DEFLAGRATION-TO-DETONATION TRANSITION IN A STRATIFIED SYSTEM "GASEOUS OXYGEN – LIQUID FILM OF n-DECANE"

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Deflagration-to-detonation transition (DDT) in the system "gaseous oxygen – liquid film of n-decane"' with a weak ignition source was obtained experimentally. In a series of experiments with ignition by an exploding wire that generates a weak primary shock wave (SW) with a Mach number ranging from 1.03 to 1.4, the DDT with the detonation run-up distances 1 to 4 m from the ignition source and run-up time 3 ms to 1.7 s after ignition was observed in a straight smooth channel of rectangular 54×24-millimeter cross section, 3 and 6 m in length with one open end. The DDT is obtained for relatively thick films with a thickness of 0.3–0.5 mm, which corresponds to very high values of the overall fuel-to-oxygen equivalence ratios of 20–40. The registered velocity of the detonation wave (DW) was 1400–1700 m/s. In a number of experiments, a high-velocity quasi-stationary detonation-like combustion front was recorded running at an average velocity of 700–1100 m/s. Its structure includes the leading SW followed by the reaction zone with a time delay of 90 to 190 μs. The obtained results are important for the organization of the operation process in advanced continuous-detonation and pulsed-detonation combustors of rocket and air-breathing engines with the supply of liquid fuel in the form of a wall film.

Introduction

In 1952, Loison [1] observed a detonation propagating at the velocity of about 1200 m/s in a tube 250 mm in diameter and 80 to 100 m long filled

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with air and with a liquid fuel (lubrication oil) film 0.1–0.3 mm thick applied to the tube wall. The detonation was initiated by transmitting a gas detonation from a 4-meter long initiating volume filled with homogeneous methane – oxygen-enriched air mixture at 7 atm, initially separated from the tube by a bursting diaphragm. Since then, the detonations in stratified gas–film systems are referred to as "film-detonations."

In a large series of works by Troshin with coworkers (see, e. g., [2–4]), 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, and individual hydrocarbons) and carbon in the form of carbon black were applied as films and layers of tens of micrometer to millimeter thickness 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. The measured velocities of film detonations ranged from 900 to 1900 m/s. The maximum deficit of the measured detonation velocity with respect to the thermodynamic value calculated for the overall fuel-to-oxidizer equivalence ratio (within the detonability limits of premixed compositions) attained 60%; however, film detonations did not exhibit a fuel-rich concentration limit. Further studies were later performed by Nicholls with coworkers [5–7] and Gel'fand with coworkers [8–10] and were revisited recently by us [11–13].

Our main motivation to revisit this issue is that the heterogeneous gas–film system has several important advantages for use in Detonation Liquid-propellant Rocket Engines (DLREs) [14]. Firstly, the gas–film system can be additionally used for active thermal protection of the walls of the DLRE when the film is fed to the highly heated sections of the combustor. Secondly, in such a system, detonation can propagate virtually at any thickness of the liquid film (see, e. g., [3, 5]), which reduces the requirements for the accuracy of dosing of fuel and increases the reliability of the operation process. Thirdly, in the stratified gas–film system, which is characterized by a relatively small area of the interface (in comparison with the gas–droplet system), the preliminary evaporation of the liquid ahead of the propagating detonation wave is insignificant, which prevents various disturbances in the operation process like flame flashback, etc.).

In contrast to known experimental studies (see, for example, [1–7]), in which detonation in the gas–film system was initiated by powerful sources, in [11–13], a weak source of ignition in the form of an exploding wire was used for detonation initiation. Experiments in [11–13] showed that in the system "gaseous oxygen – liquid film of n-heptane," DDT was possible at distances 1 to 2 m from the ignition source and at times 3.4 to 30 ms after ignition. These results were obtained in a straight smooth channel of rectangular 54×24 mm cross section 3 m in length with one open end. The exploding wire generated a weak primary SW with a Mach number less than ~ 1.2 not capable to initiate detonation directly. Despite the detected differences in the dynamics of the development of detona-

tion from one experiment to another with both different and identical ignition energies, the measured DW velocity in experiments [11–13] was 1800–2000 m/s irrespective of the ignition energy. Also, pressure and luminosity profiles in the DWs retained their shape. In a number of experiments, a high-velocity quasi-stationary detonation-like combustion regime was observed, propagating at an average velocity of 700–900 m/s. Its structure included the leading SW followed by the extended turbulent combustion zone with a time delay of 80–150 μs.

