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Fast Deflagration-to-Detonation Transition

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Abstract—Studies of fast deflagration-to-detonation transition in gas and drop air-fuel explosive mixtures are reviewed. Fast deflagration-to-detonation transition is understood as the appearance of detonation at which a turbulent flame is sped up to a much lower velocity than that required for the classic deflagration-to-detonation transition in a straight tube with smooth or rough walls. The main goal of studies was to determine conditions under which fast deflagration-to-detonation transition was possible in weakly sensitive explosive mixtures at very low ignition energies. Examples of fast deflagration-to-detonation transitions checked experimentally and by multidimensional numerical calculations are given, including deflagration-to-detonation transitions (1) in a tube segment with regular obstacles of a special shape, (2) in tube coils, and (3) in tubes with U-shaped bends. In all cases, fast deflagration-to-detonation transition occurs because of the formation of distributed ignition zones in reflections of a running shock wave formed by an accelerated flame. The use of various combinations of reflecting elements can induce fast deflagration-to-detonation transition in an air mixture of aviation kerosene at ignition energies at a level of 5 J.

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INTRODUCTION

The classic mechanism of deflagration-to-detonation transition (DDT) in a straight smooth tube includes several stages [1, 2], namely, (1) forced mixture ignition with the formation of a laminar flame, (2) progressing increase in the rate of combustion because of the appearance of instabilities and subsequently turbulent flow ahead of the flame front, (3) shock wave formation and strengthening before the accelerating flame front, and (4) self-ignition of the shock-compressed mixture in the region between the shock wave and flame front [3] ("explosion in the explosion" [4]) resulting in the formation of an overdriven detonation wave and then (5) self-sustaining Chapman–Jouguet detonation. The time and distance of the deflagration-to-detonation transition are known to be largely determined by the first three stages [5]. Detonation in air mixtures of hydrocarbon fuels requires that the "visible" velocity of the turbulent flame front in the laboratory coordinate system be higher than 1000 m/s [6]. At such a flame front velocity, the shock wave running ahead has a velocity higher than 1300 m/s (the shock wave Mach number is $M \sim 3.8$), and the pressure and temperature of the explosive mixture behind it are higher than 1.7 MPa and 1200 K, respectively.

In recent works [7–11] and reviews [12, 13], a new method for obtaining detonation in a straight smooth tube was suggested. Its essence is the forced acceleration of a comparatively weak shock wave running before the flame front to intensities sufficient for the formation of a detonation explosion. For this purpose, distributed igniters were mounted along a straight smooth tube [7–12]. To exclude the first three poorly reproducible deflagration-to-detonation transition stages from consideration, the primary shock wave was obtained using either an electric discharge [7–12] or a tube section with a Shchelkin spiral [13, 14]. The shock wave obtained was accelerated by switching on each ignition source as the wave arrived at the corresponding tube section. In other words, the shock wave was accelerated by providing fast forced explosive mixture ignition in the nearest vicinity of the running shock front. This technique allowed detonation to be initiated at a distance and in a time much smaller compared with the classic deflagration-to-detonation transition. In experiments [7–12] with detonation initiation, the mismatch between the arrival of the shock wave and gas ignition did not exceed 100 μs. At a larger mismatch, the other conditions being equal, no detonation occurred. Interestingly, the admissible mismatch value is comparable with the characteristic reaction time in the detonation wave at the limit of detonation [15].

In [7–12], the detonation of a stoichiometric propane–air mixture was obtained in a tube 51 mm in diameter at the initial shock wave velocity at a level of 800–1000 m/s (the shock wave Mach number was $M \sim$ 2.4–3.0). Note that, for the formation of a similar shock wave before a flame front, the flame front should be accelerated to a visible velocity of about 550–750 m/s. This velocity is much lower than the velocity of the flame necessary for the spontaneous deflagration-to-detonation transition (~1000 m/s). It follows that the length and time of the deflagration-to-detonation transition can be reduced substantially by providing the possibility of forced shock wave acceleration before the flame front; that is, we can then obtain a "fast" deflagration-to-detonation transition. Further, the fast deflagration-to-detonation transition will be understood as the appearance of detonation in a fuel–air mixture when a turbulent flame is accelerated to a velocity much lower than the velocity required for the classic deflagration-to-detonation transition in a straight tube. In [12], the classic deflagration-to-detonation transition is called "slow" to distinguish it from the fast deflagration-to-detonation transition. The new technique for initiating detonation studied in [7–12] was called in [7] "detonation initiation by a running forced ignition pulse."

Let us turn from deflagration-to-detonation transitions in a straight smooth tube to deflagration-to-detonation transitions in a tube with regular obstacles [2, 16]. The mechanism of deflagration-to-detonation transition in such tubes is in many respects similar to the mechanism [1–6] described above. There are also important differences. First, the flame is accelerated much more quickly in a tube with obstacles because of the additional turbulization of a fresh explosive mixture when it flows around obstacles. Secondly, there appear new possibilities for gas ignition. A gas can be self-ignited in the reflection of the shock wave from an obstacle or (if obstacles are large) because of mixing of directed jets of hot combustion products with a cold fresh mixture.

The possibility of the local self-ignition of a fresh mixture caused by shock wave reflection from an obstacle suggests an idea [12] that, in deflagration-to-detonation transitions in tubes with obstacles, not only the classic scenario [1–6], but also the scenario of detonation initiation by a running ignition pulse, however spontaneous rather than forced, is possible. Gas ignition in the vicinity of the shock wave running in front of the flame then occurs because of the self-ignition of the substance compressed by the shock wave reflected from obstacles rather than because of external stimulation of chemical activity. In other words, deflagration-to-detonation transition in tubes with obstacles includes a stage at which fast detonation initiation by a running spontaneous ignition pulse (fast deflagration-to-detonation transition) is possible in principle. As with forced ignition experiments [7–12], the possibility of fast deflagration-to-detonation transition is then determined by the degree to which the time moments of the arrival of the shock wave at one or another tube cross section and gas ignition in the section coincide. In the case under consideration, we must compare the moment of the arrival of the shock wave at an obstacle and the moment of gas self-ignition behind the reflected wave. The latter is, as is well known, characterized by ignition delay.

Ignition delay depends on the composition of the mixture, the intensity of the running shock wave, and the duration of the compression phase in it. We assume that the admissible self-ignition delay time is less than 100 μs at the normal reflection of a long shock wave from obstacles. Fast deflagration-to-detonation transition in a stoichiometric propane–air mixture then requires a shock wave running at a velocity of 950–970 m/s (the shock wave Mach number is $M \sim 2.8$) [17]. During deflagration-to-detonation transition, such a wave is formed in front of the flame propagating at a velocity of about 700 m/s. The pressure and temperature in the reflection of such a shock wave from an obstacle are approximately 4.5 MPa and 1300 K. The obtained shock wave velocity value is within the range of shock wave velocities used in experiments [7–12] with the initiation of detonation by a running forced ignition pulse. It follows that there are no prerequisites for fast deflagration-to-detonation transition at the deflagration-to-detonation transition stage in stoichiometric propane–air mixtures at which the velocity of the flame is still lower than ~700 m/s. At this stage, progressing turbulent flame acceleration occurs and the shock wave is strengthened because of interaction with compression waves generated by the flame and separate ignition zones in the vicinity of obstacles. When the velocity of the flame exceeds 700 m/s and the velocity of the shock wave before the flame front exceeds ~950–970 m/s, fast deflagration-to-detonation transition becomes possible theoretically.

Note that the above estimates ignored effects related to explosive mixture expansion in rarefaction waves inevitable in the diffraction of shock waves by obstacles. These effects depending on the shape of obstacles increase ignition delays and, therefore, increase the threshold flame velocity required for fast deflagration-to-detonation transition.

