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PHYSICAL CHEMISTRY

Initiation of Gaseous Detonation in Tubes with Sharp U-Bends

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Experimental and computational studies of shock and detonation wave propagation in tubes with two sharp U-bends have been performed for the first time. The bends have been shown to considerably facilitate gaseous detonation initiation. The minimal shock wave velocity required to initiate detonation in the stoichiometric propane–air mixture under normal initial conditions is about 800 m/s. The results obtained are important for designing an air-breathing pulse detonation engine (PDE) with a compact configuration of the combustion chamber.

Previous experimental and computational studies have been focused on initiation and propagation of gaseous and heterogeneous detonation in straight tubes or in tubes with smooth bends [1, 2]. However, it has recently become clear that sharp bends and coils of tubes considerably accelerate the deflagration-to-detonation transition (DDT) [3–7]. Since this problem is important for PDEs, we suggested to use compact configurations of detonation tubes with several U-bends [3]. On the one hand, such configurations will ensure the DDT due to an increase in the tube length and multiple reflections of compression waves, formed by an accelerating flame, upon their diffraction in U-bends. On the other hand, U-bends increase the hydraulic resistance and complicate cyclic filling of the tube with a fresh fuel–air mixture. Hence, to use such configurations in PDEs, a compromise solution should be sought that would provide a minimum DDT distance. As is known, the DDT distance is reduced with a decrease in tube diameter. However, there is a minimal (limiting) tube diameter d_{min} at which detonation propagation is still possible. According to different authors, d_{min} is in the range from $\frac{\lambda}{\pi}$ to λ [8], where λ is the multifront detonation cell width (for example, for the stoichiometric propane–air mixture under normal initial conditions, $\lambda \approx 50$ mm).

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In this paper, we report the results of the experimental and computational study of shock and detonation wave propagation in a stroichiometric propane–air mix- 2
ture in tubes of near-limiting diameter with two U-bends. The choice of propane as the hydrocarbon fuel is due to the fact that its detonation sensitivity is close to that of aviation kerosene vapors [8].

Figure 1 shows the scheme of the experimental setup. The main elements of the setup were a primary shock wave (SW) generator and a detonation tube with two U-bends. The primary SW generator (a solid propellant gas generator or an electric discharge chamber) was mounted at one end of the tube. The other end of the tube was closed. Smooth-walled tubes, 51 and 41 mm in inner diameter, with U-bends of extreme curvature, which provided the most compact configuration of the tube, were used. The bends were made by electric welding of four segments cut from a standard bent tube. The inner curvature radius of the U-bends was $R = 11 \pm 2$ mm. Before each run, the tube was evacuated and filled with the stoichiometric propane–air mixture under normal initial conditions (293 ± 2 K, 0.1 MPa). The LKh600 piezoelectric pressure transducers PT0–PT9 (table) were used for recording the SW profiles in tubes and determining the propagation velocity of these waves. The error of determination of the mean SW velocity was no more than 3%. To detect detonation, photodiodes were mounted in some measuring cross sections, in addition to pressure transducers. These photodiodes measured the luminosity of combustion products. Signals from the pressure transducers and photodiodes were input to an analog-to-digital con-

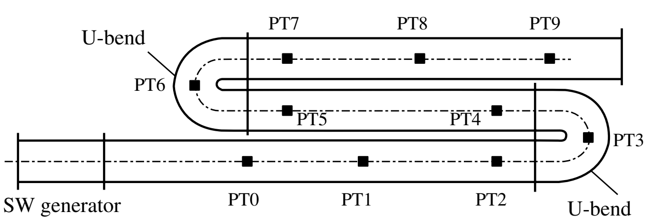

Fig. 1. Tube with two U-bends, an SW generator, and pressure transducers PT0–PT9. PT0 is the triggering transducer.

verter (L-Card L-783 ADC) based on a personal computer. Before a run, a thin smoked plate was placed in the straight output section of the tube, which allowed us to additionally identify detonation from soot imprints.