Although the experiments in [11–13] were carried out in a stratified system under normal conditions, nevertheless, the saturated vapor pressure of n-heptane at room temperature (4.4 kPa) is sufficient to form a layer of a homogeneous combustible mixture with the fuel-to-oxygen equivalence ratio $\Phi = 0.5$ above the liquid film, in which detonation could propagate. Therefore, to evaluate the effect of the vapor phase of the fuel on the DDT mechanism, a comparative study with less volatile hydrocarbon fuels is necessary.

The objective of this work is to continue the experimental studies started in [11–13], using a much less volatile n-decane instead of volatile n-heptane. Compared with n-heptane, the saturated vapor pressure of n-decane at room temperature is 40–60 times lower and is only 0.1 kPa. These studies are important for the organization of the operation process in the continuous-detonation and pulsed-detonation combustion chambers of advanced rocket and air-breathing engines.

Experimental Setup and Measurement Procedure

The studies of DDT in the "gas–film" system were performed on an experimental setup described in detail in [11]. In the same reference, the measurement procedure is described in detail. Here, we provide only a brief description of the setup and measurement procedure.

Figure 1 presents four configurations of the main element of the experimental setup — a detonation channel of rectangular cross section 24×54 mm. In the experiments, two channel arrangements were used (shown in the circles on the left): in the form of a channel 54 mm wide and 24 mm high (hereinafter referred to as the "wide" channel, Figs. 1a and 1c) and as a channel 24 m wide and 54 mm high (hereinafter referred to as the "narrow" channel, Figs. 1b and 1d).

The length of the channels is either 3 m (hereinafter referred to as the "short" channels, Figs. 1a and 1b) or 6 m (hereinafter referred to as the "long" channels, Figs. 1c and 1d). The channel is inclined at an angle of 3° to the horizon. Liquid fuel (n-decane) is fed into the channel through a series of capillaries located 20 mm from the closed end (in Fig. 1 on the right), and by spreading the liquid, a thin film forms on the bottom wall of the channel. The time of supply of liquid fuel to the channel is selected so that the bottom wall of the

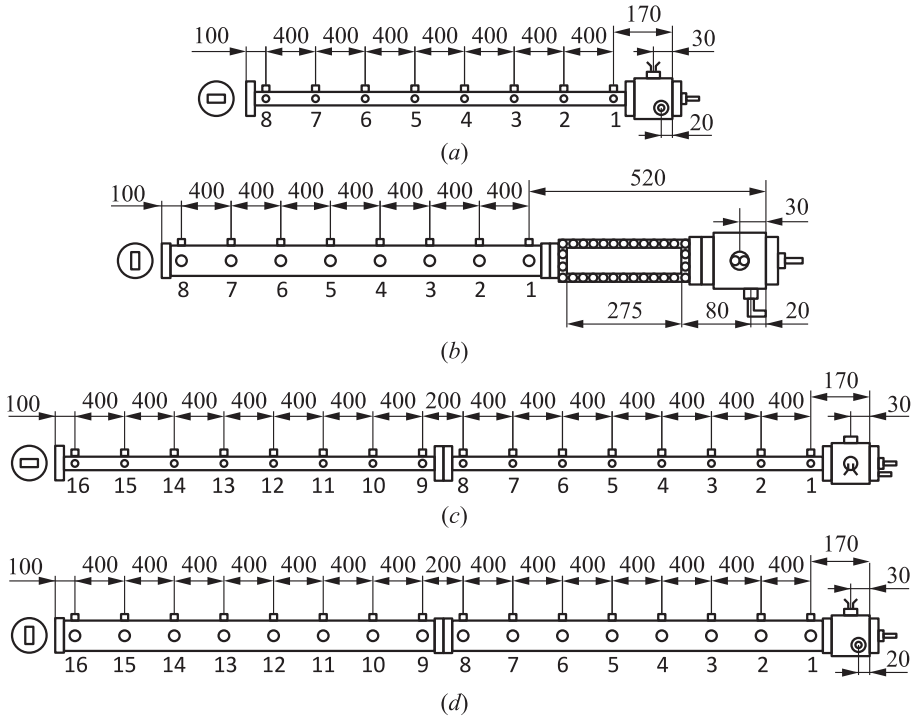

Figure 1 Schematic of the detonation channel: (*a*) wide/short channel (height 24 mm, width 54 mm and length 3 m); (*b*) narrow/short channel (height 54 mm, width 24 mm and 3 m long) with an optical section; (*c*) wide/long channel (height 24 mm, width 54 mm and length 6 m); and (*d*) narrow/long channel (height 54 mm, width 24 mm, length 6 m). Dimensions are shown in millimeters

channel is wetted by the film along the entire length. Gaseous oxygen is fed into the channel at a flow rate of 10 l/min in a volume exceeding the volume of the channel by a factor of at least 5.

