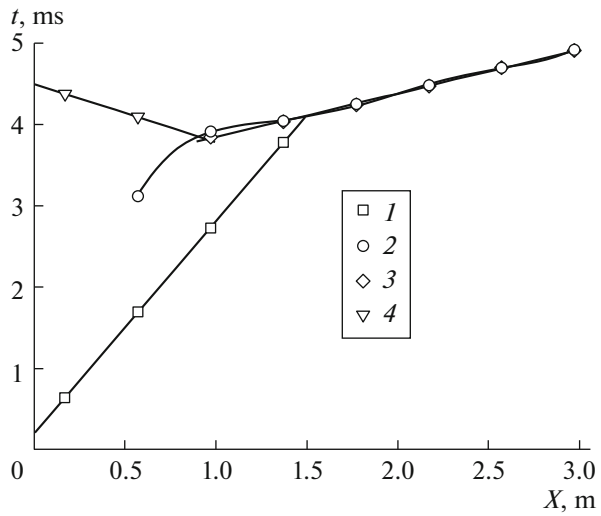

Fig. 3. Experimental $x(t)$ diagram of test 2: (*1*) weak shock wave from the ignition source, (*2*) flame front, (*3*) detonation wave, and (*4*) retonation wave.

Figure 3 presents the x–t diagram of the development of the process in test 2. To construct such diagrams, the pressure and luminosity readings were analyzed to identify characteristic points corresponding to the SW and DW fronts, as well as to the reaction, retonation, and rarefaction waves. It is seen that, after the initial stage of the flame acceleration, a secondary explosion occurs in the channel (kink in curve *2* at a distance of ~1 m); after that, a DW forms (curves *2* and *3* merge), which catches up with the quasi-acoustic SW from the ignition source (curve *1*).

In test 1 performed at lower (14 J) ignition energy than test 2, an interesting feature was observed: the high-velocity combustion mode with a detonation wave was replaced after a while by a low-velocity combustion mode with separated shock and reaction waves (Fig. 4). Indeed, in Fig. 4, beginning with cross section 6, one can see a certain lag of the luminosity signal from the shock front. Moreover, the average detonation wave velocity in measurement segment PG6–PG7 decreases approximately by 1200 m/s from $D_{4-5} = 2020$ m/s to $D_{6-7} = 820$ m/s; and in measurement segment PG7–PG8, to $D_{7-8} = 860$ m/s. Because of the limited length of a measurement section, it cannot be confidently determined whether or not the observed low-velocity (800–900 m/s) mode of the reaction front propagation is stable. The determination of the cause of the short-term existence of the DW in test 1 with subsequent change of the reaction front propagation mode requires additional investigations.