In view of the possibility in principle of fast deflagration-to-detonation transitions, fundamental questions concerning the conditions of their occurrence and methods for preventing them arise. In this review, examples of fast deflagration-to-detonation transitions under conditions when distributed self-ignition zones spontaneously form in a flow behind a running shock wave are given.

PROFILED OBSTACLES

Most of the deflagration-to-detonation transition studies in fuel–air mixtures were performed in straight tubes and channels with Shchelkin spirals [2] or regular orifice plates [16]. The purpose of these studies was to determine the influence of obstacle parameters (height and pitch) on the DDT run-up distance and time. However, because of the possibility of fast deflagration-to-detonation transitions, an important role can also be played by the shape of obstacles. By varying the shape, we can control the location and size of self-ignition zones in the reflection of a running shock wave and ignition delay [18, 19]. Surprisingly, the influence of the shape of obstacles on deflagration-to-detonation transition had not been studied before our publications [18, 19], although the phenomenon of gas dynamic focusing of shock waves in reflection from a nonplanar end of a shock tube had long been known [20].

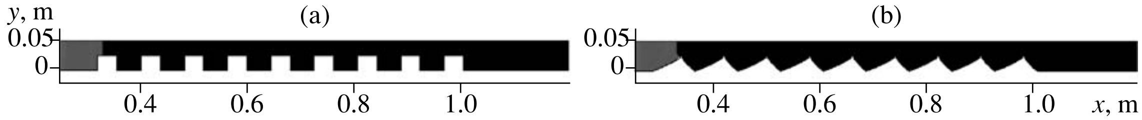

Fig. 1. Entrance of a shock wave into a channel with regular obstacles in the form of (a) rectangular projections and (b) combinations of parabolas. Only the lower part of the plane channel is shown.

The calculation and experimental studies [18, 19] presented in this section show how the use of regular obstacles of a special shape allows fast deflagration-to-detonation transitions to be induced. Two-dimensional gas dynamic calculations were performed for regular rectangular projections (Fig. 1a) and a combination of two parabolas (Fig. 1b). The height and total cross-sectional area of rectangular projections in the plane of Fig. 1 were the same as those of parabolic obstacles. At the initial time, the plane channel was filled with an quiescent gaseous explosive mixture with temperature T_0 and pressure p_0. A planar shock wave with the initial Mach number M and compression phase duration τ was obtained using the initiation section filled with a high-pressure gas. The shock wave propagated from left to right and entered the channel with obstacles.

Because of running shock wave reflections and the interaction of reflected waves with each other, gas self-ignition can occur in the segment with obstacles [2]. After self-ignition, two scenarios are possible, fast and slow. According to the slow scenario, turbulent flame zones are formed in the channel. They grow and cause the formation of pressure waves, which overtake and accelerate the shock wave. In prospect, an explosion in the explosion can occur in the region between the developed turbulent combustion zone and shock wave; this leads to detonation. It follows that a determining role in the slow scenario is played by the development and propagation of turbulent flame, as in the classic deflagration-to-detonation transition. In the fast scenario, the role of turbulent flame becomes unimportant. Energy release in directed self-ignition fronts propagating over a fresh explosive mixture, which experiences shock compression, comes to the fore.

Here, we only consider the second (fast) scenario of deflagration-to-detonation transitions. Phenomena caused by the propagation of turbulent flame develop comparatively slowly. For this reason, the mathematical model of fast deflagration-to-detonation transitions was constructed in [18, 19] on the basis of the equations of motion for a viscous gas under compression augmented by equations for energy and chemical kinetics and the equation of state of an ideal gas. The turbulent flow character was ignored. The chemical transformation was described by a one-stage reaction with the Arrhenius dependence of the rate constant on temperature. The Arrhenius equation was preliminarily calibrated against the experimental data on self-ignition delays for a stoichiometric propane–air mixture. The initial conditions were pressure 0.1 MPa and temperature 293 K. The system of equations was integrated by the method of finite volumes with approximating fluxes according to Godunov [18]. The calculations were performed for the lower channel half (Fig. 1) on structured grids with the number of computational cells up to 200000. The maximum cell size was 500 μm, and the maximum integration time step, 10 ns.

The calculated temperature fields in a channel with regular obstacles in the form of rectangular projections and a combination of parabolas are shown in Figs. 2a and 2b, respectively. The initial shock wave parameters were $M = 3$ and $\tau \approx 800$ μs. In calculations with rectangular obstacles, there was no detonation (Fig. 2a), although gas self-ignition occurred earlier than in Fig. 2b.

In Fig. 2b, gas self-ignition occurs in the flow core above the fifth obstacle close to the hydrodynamic focus at time about 490 μs. This local explosion results in a fast development of detonation. The detonation wave passes through the channel segment with obstacles and then propagates at a constant mean velocity in the smooth segment. When a shock wave of equal initial intensity and duration entered the segment with obstacles from the right rather than from the left (see Fig. 1), no fast deflagration-to-detonation transition occurred. This is evidence that not only the shape of the windward side but also the shape of the leeward side is of importance for fast deflagration-to-detonation transitions.

To understand the reason for fast deflagration-to-detonation transitions in a channel with regular obstacles in the form of a combination of parabolas, spatial temperature distributions in the vicinity of the self-ignition zone above the fifth obstacle immediately before explosion were thoroughly analyzed in [18]. Calculations showed that, at the self-ignition moment, a region of a nonuniformly heated shock-compressed fresh explosive mixture of size about 10 × 3 mm with a temperature above 2000 K was formed in the central part of the channel. Self-ignition in this region caused the formation of a directed secondary explosion wave. The interaction of this wave with a similar secondary explosion in the focal region above the sixth obstacle caused the development of detonation.

In calculations with parabolic obstacles of a different shape, the self-ignition region formed far from the central part of the shock wave front and experienced the action of rarefaction waves formed in the diffraction of shock waves by obstacles. When a shock wave propagates in a channel with obstacles in the form of rectan-

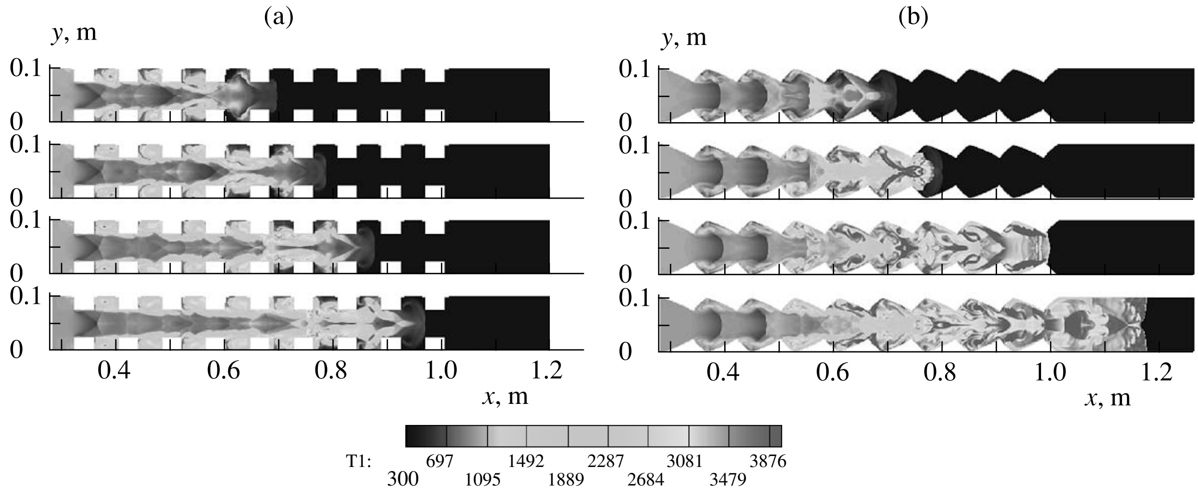

Fig. 2. Calculated temperature fields for deflagration-to-detonation transition in a channel with regular obstacles in the form of (a) rectangular projections and (b) combinations of parabolas. The upper field corresponds to the time moment 480 μs. The other fields were constructed in time steps of 100 μs.