Ignition is triggered by exploding a copper wire with a diameter of 130 μm and a length of 6 mm, placed above the surface of the film at the closed end. The wire is exploded by closing an electrical circuit with a capacitor. Changing the capacity of the capacitor from 25 to 6900 μF and its voltage from 120 to 380 V allowed us to vary the ignition energy from 0.2 to 500 J with an error of not exceeding 10%. The development of the combustion process in the channel is detected by photodiodes (PDs) and high-frequency pressure transducers (PTs) installed along the channel. In each measuring section, two sensors, the PD and DD, are installed on the adjacent channel walls. The numbering of the measuring sections is shown in Fig. 1. In the narrow/short chan-

nel shown in Fig. 1*b*, in addition to recording the self-luminosity of the reaction front and pressure, video recording of the shadow pattern of the process development in the initial section of the channel could be made using a high-speed video camera through an optical window 275 mm long and 50 mm high.

Results of Experiments in a Short Channel

Tables 1 and 2 show the results of experiments in a wide/short (see Table 1) and narrow/short (see Table 2) channels. The tables indicate: the number of the experiment; the average thickness of the fuel film δ_f calculated by the mass of fuel supplied to the channel; Mach number, M_0, of an SW generated by ignition (calculated based on the average velocity of the SW on the measuring segment between sections 1 and 4); the measured values of the detonation run-up distance L^* and time T^*; the measured value of the average velocity of the reaction front, D, determined as the average value at the steady-state propagation

Table 1 Results of experiments in a wide/short channel

No.	δ_f, mm	M_0	L^*, m	T^*, ms	$\overline{D}$, m/s	Mode
1	0.35	1.03	2.5	1068	—	D
2	0.52	1.10	1.3	47	1690	D
3	0.47	1.14	1.4	77	1440	D
4	0.27	1.38	0.9	2.8	1400	D
5	0.29	1.51	1.5	3.2	1510	D
6	0.18	1.21	—	—	900	HC
7	0.16	1.34	—	—	1050	HC
8	0.13	1.06	—	—	~ 75	LC
9	0.38	1.06	—	—	~ 10	LC
10	0.38	1.07	—	—	~ 40	LC
11	0.18	1.17	—	—	~ 80	LC
12	0.19	1.14	—	—	~ 150	LC

Table 2 Results of experiments in a narrow/short channel

No.	δ_f, mm	M_0	L^*, m	T^*, ms	$\overline{D}$, m/s	Mode
1	0.31	1.14	—	—	1030	HC
2	0.65	1.47	—	—	770	HC
3	0.78	1.09	—	—	~ 70	LC
4	0.65	1.04	—	—	~ 10	LC
5	0.68	1.12	—	—	~ 80	LC

mode or the value at the last measuring segment for the transient propagation mode; and the notation of the registered combustion regime: D = detonation; HC = high-speed combustion; and LC = low-speed combustion. The error in determining the velocity of the reaction front is 3%.

The most important experimental finding reported herein is registration of DDT in the system "gaseous oxygen – liquid film of *n*-decane" with a weak ignition source. The DDT was recorded only in a wide/short channel (see Table 1) with the Mach number of the primary SW generated by the exploding wire, $M_0 = 1.03$–1.51 (experiments 1 to 5 in Table 1), and at a film thickness $\delta_f = 0.3$–0.5 mm. At the minimum values of the ignition energy at which the DDT is detected, the Mach number of the primary SW was $M_0 < 1.15$ (exper-