A solid propellant gas generator was a cylindrical
3 combustion chamber equipped with a displaceable discharge nozzle and a bursting diaphragm. A charge of 12/7 BA cotton powder, 1.5–2.5 g, was placed in the gas generator. A 0.3-g tablet of porous cotton powder with a Nichrome wire was used for igniting the charge. The solid propellant gas generator generated an SW with a long compression phase duration: the powder gas discharge time was 1–2 ms. The use of copper and steel membranes of various thickness, as well as a discharge nozzle 5 to 14 mm in diameter, allowed us to vary the initial velocity of a primary SW.

An electric discharge generator generated a triangle SW with a short compression phase: the characteristic energy release time in the electric discharge was 20–40 μs. The initial velocity of a primary SW was changed by varying the charging voltage of a high-voltage capacitor with a capacity of 800 μF from 1.0 to 2.5 kV. Thus, the variable parameters in the experiments were the tube diameter and the initial velocity and the compression phase duration of the primary SW.

Our experiments demonstrated that, once the SW achieves a certain minimal velocity D_{min} at the input of the first U-bend, detonation always occurs at the straight tube segment downstream of the second U-bend. In the runs, the minimal velocity was independent of the tube diameter and the SW generator used and was about 800 m/s (at the PT2–PT3 measuring segment). At $800 < D < 950$ m/s, detonation occurred downstream of the second U-bend, and at $D > 950$ m/s, it occurred downstream of the first U-bend (Fig. 2). For comparison, it is worth noting that, in a tube 51 mm in diameter with one U-bend with a larger inner curvature radius ($R = 51$ mm), detonation occurred downstream of the bend at the primary SW velocity exceeding 1100 m/s [3]. Noteworthy is also the fact that, for detonation to be initiated in straight tubes 51 and 41 mm in diameter, primary SWs should have a velocity of 1700–1800 m/s.

Figure 3 shows characteristic pressure profiles recorded upon detonation in a tube 51 mm in diameter downstream of the second U-bend. In this run, the SW velocity D over the measuring segments PT0–PT1, PT1–PT2, PT2–PT3, PT3–PT4, PT4–PT5, PT5–PT6, PT6–PT7, PT7–PT8, and PT8–PT9 was 865, 844, 876, 769, 1237, 1188, 1558, 1796, and 1734 m/s, respectively; i.e., the velocities recorded at the PT7–PT8 and PT8–PT9 measuring segments were close to the detonation velocity. In the cross sections where the PT7 and PT8 pressure transducers were located, the signals of the photodiodes deviated sharply from the baseline simultaneously with the signals of the pressure transducers. This is a characteristic feature of the detonation wave consisting of the shock front followed by the reaction front. The soot imprint clearly reflected the trajectories of triple points, which form a cellular structure with a cell width close to the tube diameter. All above features are evidence that, in this experiment, detonation was detected. It should be noted that calculated the Chapman–Jouguet thermodynamic detonation velocity in the stoichiometric propane–air mixture is D_0 = 1804 m/s. The fact that the measured detonation velocity turned out to be somewhat lower than the thermody-

Table 1. Location of pressure transducers in tubes 51 and 41 mm in diameter

Pressure transducer	Distance between transducers for tubes with	
	$d = 51$ mm	$d = 41$ mm
PT0	400	450
PT1	650	750
PT2	900	1050
PT3	1140	1335
PT4	1380	1590
PT5	1816	1953
PT6	2056	2241
PT7	2296	2494
PT8	2596	2794
PT9	2896	3294