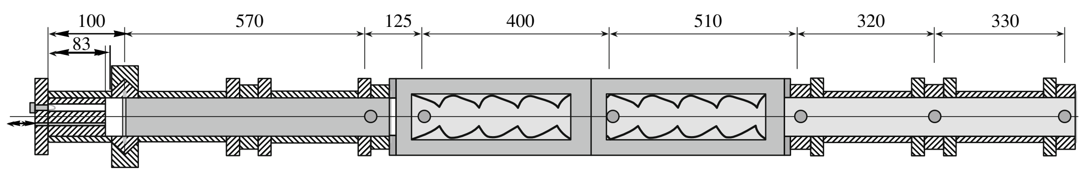

Fig. 3. Scheme of experimental unit with profiled regular obstacles.

gular projections, self-ignition occurs on the windward side of obstacles rather than in the free flow core. It therefore experiences strong action of rarefaction waves. For this reason, there was no detonation in the channel with such obstacles. The mechanism of formation of a directed explosion wave in the self-ignition of a nonuniformly heated gas was studied in detail in [21].

A scheme of a membrane-type laboratory shock tube of length 2.5 m is shown in Fig. 3. The tube consists of a high-pressure chamber and a low-pressure chamber. The tube test segment with obstacles was placed into the low-pressure chamber. The tube was used to check the results of calculations.

Two series of experiments were performed with regular obstacles of the shape and size as in the calculations and corresponding to Fig. 1. The obstacles were made of a plywood sheet 7 mm thick using a template, tied up into a packet 100 mm thick by pins, and mounted on the upper and lower walls of the working tube part. The high-pressure chamber 70 mm in diameter and 0.1 m long, which was separated from the low-pressure chamber by a bursting diaphragm, was filled with a stoichiometric propylene–oxygen mixtures with different initial pressures (up to 0.8 MPa). The low-pressure chamber included a buffer segment, a smooth tube 70 mm in diameter and 0.6 m long filled with air, a test segment with a 100 × 100 mm square section of length 1 m, and an exit segment, which was a smooth tube 70 mm in diameter and 0.8 m long filled with a stoichiometric propylene–air mixture. The buffer segment was separated from the working segment by a thin film.

All experiments were performed in an armored chamber at normal initial mixture pressure (0.1 MPa) and 290 ± 2 K. The shock wave was initiated by burning up a wire in a high-pressure chamber, which caused rapid combustion of the propylene–air mixture and diaphragm bursting. The shock wave parameters were measured using six DD3-026 M high-frequency tensoresistive pressure transducers placed at distances of 0.57, 0.695, 1.095, 1.605, 1.925, and 2.255 m from the diaphragm. Each transducer was equipped with a signal follower with independent power supply and was connected to a PC through an analog-to-digital converter. The error in shock wave velocity measurements was no more than 3%. Two 350 × 110 mm optical windows (Plexiglas 40 mm thick) were mounted on a working segment wall for high-speed video recording (5000 frames/s).

The time dependences of pressure in an experiment with fast deflagration-to-detonation transition in the channel with parabolic obstacles are presented in Fig. 4. The table contains the results of two experiments with

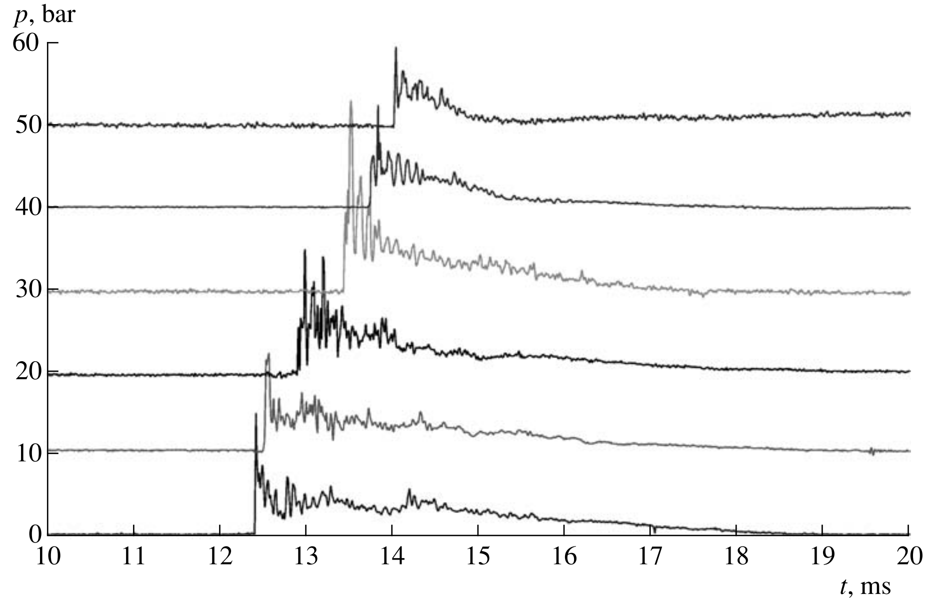

Fig. 4. Pressure records in a tube with regular obstacles in the form of combinations of parabolas in a stoichiometric propylene–air mixture. The initial shock wave velocity is 1070 ± 30 m/s.

equal (to within measurement errors) initial shock wave intensities and obstacles of different shapes. According to these data, the use of obstacles in the form of a combination of parabolas caused detonation at the last measuring segment (1925–2255 mm). The detonation propagated at a velocity of 1590 ± 50 m/s, whereas the shock wave velocity over the same measuring segment was 970 ± 30 m/s when obstacles in the form of rectangular projections were used (no detonation).

These results substantiate the possibility of fast deflagration-to-detonation transitions in a tube with regular obstacles of a special shape. In both calculations and experiments, fast deflagration-to-detonation transition occurred at the stage at which a shock wave with Mach number $M \sim 3.0$ entered the segment with obstacles. No fast deflagration-to-detonation transition was observed in calculations and experiments with rectangular projections.

Comparison of experimental shock wave velocities in tubes with regular obstacles in the form of rectangular projections and combinations of parabolas

Measuring segment, mm	Shock wave velocity, m/s	
	parabolas	projections
570–695	1070 ± 30	1070 ± 30
695–1095	1061 ± 30	714 ± 20
1095–1605	836 ± 25	637 ± 20
1605–1925	1025 ± 30	1000 ± 30
1925–2255	1590 ± 50	970 ± 30

COILS

As shown above, curvilinear surfaces favor the occurrence of fast deflagration-to-detonation transitions because of the formation of self-ignition zones in a flow core behind a running shock wave. It can therefore be expected that fast deflagration-to-detonation transitions are more probable in curved compared with straight tubes, because tube coils and bends are elements that facilitate them. The experimental data and calculation results presented in this section do indeed show that a tube bend along a running shock wave path can cause fast deflagration-to-detonation transitions.