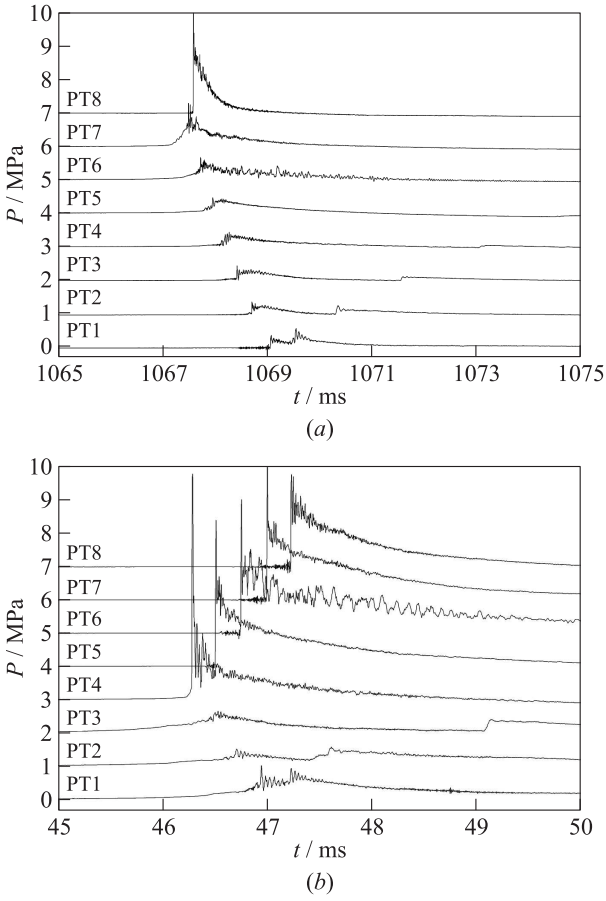

Figure 2 Pressure records in experiments 1 (*a*) and 2 (*b*) (see Table 1)

iments 1 to 3), i. e., the intensity of the primary SW was very low to initiate the detonation directly. The measured values of the detonation run-up distance L^* and time T^* in experiments 1 to 5 were 0.9–2.5 m and 2.8–1068 ms, respectively. The average detonation velocity was $D = 1400$–1700 m/s. In a narrow/short channel, at close values of M_0 and δ_f, detonation did not occur (see Table 2).

As an example of flow development with DDT, Fig. 2 shows the records of PTs in experiments 1 and 2 from Table 1. In experiment 1 (Fig. 2*a*), based on the observed profile and amplitude of the pressure wave, one concludes that the DDT occurred at the very end of the channel in the vicinity of the measuring section 8 (see Fig. 1*a*) approximately 1 s after ignition. The luminosity front registered by the PD in the same measuring section (not shown in Fig. 2) arrives virtually simultaneously with the front of the SW (the delay in arrival of the luminosity front did not exceed 15 μs in this cross section). The large value of the detonation run-up time T^* means that the DDT process can be affected by the outflow of gas through the open end of the channel, that is, the channel length in experiment 1 is insufficient for a reliable conclusion about the possibility of DDT.

In contrast to experiment 1, in experiment 2, the DDT occurred in the middle of the channel, at a distance of about 1.3 m from the ignition source in a relatively short time (47 ms) after ignition. Based on the space–time diagram of the wave processes in experiment 2 (Fig. 3*a*) and on the measured dependencies of the propagation velocities of the pressure and luminosity wave fronts (Fig. 3*b*), one concludes that in this experiment, the open end of the channel also affected flame acceleration and DDT. In this case (see Fig. 3*b*), four stages of flame evolution can be distinguished: slow propagation for a distance of up to 0.5 m from the ignition source, accelerated propagation between 0.5 to 1.2 m until reaching a transonic velocity (~ 300 m/s), abrupt acceleration and DDT at $L^* \approx 1.3$ m, and further propagation to the end of the channel as a DW.

An increase in the Mach number of the primary SW (see experiments 4 and 5 in Table 1) led to a sharp reduction in the detonation run-up time to 2.8–3.2 ms. Under these conditions, the open end of the channel did not obviously affect the DDT, although the detonation run-up distance remained at a level of 1.0–1.5 m, i. e., the DDT occurred in the middle of the channel. It is worth noting that in experiments, the location and time of the DDT were determined from the space–time diagram (see Fig. 3*a*) by finding the intersection of the trajectories of the DW and retonation wave. The DDT process is accompanied by the formation of a strong SW with an amplitude exceeding 6.8 MPa (that is, the maximum pressure value for the PCB 113B24 pressure transducers used herein, see, e. g., the record of the PT4 in Fig. 2*b*). Detonation in the experiments was identified by the simultaneous (with a time shift less than 15 μs) arrival of pressure and luminosity waves to a certain measuring section and also by the propagation velocity above 1400 m/s.