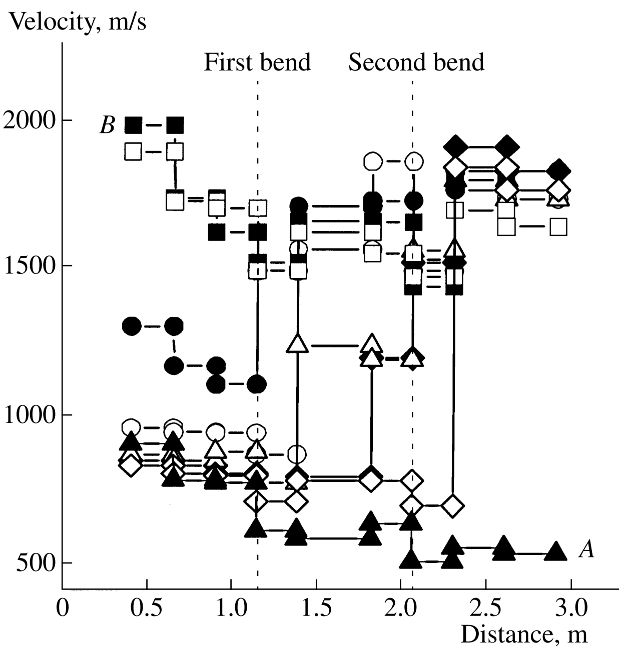

Fig. 2. Mean SW velocity over different measuring segments in a tube 51 mm in diameter with two U-bends. Symbols are used for symplifying curve identification. The vertical dashed lines correspond to the location of pressure transducers PT3 and PT6 in the U-bends. 1

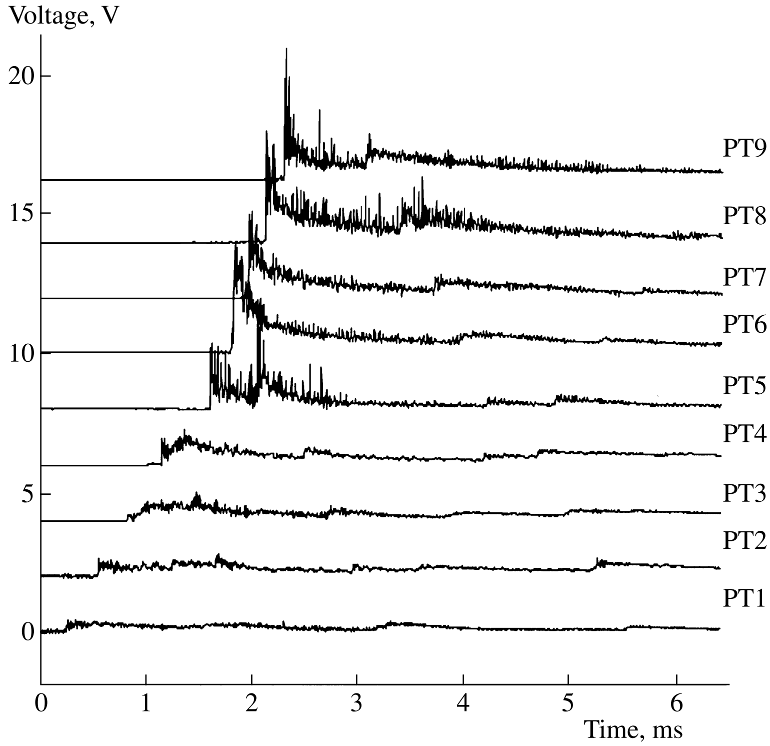

Fig. 3. Records of pressure transducers PT1–PT9 in the run with detonation initiation downstream of the second U-bend in a tube 51 mm in diameter.

namic velocity is associated with momentum and energy losses in a tube of near-limiting diameter.

At $D < 800$ m/s, detonation was absent (curve *A* designated by solid triangles in Fig. 2), although the pressure transducers recorded secondary explosions in the region behind the primary SW.

Upon direct detonation initiation by a primary SW generator (D = 1700–1800 m/s), the detonation wave passed through both U-bends with a short-term 15–20% decrease in the propagation velocity, which was then recovered (curves *B*, designated by solid and open squares, Fig. 2).

To elucidate the phenomena under consideration, we performed two-dimensional gas dynamic calculations based on the numerical solution of the Euler equations augmented with the one- or multistage kinetic mechanism of propane oxidation [6]. Flows in plane channels with a height of 41 and 51 mm with two U-bends of limiting curvature were considered. The calculations confirmed basic features of the observed phenomena and clarified their mechanisms. In addition, the calculations allowed us to elucidate the effect of the compression phase duration in the primary SW on evolution of waves of different intensity. This effect was not detected experimentally.