A scheme of a flow tube 36 mm in diameter with air-assist atomizer A, high-voltage electric discharger ED, Shchelkin spiral, and detachable segment (bend) is shown in Fig. 5 [22, 23]. We also used a tube 28 mm in diameter of the same design. The atomizer provided the complete consumption of finely dispersed *n*-hexane–air mixture through the tube. The explosive mixture with a fuel equivalence ratio of about 1.3 was ignited by the ED situated at a distance of 60 mm from the atomizer nozzle, where the mean size of spray drops was 5–6 μm. The Shchelkin spiral 600 mm long wound of steel wire 4 mm in diameter with a coil pitch of 18 mm was used to increase the intensity of turbulence in the atomizer spray supplied from the sprayer. To check the possibility of fast deflagration-to-detonation transitions, a new element (a tube coil) was mounted behind the segment with the Shchelkin spiral. PT1–PT5 piezoelectric pressure transducers were used to record pressure wave profiles in the tube and determine the velocity of the propagation of these waves. We expected that the presence of reflecting surfaces in the coil could cause gas dynamic shock wave focusing and fast deflagration-to-

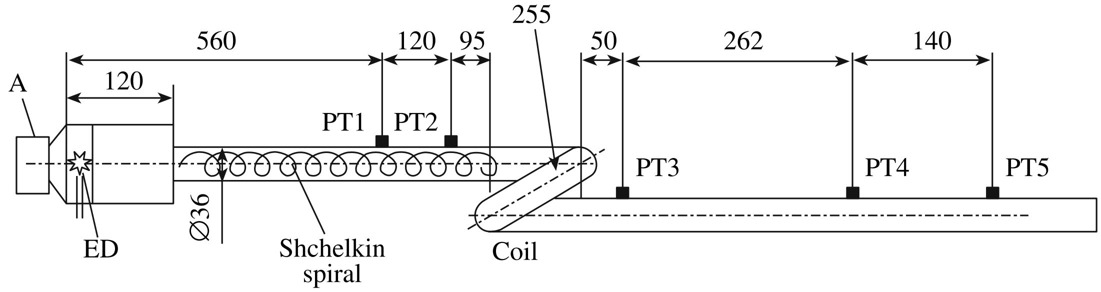

Fig. 5. Scheme of a tube 36 mm in diameter with a Shchelkin spiral and a coil [22].

detonation transition. Note that the focusing action of coils of explosion tubes in reacting media had not been studied before the appearance of our works [22, 23].

In experiments in a straight tube 36 mm in diameter with the Shchelkin spiral but without a coil, the shock wave velocity at the exit of the spiral amounted to 900–1000 m/s, but no DDT transition was observed. Changes in the diameter of spiral wire and coil pitch and spiral length did not cause any substantial changes in the characteristics of shock waves at ignition energies up to 240 J. Similar experiments were performed in the straight tube 28 mm in diameter with the Shchelkin spiral. As in the tube 36 mm in diameter, no deflagration-to-detonation transition was observed, and the shock wave velocity at the exit of the spiral reached 800–900 m/s.

The pressure records obtained using the PT1–PT5 pressure transducers in experiments with the 36-mm tube with the spiral and coil and ignition energy $E = 60$ J are shown in Fig. 6. In this experiment, a detonation wave was observed at the exit of the coil (PT3 pressure transducer). Detonation was produced inside the coil at a distance of 1 m (about 28 tube diameters) from the discharger. The detonation wave propagated to the end of the tube at a velocity of 1750 ± 20 m/s.

This effect can be explained by multiple reflections of the shock wave emerging from the spiral inside the coil, which contribute to the arising of detonation. Such reflections resemble reflections that appear when a shock wave propagates in a straight channel with regular obstacles of a special shape.

In calculations [24], the spatial effects inherent in the propagation of shock waves in tube coils were reproduced using three-dimensional Euler equations for a gas experiencing compression and a one-step fuel oxidation reaction equation calibrated for stoichiometric propane–air mixtures. The system of determining equations was solved using the algorithm of parallel computations. Unstructured computational grids contained up to 1400000 cells with minimum and maximum grid sizes of 0.25 and 0.7 mm, respectively. The integration time step did not exceed 50 ns. The calculations were performed on a 32-processor MVS-15000BM complex at the Supercomputer center of the Russian Academy of Sciences.

We considered deflagration-to-detonation transitions in coils of two configurations filled with a stoichiometric propane–air mixture under normal initial conditions. The first configuration was a tube coil 28 mm in diameter and 365 mm long (along the tube axis). The second configuration was a tube coil 36 mm in diameter and 255 mm long (along the tube axis). The entrance and exit coil sections were situated in one plane and were in contact with each other. The primary shock wave parameters at the entrance of the coil were modeled using the Rankine–Hugonoit equations.

Calculations allowed us to understand the special features of the fast deflagration-to-detonation transition phenomenon; they qualitatively corresponded to the experimental data. The minimum (critical) Mach number value of the primary shock wave necessary for

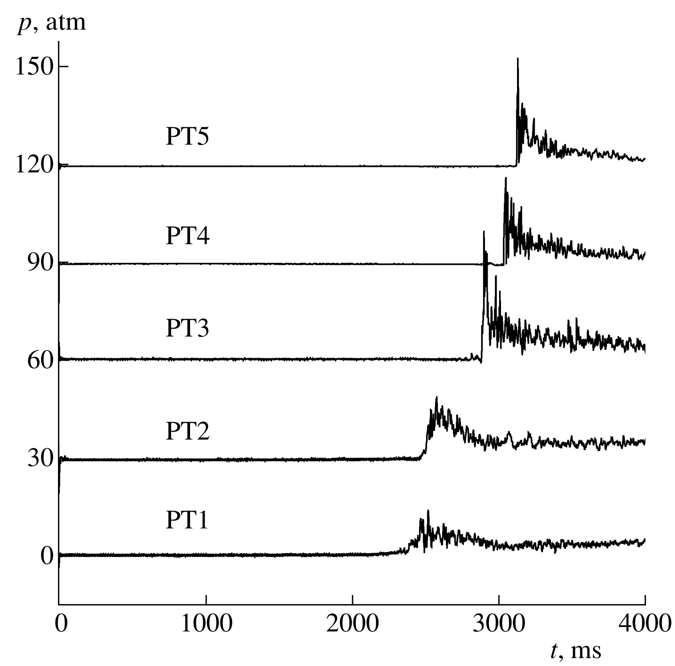

Fig. 6. Pressure records in an experiment with a 60 J ignition energy [22].

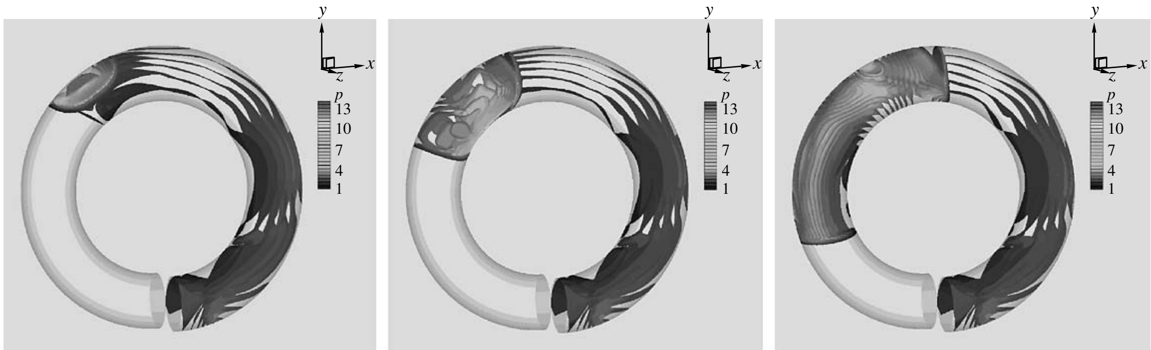

Fig. 7. Calculated dynamics of static pressure isosurfaces (in MPa) during a deflagration-to-detonation transition in a tube coil 28 mm in diameter (the first configuration); the Mach number of the primary shock wave $M = 3.9$.