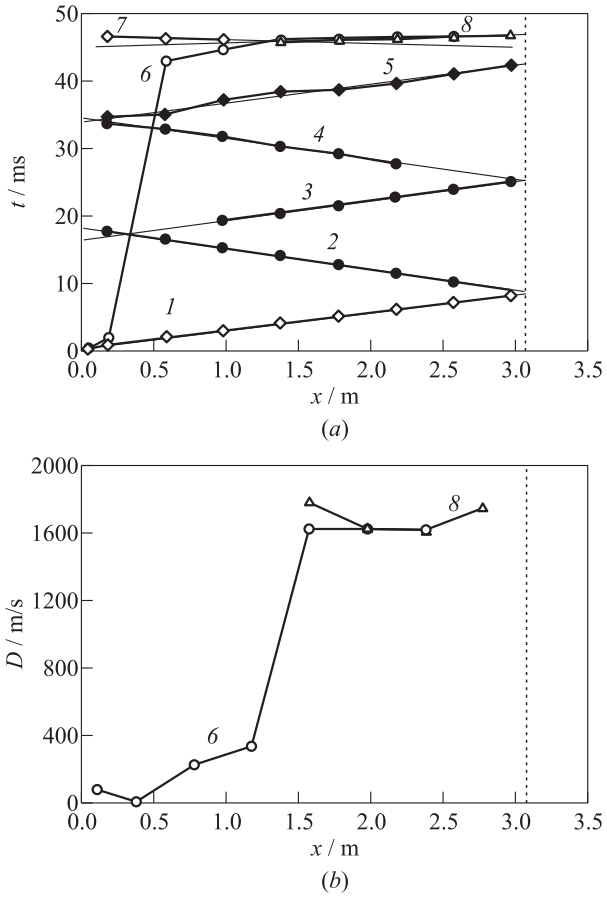

Figure 3 Space–time diagram (*a*) and the velocities of the pressure and luminosity fronts (*b*) for experiment 2 in Table 1: *1* — shock front; *2* — front of the rarefaction wave; *3*, *4*, and *5* — fronts of acoustic waves; *6* — luminosity front (flame); *7* — front of the retonation wave; and *8* — front of the DW

Reduction of the film thickness with other conditions being nearly the same led to the failure of DDT: instead of detonation, either an HC mode with a propagation velocity ranging from 700 to 1100 m/s or an LC mode with a propagation velocity below 150 m/s occurred in the channel. The HC mode registered in the "gaseous oxygen – liquid film of *n*-decane" system had much in common with the high-velocity quasi-stationary detonation-like combustion front observed in [11–13] in the "gaseous oxygen – liquid film of *n*-heptane" system: it propagated with the same visible velocities and its structure included the leading SW followed by the reaction zone with a time delay of 90 to 190 μs.

Results of Experiments in a Long Channel

Tables 3 and 4 show the results of experiments in a wide/long (Table 3) and narrow/long (Table 4) channels (see Figs. 1*c* and 1*d*, respectively). They list the same parameters as in Tables 1 and 2.

Experiments in the long channel confirmed the possibility of DDT in the system "gaseous oxygen – liquid film of *n*-decane" with a weak ignition source. In contrast to the experiments in the short channel, DDT is recorded in both wide/long (see Table 3) and narrow/long (see Table 4) channels. In the wide/long channel, experiments were carried out with $M_0 = 1.13001.14$ (experiments 1 to 5 in Table 3) and with $\delta_f = 0.35$–0.40 mm, i. e., under conditions close to

Table 3 Results of experiments in a wide/long channel

No.	δ_f, mm	M_0	L^*, m	T^*, ms	$\overline{D}$, m/s	Mode
1	0.40	1.14	3.9	1231.5	1635	D
2	0.35	1.14	4.4	1603	1580	D
3	0.35	1.14	4.7	1656.8	1560	D
4	0.39	1.14	4.4	1159	1795	D
5	0.40	1.13	4.1	1309.5	1710	D

Table 4 Results of experiments in a narrow/long channel

No.	δ_f, mm	M_0	L^*, m	T^*, ms	$\overline{D}$, m/s	Mode
1	0.43	1.43	1.5	5.2	1645	D
2	0.52	1.32	2.3	6.5	1570	D
3	0.46	1.17	2.8	57	1120	HC
4	0.43	1.39	1.4	5	805	HC
5	0.47	1.24	1.6	10	980	HC
6	0.42	1.19	2	9	825	HC
7	0.48	1.44	1.4	4.5	970	HC
8	0.48	1.37	1.4	5.5	835	HC
9	0.40	1.38	1.5	6	1460	HC⁄D
10	0.41	1.38	1.4	5.5	800	HC
11	0.43	1.34	1.5	7	910	HC
12	0.44	1.27	1.8	9.7	815	HC
13	0.57	1.33	1.4	6	825	HC
14	0.43	1.35	1.4	5.5	800	HC
15	0.44	1.34	1.7	9.5	825	HC
16	0.43	1.42	1.3	4.3	790	HC
17	0.48	1.41	1.5	6	800	HC
18	0.51	1.03	—	—	~ 25	LC
19	0.47	1.17	—	—	~ 20	LC