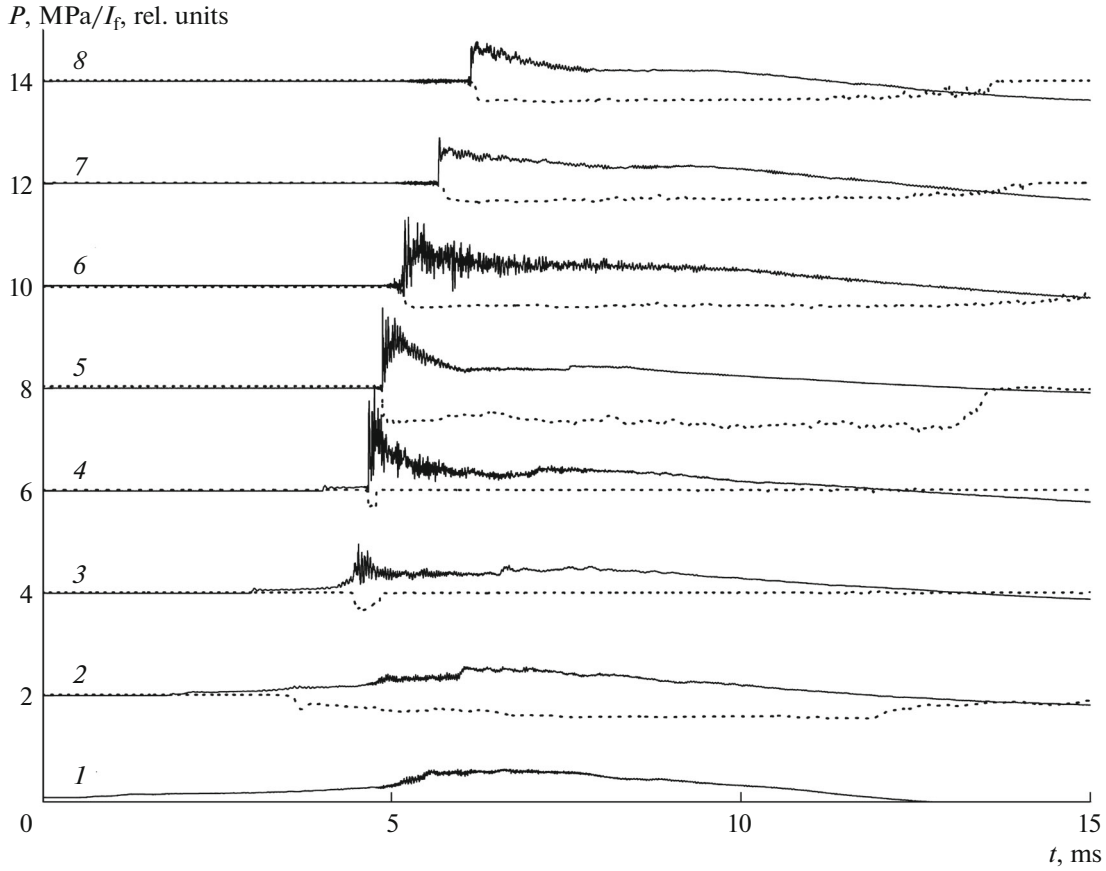

Fig. 4. Readings of pressure gauges (continuous curves) and photodiodes (dashed curves) in test 1.

In the other tests at an ignition energy of 27 J, and also in the tests at $E_i = 52$ J, DDT were observed with both the very short predetonation period and the significantly longer predetonation period but without switching from the high-velocity combustion mode to a low-velocity one (e.g., in tests 4 and 8). In some tests at such an ignition energy (tests 5 and 7), only a low-velocity combustion mode was observed. In other words, from test to test, the predetonation period duration and the predetonation distance somewhat changed.

In the tests at relatively high (210 J) ignition energy, changes in the predetonation distance from test to test were also detected. For example, in test 12, a DDT occurred at a distance of $L_* \sim 1.1$ m, and in test 13, at a distance of $L_* \sim 2.1$ m, although the experimental conditions were basically identical, and the differences in film thickness were within the measurement error. In fact, the actual film thickness is very difficult to determine even by thoroughly measuring the flow rates because the accurate value of the wetted surface area is unknown on account of capillary effects and partial carryover of the fuel during oxygen blowing through the channel.

Thus, in this work, a DDT was experimentally detected for the first time in the gas–film system using a weak ignition source. Although the dynamics of the development of the detonation explosion somewhat differed from test to test at both different and equal ignition energies, the measured DW velocity was independent of the ignition energy and was 1800–2000 m/s (77–85% of the Chapman–Jouguet detonation velocity), and the pressure and luminosity profiles in the DW retained their shape. In a number of tests, a low-velocity quasi-stationary detonation-like combustion front traveling at an average velocity of 700–900 m/s was recorded, the structure of which included a leading SW and a reaction zone following after a time delay of 80 to 150 μs.

The obtained results can be used for designing the process in CDCs and PDCs to which a liquid fuel is fed as a wall film.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 15-08-00782).

REFERENCES

1. Loison, R., *C. R.*, 1952, vol. 234, no. 5, pp. 512–513.
2. Komov, V.F. and Troshin, Ya.K., *Dokl. Akad. Nauk SSSR*, 1967, vol. 175, no. 1, pp. 109–112.
3. Ragland, K.W. and Nicholls, J.A., *AIAA J.*, 1969, vol. 7, no. 5, pp. 859–863.
4. Sichel, M., Rao, C.S., and Nicholls, J.A., *Proc. Combust. Inst.*, 1971, vol. 13, pp. 1141–1149.
5. Roy, G.D., Frolov, S.M., Borisov, A.A., and Netzer, D.W., *Progr. Energy Combust. Sci.*, 2004, vol. 30, no. 6, pp. 545 – 672.
6. Voitsekhovskii, B.V., *Dokl. Akad. Nauk SSSR*, 1959, vol. 129, no. 6, pp. 1254–1256.

Translated by V. Glyanchenko