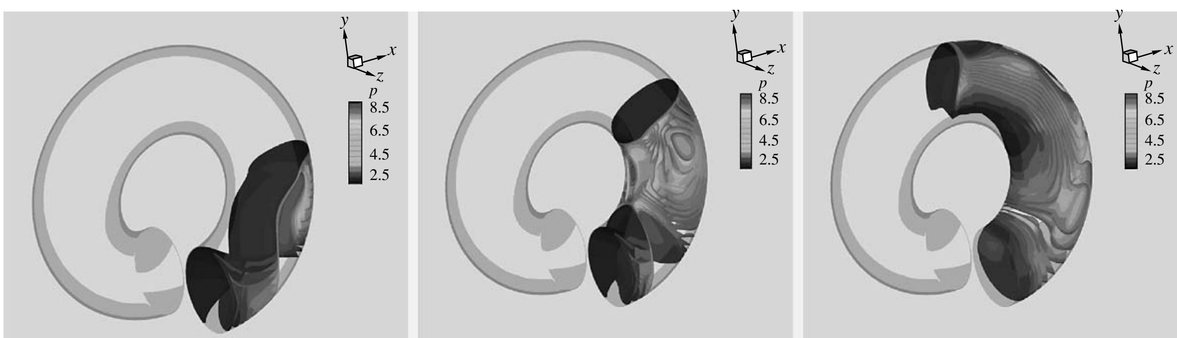

Fig. 8. Calculated dynamics of static pressure isosurfaces (in MPa) during a deflagration-to-detonation transition in a tube coil 36 mm in diameter (the second configuration); the Mach number of the primary shock wave $M = 3.8$.

deflagration-to-detonation transitions in coils of the first and second configurations was found to be 3.9 and 3.6, respectively. According to calculations, there were several discrete explosion-in-explosion positions initiating detonation. All of them were in the vicinity of running shock wave reflections from coil walls. Under near-critical conditions, fast deflagration-to-detonation transition occurred in the second half of the coil closer to the exit section (Fig. 7). The region of deflagration-to-detonation transition initiation shifted into the first half of the coil closer to the entrance section as the Mach number of the primary shock wave increased above the critical value (Fig. 8). Three-dimensional effects were more pronounced in the coil of the second configuration with a smaller radius of curvature; the shape of the primary shock wave front was then substantially nonplanar.

U-SHAPED BENDS

Tube bends are extensively used in various industrial applications. Surprisingly, little work was done on the diffraction of shock and detonation waves in such elements [25]. Our recent works on deflagration-to-detonation transitions in bent tubes [26–29] unambiguously show that tube curvature effectively accelerates deflagration-to-detonation transitions.

The results of experimental and computational studies of deflagration-to-detonation transitions in a stoichiometric propane–air mixture in a tube with one U-shaped bend whose radius of curvature equaled the tube diameter (51 mm) were reported in [26–29]. The influence of a U-shaped bend on the initiation and propagation of detonation was observed. On the one hand, a U-shaped bend favored deflagration-to-detonation transitions. The shock wave entering the bend at a velocity above 1100 m/s always transformed into detonation. On the other hand, a detonation wave entering a U-shaped bend at a velocity of 1700–1800 m/s first temporarily weakened, and the velocity of its propagation decreased by approximately 250 m/s (15%), and then it restored its velocity along the straight segment behind the bend.

Two-dimensional calculations of the propagation of detonation waves in such bends revealed interesting transition process features. It was shown that different head wave front regions behaved differently because of the time and spatial shifts in the interaction of compression and rarefaction waves and a finite rate of chemical transformations. Close to the internal bend wall, both detonation decay and repeated detonation initiation

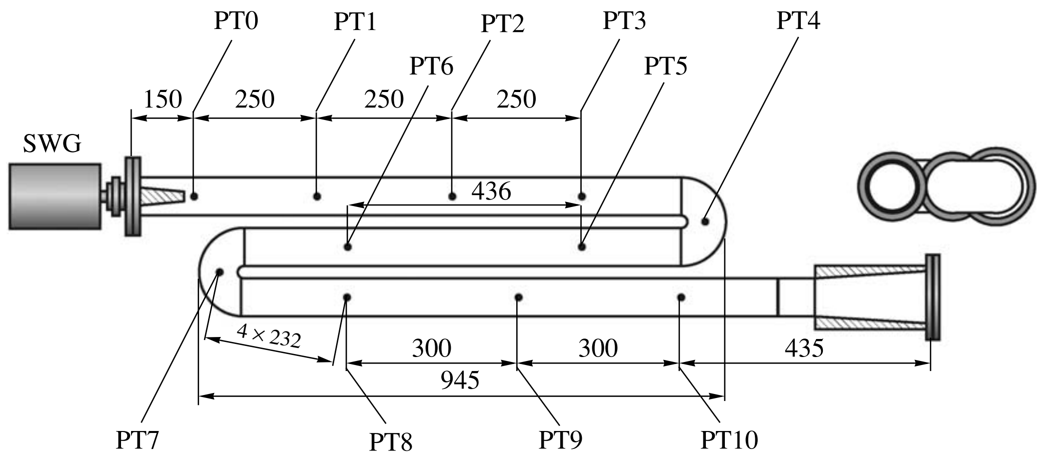

Fig. 9. Scheme of a tube 51 mm in diameter with a shock wave generator (SWG) and two U-shaped bends. Dimensions are in mm. Symbols correspond to the positions of pressure transducers.

were recorded. It was in addition shown that, in the transition process, far behind the leading front, large volumes of unburned gas formed. After exit from the bend, detonation was restored at a distance of 8 to 10 tube diameters and acquired a characteristic cellular structure.

The curvature of U-shaped bends, tube diameter, and duration of the compression phase in the primary shock wave are likely the most important problem parameters, which determine the evolution of initiating shock waves or developed detonation waves in such a system [26–29]. In this section, we present some experimental data and calculation results on the propagation of shock waves in tubes with U-shaped bends of a limiting curvature filled with a gaseous explosive mixture.

An experimental unit consisting of a detonation tube with a round section and two U-shaped bends is shown in Fig. 9. The tube was mounted on an experimental test bench equipped for work with gaseous explosive mixtures. A stoichiometric propane–air mixture was used in experiments. The mixture was prepared in a mixer. A shock wave generator was placed on one side of the tube. Two types of shock wave generators were used, a powder gas generator and an electric discharge shock wave generator described in detail in [26–29].

A tube with a 51 mm inside diameter consisted of three straight segments and two U-shaped bends mounted in one plane. The internal radius of the bends was 11 mm.

The bends were made of four standard segments by arc welding. The internal surface of the bends was smooth. Up to ten piezoelectric pressure transducers PT1–PT10 were placed along the tube. The error in shock wave velocity measurements was estimated at 4%. The recording system was started by the PT1 pressure transducer.

Changes in the mean shock wave velocity along the tube at different initial shock wave velocities in the first measuring segment (from 850 to 1300 m/s) are shown in Fig. 10a. In this series of experiments, the shock wave transformed into detonation after the passage through either the first or second bend. The lowest mean shock wave velocity at the entrance of the first bend necessary for obtaining detonation behind the second bend was close to 800 m/s. This shock wave velocity should be considered a critical condition for the configuration shown in Fig. 9. Recall that, in experiments with bends of a large radii of curvature [26–29], the critical shock wave velocity was about 1100 m/s. Figure 10a shows that the higher the velocity of the primary shock wave, the more quickly does the deflagration-to-detonation transition occur. Pressure records in Fig. 10b correspond to one of the experiments shown in Fig. 10a. A secondary explosion is clearly seen in the PT4 and PT5 records. Detonation appears when the secondary explosion wave reaches the primary shock wave.