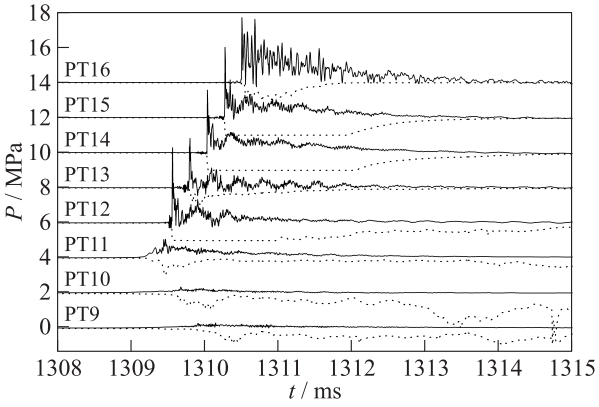

Figure 4 Records of PTs (solid curves) and PDs (dotted curves) in experiment 5 (see Table 3)

experiments 2 and 3 in the wide/short channel (see Table 1), and demonstrated good reproducibility of the results. The measured values of the detonation run-up distance L^* and time T^* in experiments 1 to 5 in Table 3 were 3.9–4.7 m and 1.2–1.7 s, respectively. The average detonation velocity was $D = 1600$–1800 m/s. In the narrow/long channel, DDT was observed at a higher intensity of the primary SW of $M_0 \approx 1.3$–1.4 with n-decane films of thickness $\delta_f = 0.4$–0.5 mm (see Table 4). In this case, the measured values of the detonation run-up distance L^* and time T^* in experiments 1 and 2 of Table 4 were 1.5–2.3 m and 5.2–6.5 ms, respectively.

As an example, Fig. 4 shows the records of PTs and PDs in experiment 5 of Table 3. A noticeable increase in pressure is observed starting from the PT11 located at a distance of 3967 mm from the closed end of the channel, when the apparent flame velocity in the vicinity of this transducer is already quite high ($\sim$ 1300 m/s). At the next transducer (PT12), a pressure wave with a steep front and with an amplitude of 5.4 MPa is observed, with pressure and luminosity waves coming to this measuring section simultaneously. At the transducer PT13, the amplitude of the pressure wave decreases to 4.3 MPa, but the arrival of the luminosity front is still synchronous with the arrival of the SW.

Figure 4 is complemented by the data in Fig. 5, which shows the dependence of the visible velocity of the luminosity front on the traveled distance in the same experiment in the wide/long channel. Here, the onset of detonation ($L^* \approx 4.1$ m) was preceded by a long period of flame propagation with a very low velocity (from 2 to 10 m/s) with a subsequent stage of rapid flame acceleration. It is interesting that this stage begins in the middle of the channel at a distance of 2.5–3 m from the ignition source.

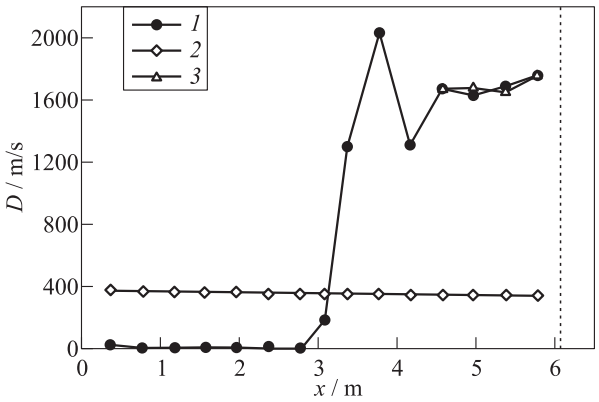

Figure 5 The velocities of the flame front (*1*), SW (*2*), and DW (*3*) in experiment 5 (see Table 3)

The observed regularity of the noticeable flame acceleration in the middle of the channel can be related to the interaction of flame with acoustic oscillations.