Figure 4 shows the calculated change in the velocity of the SW as it propagates along the tube for waves with the same initial velocity $\frac{D}{D_0} = 0.64$ but with different initial compression phase duration τ, a "short" wave ($\tau \approx 60$ μs) and a "long" wave ($\tau \approx 600$ μs). The inset in Fig. 4 shows the determination of τ from the pressure profile in the primary SW. As is seen, in the first U-bend, the velocity of both waves changes in the same way: first it increases approximately to $\frac{D}{D_0} = 1.5$ at the center of the bend and then decreases to $\frac{D}{D_0} = 0.2$ at the exit from the bend. The subsequent sharp increase in the SW velocity to $\frac{D}{D_0} = 1.65–1.95$ is caused by strong secondary explosions near the outer wall of the bend and the coalescence of the secondary waves with the primary SW. At the straight segment of the channel downstream of the first U-bend, both SWs propagate at roughly the same mean velocity equal to the detonation velocity ($\frac{D}{D_0} \approx 1$). However, the long wave consists of three transverse waves (induced by several secondary explosions), whereas the short wave consists of one transverse wave. This difference manifested itself during wave diffraction in the second U-bend: the short wave could not overcome the cooling action of the cen-

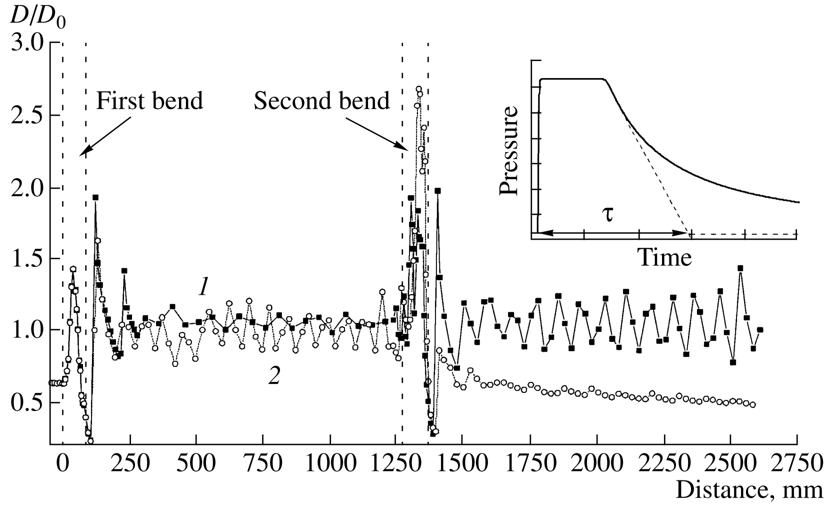

Fig. 4. Calculated change in the SW velocity along the symmetry line of a plane channel 51 mm in height with two sharp U-bends. The origin corresponds to the input cross section of the first U-bend. The vertical lines correspond to the locations of the input and output cross sections of the U-bends. (*1*) long SW with the compression phase duration $\tau = 600$ μs, and (*2*) short SW with the compression phase duration $\tau = 60$ μs. Inset: Determination of τ from the pressure profile in the primary SW.

tered rarefaction wave arising at the inner wall of the bend, whereas the long wave overcame this action. In the second U-bend, formation of a highly overdriven detonation wave (up to $\frac{D}{D_0}$ = 2.–2.7) was observed.

Thus, the experimental and computational studies of shock and detonation wave propagation in tubes with two sharp U-bends showed that the bends considerably facilitate the initiation of gaseous detonation. The minimal SW velocity required to initiate detonation in the stoichiometric propane–air mixture in tubes 51 and 41 mm in inner diameter under normal initial conditions turned out to be about 800 m/s (rather than 1700–1800 m/s required for straight tubes). Such waves are easy to generate in a straight tube with a Shchelkin spiral by a weak ignition source [4–6]. The detonation initiation mechanism is related to multiple reflections of SWs as they pass through the bends and to secondary explosions. The results obtained are important for designing an aircraft air-breathing pulse detonation engine with a compact configuration of the combustion chamber.

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SPELL: 1. symplifying, 2. stroichiometric, 3. displaceable