A mathematical model was based on two-dimensional Euler equations, the equation of the conservation of energy with a chemical source, and chemical kinetics equations. The kinetics of propane oxidation was modeled by either a one-step reaction or using a semiempirical five-stage mechanism. A more detailed description of the procedure for calculations is given in [26–29].

The calculations revealed the important role played by the duration of the compression phase in the primary shock wave during deflagration-to-detonation transition and in the structure of detonation. A primary shock wave with a longer compression phase but lower velocity transforms into detonation after the second U-shaped bend (Fig. 11a), whereas a primary shock wave with a shorter initial compression phase but higher initial velocity does not transform into detonation behind the second bend (Fig. 11b). Interestingly, one-head detonation that appears behind the first bend in Fig. 11b suddenly becomes destroyed as the wave enters the second bend, which is related to a strong rarefaction wave

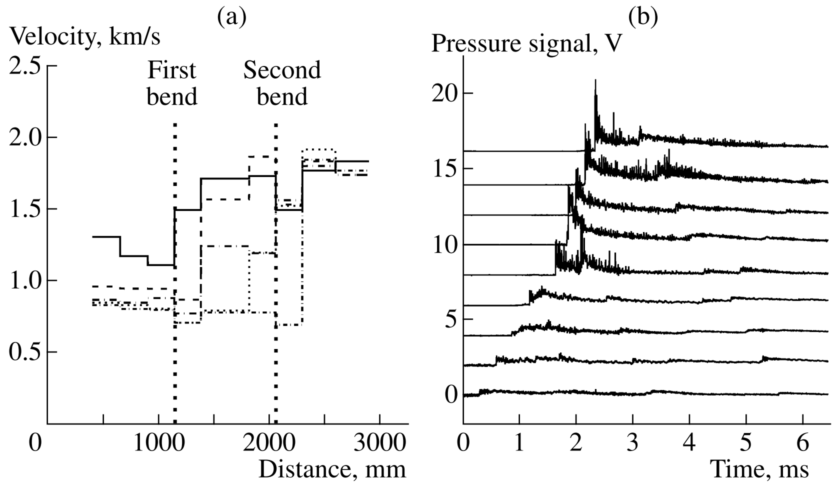

Fig. 10. Mean shock wave velocity along different measuring segments in a tube with two U-shaped bends (shown by vertical lines) in several typical experiments: (a) shock wave passage through bends with detonation formation and (b) pressure records in one of the experiments.

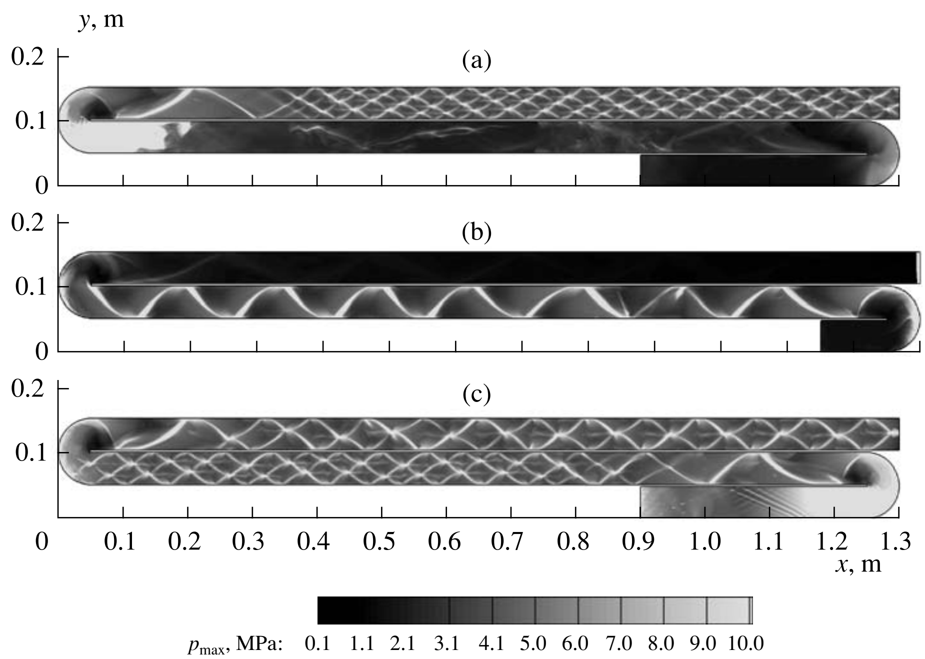

Fig. 11. Maximum pressure records in a channel 51 mm wide with two U-shaped bends of a limiting curvature. The initial shock wave velocity and the duration of the compression phase at the entrance of the first bend: (a) $D = 0.62D_0$ and $\tau_+ = 310$ μs, (b) $D = 0.64D_0$ and $\tau_+ = 60$ μs, and (c) $D = 0.64D_0$ and $\tau_+ = 600$ μs.

formed on the internal bend wall. The dynamic cell structure of detonation in Figs. 11a and 11c is likely unstable. It tends to a structure with two transverse waves with time.

A FAST DEFLAGRATION-TO-DETONATION TRANSITION IN A KEROSENE–AIR MIXTURE

In this section, we report the results of experimental studies [30, 31] aimed at obtaining detonation for an air–aviation kerosene TS-1 mixture in tubes at the shortest distances with the use of minimum ignition energies. For this purpose, regular obstacles and multiple shock wave reflections in a special focusing device (coil pipe) were used.

A scheme of the experimental unit consisting of continuous-action air-assist fuel atomizer *1*, heated detonation tube *2*, ignition source *3*, pressure transducers *4*, flame arrester *5*, air cylinder *6*, fuel valve *7*, air compressor *8*, fuel tank *9*, fuel filter *10*, digital control-