When we changed ignition with exploding wire by ignition with hot (non-exploding) wire generating a much weaker initial acoustic disturbance, only the LC mode with an apparent flame propagation velocity of 1–3 m/s was observed in experiments in both short and long channels.

Figure 6 shows the records of PTs and PDs in experiment 1 of Table 4, that is, in the narrow/long channel. These records were used to plot Fig. 7 showing the space–time diagram of the wave process (Fig. 7*a*) and the dependence of the velocities of the pressure and luminosity waves on the traveled distance (Fig. 7*b*). In this experiment, the *n*-decane film had a thickness of $\delta_f = 0.43$ mm, the primary SW had an intensity of $M_0 \approx 1.43$, and the measured values of the detonation run-up distance L^* and time T^* were 1.5 m and 5.2 ms, respectively.

It can be seen on the records of Fig. 6 that as the flame accelerates, the steepness of the fronts of the pressure waves increases and SWs form. At the transducer PT4 at the time of 4.74 ms, one can see the formation of one of the SWs. The same SW can be traced on the transducer PT5 at a time of 5.16 ms. Behind this SW, another SW is formed at a time of 5.21 ms, followed by a sharp rise in pressure and luminosity at a time of 5.23 ms.

In Fig. 7, this event occurs at a distance of about 1.7–1.8 m from the ignition source, i. e., in the location at which two SWs collapse producing a DW propagating further downstream. The amplitude of the pressure wave at this point (the transducer PT5 is located at a distance of 1.77 m from the ignition source) exceeds 6 MPa and its duration is less than 20 μs. The pressure rise

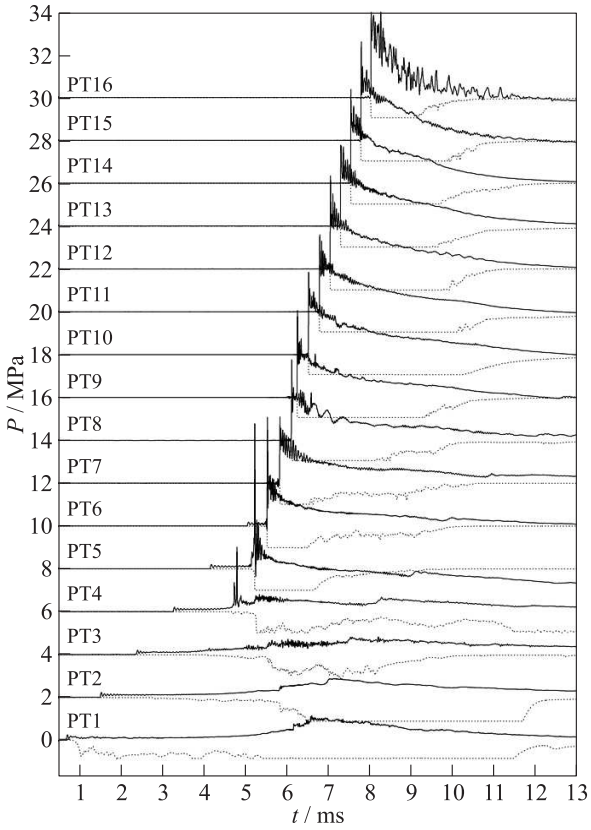

Figure 6 Records of PTs (solid curves) and PDs (points) in experiment 1 (see Table 4)

is followed by a sharp drop in pressure and its oscillations with a frequency of about 25 kHz, corresponding to transverse waves propagating normally to the film surface.

After the DW reaches the quasi-stationary propagation mode at a velocity of $\sim$ 1600 m/s, the pressure profile in it remains unchanged: there are pressure oscillations behind the front with a frequency of 18–24 kHz, i. e., there is a pressure wave propagating in the transverse direction with an amplitude of 0.5–1.0 MPa. This amplitude is much larger than the amplitude of acoustic oscillations observed behind the front of the pressure wave in the HC mode (at the level of 0.1 MPa). Luminosity behind the front of the DW is so intense that the signals of the PDs are off scale for 2–3 ms and it is not possible to follow changes in the luminosity signal behind the detonation front.