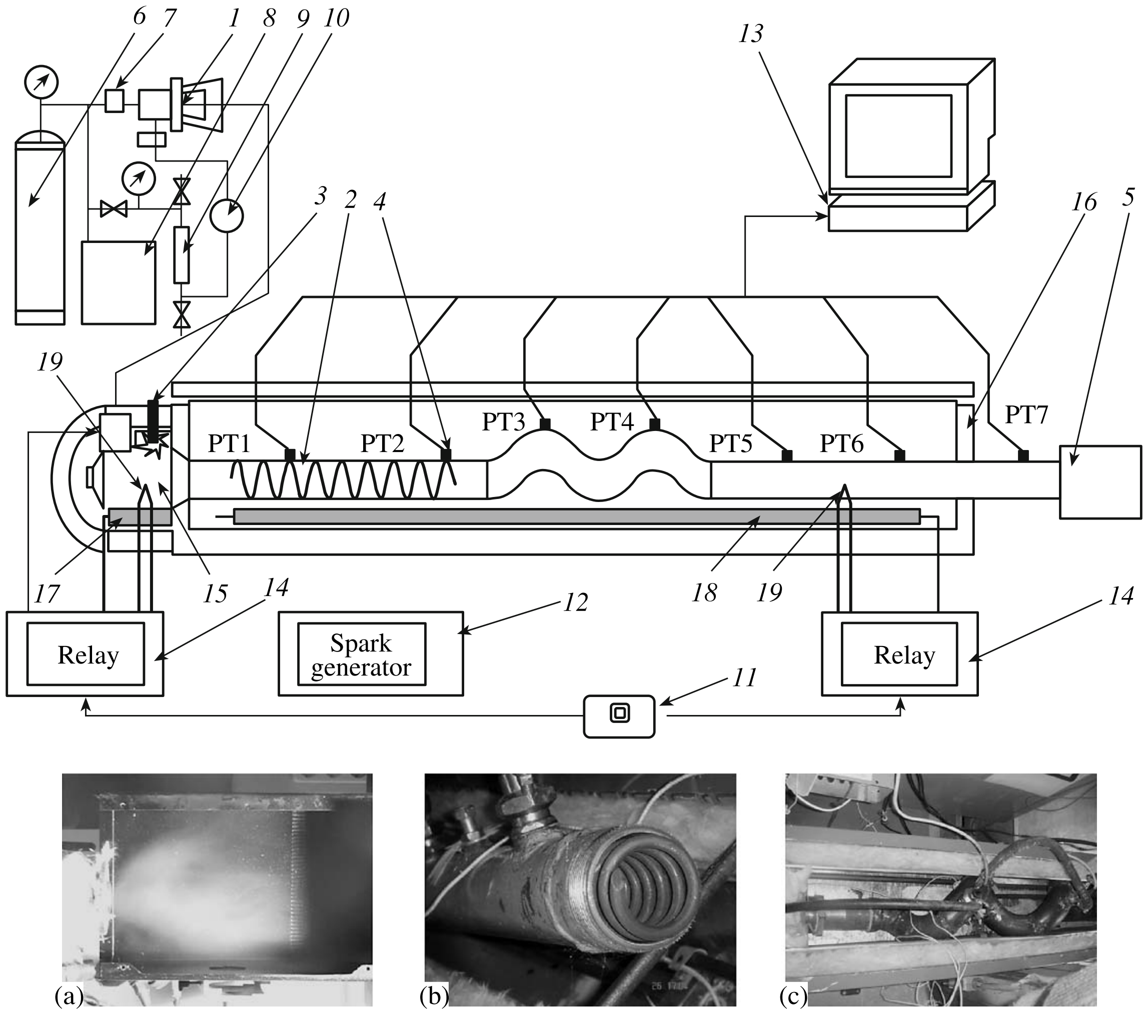

Fig. 12. Scheme of experimental unit with (a) kerosene prevaporizer, (b) Shchelkin spiral, and (c) coil pipe. See text for description.

ler *11*, power supply unit *12*, PC with a 16-channel analog-to-digital converter *13*, relay *14*, fuel prevaporizer *15*, thermostat *16*, electric heaters *17* and *18*, and thermocouples *19* is shown in Fig. 12. The systems for supplying fuel and air provided a constant ratio between the mass flow retes of mixture components, liquid kerosene TS-1 and air, in the atomizer, because the pressures of supplying the components were maintained equal (6–4.8 atm). Fuel–air mixing began in the atomizer and ended in the detonation tube (inside diameter 52 mm and length 3 m). The air-assist atomizer finely dispersed kerosene into drops 5 to 10 μm in diameter. The drop size distribution was measured by the soot print method [32]. Air was supplied from cylinder *6* connected to air compressor *8*. The two-phase kerosene–air mixture was introduced continuously into prevaporizer *15*. The prevaporizer was used to increase the detonation ability of the drop fuel–air mixture, as recommended in [15]. While passing through the prevaporizer, the kerosene partially vaporized on hot walls. A heterogeneous mixture of air, kerosene vapor, kerosene drops from the air-assist atomizer, and mist (condensed vaporized kerosene) therefore formed in the prevaporizer (see Fig. 12, photograph (a)). This mixture was transferred through an exit nozzle into the straight detonation tube segment with a Shchelkin spiral (Fig. 12, photograph (b)) and then either into the straight segment of a smooth tube or into the coil pipe with a smooth inside surface (Fig. 12, photograph (c)). The end of the detonation tube was connected to a flame arrester, which was in contact with the atmosphere. The flame arrester was a tube segment 80 mm in diameter packed with a corrugated metallic band. Explosion processes in the detonation tube were tracked using water-cooled PT1–PT7 high-frequency piezoelectric pressure transducers and ionization probes mounted in the detonation tube.

The system for tube heating included two thermostats, prevaporizer thermostat *15* and detonation tube thermostat *16*. The prevaporizer thermostat was equipped with electric heater *17*, power 0.6 kW, and the detonation tube thermostat, with a three-section electric

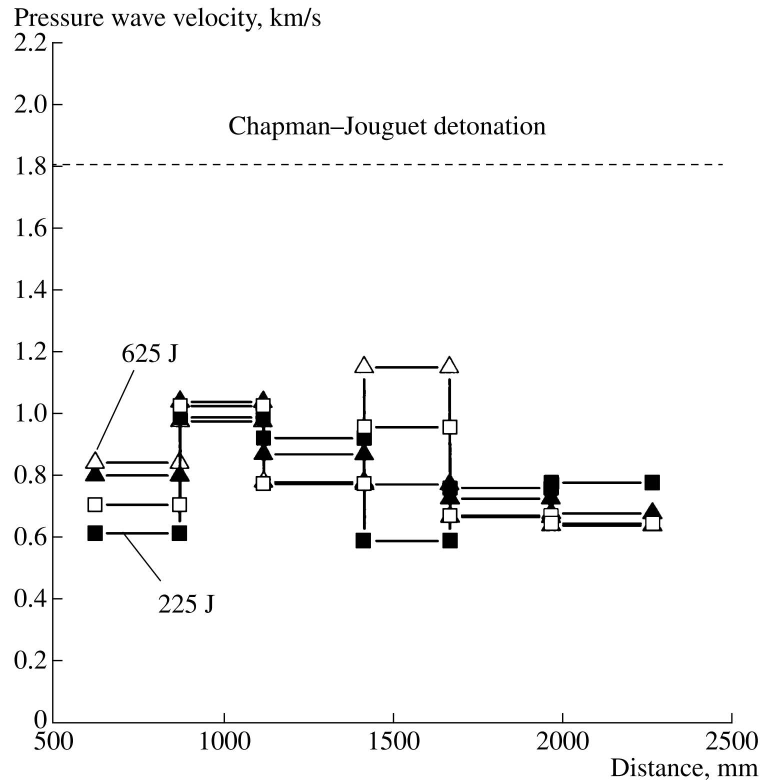

Fig. 13. Changes in the pressure wave velocity in a flow of a kerosene–air mixture in four experiments in a straight detonation tube caused by ignition energy changes from 225 to 625 J.

heater *18*, power 2.5 kW, and thermocouples *19*. Temperature was controlled using relay *14*. A typical duration of one experiment in the preliminarily heated tube was about 1 s.

The temperature of prevaporizer walls was 190 ± 10°C, the temperature of the straight tube segment with the Shchelkin spiral was 120–130°C, and the temperature of the adjoining tube segment up to the PT6 pressure transducer was 110–120°C. The tube segment between PT6 and flame arrester was not temperature-controlled; its temperature was 20–30°C.

Two series of experiments were performed. In the first series, a straight smooth detonation tube was connected to the segment with the Shchelkin spiral. In the second series, the coil pipe shown in Fig. 12, photograph (c), was connected to this segment.

The Shchelkin spiral was used for flame acceleration and obtaining a shock wave that propagated at a velocity higher than 800–900 m/s. The spiral was wound of a steel wire 7 mm in diameter; the coil pitch was 22 mm. The length of the spiral was 800 mm in both series of measurements. The spiral was situated at a distance of 70 mm from the exit nozzle of the prevaporizer. The fuel–air mixture was ignited in the prevaporizer by either a modernized sparkplug with a copper central electrode or a three-electrode electric discharger [14].

In the first series of experiments, the ignition energy was varied from 5 to 700 J. The ignition energy was calculated from the capacitance of the discharge capacitor and voltage. The experimental pressure wave velocities along the detonation tube in four typical experiments of the first series are shown in Fig. 13. The symbols are used to identify the data of each experiment. We see that no deflagration-to-detonation transition occurred in the straight tube even at a high ignition energy. The pressure wave velocity at the exit of the segment with the Shchelkin spiral did not exceed 1200 m/s.

In the second series of experiments, a coil pipe was placed behind the segment with the Shchelkin spiral. The idea of using a combination of a Shchelkin spiral and a coil pipe was based on the results obtained in [22, 23]. In these works, the effective action of tube coils on deflagration-to-detonation transition in flows of two-phase *n*-hexane–air and *n*-heptane–air mixtures was demonstrated for the first time. The coil pipe was two complete tube revolutions with a 60 mm outside diameter (inside diameter 52 mm), coil pitch 255 mm. The tube was wound around a straight rod 28 mm in diameter. The ignition energy was varied from 5 to 180 J in the second series of experiments.

As distinct from the first series of measurements, deflagration-to-detonation transitions in flows of kerosene TS-1–air mixtures were stably recorded in the second series of experiments. The pressure wave velocities

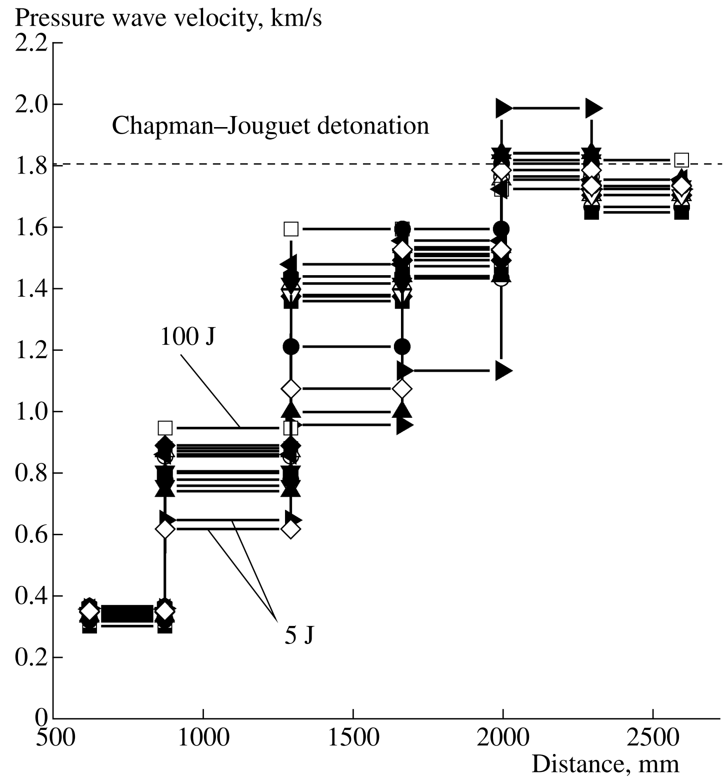

Fig. 14. Changes in the pressure wave velocity in a flow of a kerosene–air mixture in twelve experiments in a detonation tube with a Shchelkin spiral and a coil pipe caused by ignition energy changes from 5 to 100 J.

along the detonation tube obtained in 12 second series experiments (ignition energies of 5–100 J) are shown in Fig. 14. As in Fig. 13, symbols are used to identify the data of each experiments. We see that deflagration-to-detonation transitions occurred in the coil pipe even at ignition energies of 5 J. The pressure wave velocity at the exit of the coil pipe (at a distance of about 2 m from the ignition source) was 1600–1800 m/s; that is, it was at the Chapman–Jouguet detonation velocity level for hydrocarbon–air mixtures. The detonation wave formed in the coil pipe propagated at a constant velocity along the last two measuring segments between the PT5 and PT6 and between the PT6 and PT7 pressure transducers. Current pulses recorded by ionization probes in sections where the PT5, PT6, and PT7 transducers were placed coincided with the moments of shock wave arrival at the corresponding sections, which substantiated the existence of detonation.

Pressure records by the PT1–PT7 pressure transducers in the experiment with a 5 J ignition energy are shown by way of example in Fig. 15. In this experiment, detonation formed in the tube segment between PT5 and PT6 approximately 5–6 ms after ignition. Clearly, deflagration-to-detonation transitions in the second series of experiments were completely caused by the use of the coil pipe, in which multiple reflections

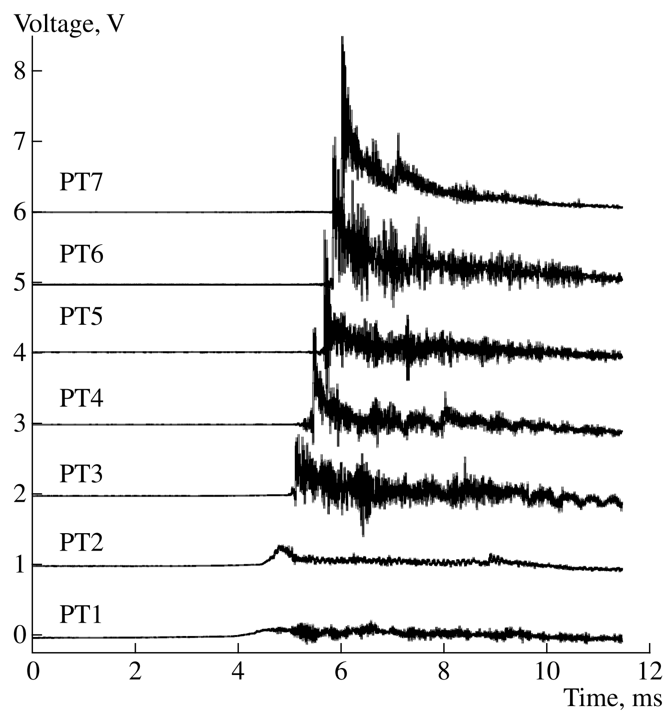

Fig. 15. PT1–PT7 pressure records during a deflagration-to-detonation transition in an experiment with the ignition energy 5 J.

of shock and pressure waves generated by an accelerating flame occurred.

To summarize, the possibility of deflagration-to-detonation transitions in a continuous flow of an air–partially vaporized aviation kerosene TS-1 mixture at atmospheric pressure and tube wall temperature 110–130°C was for the first time demonstrated in [30, 31]. It was shown that, in a temperature-controlled tube 52 mm in diameter consisting of a kerosene prevaporizer, a straight segment with a Shchelkin spiral, and a smooth coil pipe, deflagration-to-detonation transition occurred at a distance of 2 m in time 5–6 ms at a low ignition energy of about 5 J. These results open up the possibility of work on creating new jet propulsion systems with detonation fuel combustion, pulsed detonation engines [33].

CONCLUSIONS

We presented several examples that illustrate the occurrence of fast deflagration-to-detonation transitions whose possibility was discussed in [12]. Fast deflagration-to-detonation transitions can occur under conditions when, in a flow of an explosive mixture, self-ignition zones behind a comparatively weak shock wave are formed synchronously with the running wave. They are formed because of reflections of the wave from profiled obstacles or curved surfaces in bends, tube coils, etc. It was shown experimentally and by calculations that the critical velocity required for fast deflagration-to-detonation transitions to occur can be fairly low, about 800 m/s. Such shock waves can be formed in straight tubes with rough inside surfaces, regular obstacles in the form of Shchelkin spirals, or orifice plates at a fairly low ignition energy. On the one hand, various combinations of tube elements (and ignition sources) resulting in the formation of shock waves propagating at a velocity higher than 800 m/s with coils, bends, local profiled obstacles, etc., should be considered potentially dangerous. In designing explosion-proof works, such combinations should be avoided. The possibility of fast deflagration-to-detonation transitions therefore poses fundamental problems of conditions of their occurrence and precautions that should be taken to prevent them. On the other hand, the combinations considered offer much promise for fast initiation of detonation explosions, for instance, in pulsed detonation engines [33]. Further research is needed to gain better understanding of the accompanying phenomena.

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