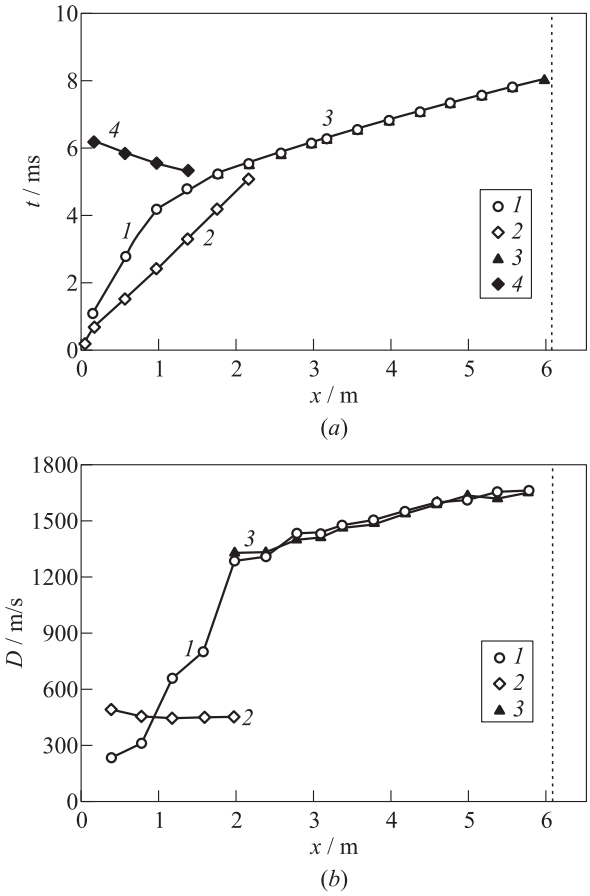

Figure 7 The space–time diagram (*a*) and the velocities of the pressure and luminosity fronts (*b*) for experiment 1 (see Table 4): *1* — luminosity front (flame); *2* — shock front; *3* — detonation front; and *4* — retonation front

Concluding Remarks

Deflagration-to-detonation transition was experimentally detected in the system "gaseous oxygen – liquid film of *n*-decane" with a weak ignition source. In a series of experiments with ignition by an exploding wire that generates a weak primary SW with a Mach number ranging from 1.03 to 1.4, the DDT at a detonation run-up distances of 1 to 4 m from the ignition source in the run-up time from 3 ms to 1.7 s after ignition was obtained in a straight smooth channel of rectangular 54 × 24 mm cross section, 3 and 6 m long, with one open end. The DDT

was obtained for n-decane films 0.3–0.5 mm thick which corresponds to very high overall fuel-to-oxygen equivalence ratio of 20–40. The measured detonation velocity was 1400–1700 m/s.

In some experiments, a high-velocity quasi-stationary detonation-like combustion front running at an average velocity of 700–1100 m/s was detected. Its structure includes a leading SW followed by the reaction zone with a time delay of 90 to 190 μs. The obtained results are important for the organization of the operation process in the continuous-detonation and pulsed-detonation combustors of advanced rocket and air-breathing engines with the supply of liquid fuel in the form of a wall film.

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ПЕРЕХОД ГОРЕНИЯ В ДЕТОНАЦИЮ В СТРАТИФИЦИРОВАННОЙ СИСТЕМЕ «ГАЗООБРАЗНЫЙ КИСЛОРОД – ЖИДКАЯ ПЛЕНКА *н*-ДЕКАНА»

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Впервые экспериментально зарегистрирован переход горения в детонацию (ПГД) в системе «газ (кислород) – пленка жидкого н-декана» при слабом источнике зажигания. В серии экспериментов с зажиганием взрывающейся проволочкой, которое генерирует слабую первичную ударную волну (УВ) с числом Маха от 1,03 до 1,4 в прямом гладком канале прямоуголь-

ного сечения 54 × 24 мм длиной 3 и 6 м с одним открытым концом получен ПГД на расстояниях от 1 до 4 м от источника зажигания за время от 3 мс до 1,7 с от момента зажигания. Переход горения в детонацию получен для относительно «толстых» пленок толщиной 0,3–0,5 мм, что соответствует коэффициенту избытка горючего 20–40. Скорость детонации составила 1400–1700 м/с. В ряде опытов зарегистрирован низкоскоростной квазистационарный детонационноподобный фронт горения, бегущий со средней скоростью 700–1100 м/с, структура которого включает лидирующую УВ и следующую за ним зону реакции, разделенные временной задержкой от 90 до 190 мкс. Полученные результаты важны для организации рабочего процесса в непрерывно-детонационных и импульсно-детонационных камерах сгорания перспективных ракетных и воздушно-реактивных двигателей с подачей жидкого топлива в виде пристеночной пленки.