Detonation initiation, propagation and stability in U-shaped tubes

S. M. Frolov, V. S. Aksenov, I. O. Shamshin
Semenov Institute of Chemical Physics
4, Kosigin Street, Moscow, 119991 Russia

The objective of the research outlined in this paper was to provide new experimental and computational data on initiation, propagation, and stability of gaseous stoichiometric propane–air detonations in tubes with U-bends considered for possible application in pulse detonation engines. Extensive experimental and computational studies with the tubes 51 and 41 mm in diameter with U-bends of two curvatures and two different shock-wave generators were performed. Numerical simulations of the process were used to reveal the salient features of the accompanying phenomena.

Introduction

Tube bends and coils are the elements, which are widely used in various industrial applications. Surprisingly little work has been done on the reactive shock and detonation diffraction in such elements [1–8]. Our recent research on deflagration-to-detonation transition (DDT) and shock-to-detonation transition (SDT) in curved tubes [2–8] has unequivocally demonstrated that tube curvature promoted DDT and SDT efficiently.

The effect of tube coils on DDT and direct detonation initiation in homogeneous and two-phase reactive media was studied in [2–5]. The use of smooth-walled tubes with coils allowed decreasing the critical energy of direct detonation initiation at least by a factor of two. As for the DDT in the straight tube with the Shchelkin spiral followed by the tube coil, it was solely attributed to the use of the tube coil.

In [6-8], the experimental and computational results were reported for the SDT in a stoichiometric propane–air mixture in tubes 51 mm in diameter with one and two U-bends of different curvature. The results demonstrated a considerable effect of the U-bend on detonation initiation and propagation.

The curvature of the U-bend, tube diameter, initial pressure, and compression phase duration of the initiating shock wave are the most important governing parameters of the problem which determine the evolution of the initiating shock wave or a developed detonation wave in such a system. The objective of the research outlined in this paper was to provide new experimental and computational data on propagation of reactive shock and detonation waves in tubes with U-bends. The research was focused on the effect of U-tube curvature and diameter, and compression-phase duration of the incident shock wave on SDT.

1. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. The setup comprised the detonation tube of round cross-section with two U-bends. The tube was fixed at the experimental stand, which was equipped with the utilities required for working with gaseous explosive mixtures. The explosive mixture was the stoichiometric propane–air. The mixture was prepared in the mixer at normal atmospheric conditions. The theoretical Chapman–Jouguet detonation velocity of the mixture is 1804 m/s. At one end of the tube, a Shock Generator (SG) was mounted. Two types of SG were used: solid-propellant SG (Cases 1, 4, 5, and 7 in Table 1) and electric-discharge SG (Cases 2, 3, 6, 8 and 9 in Table 1). The solid-propellant SG was the same as in [6-8]. Before the run the combustion chamber 22 cm^3 in volume with a changeable nozzle and bursting diaphragm was filled with solid propellant. The propellant was ignited by a primer. The electric- discharge SG was the same as used

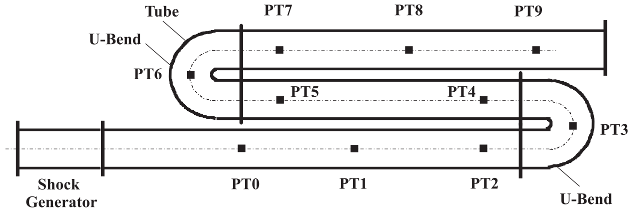


Figure 1: Schematic of the experimental setup. Dots indicate the positions of pressure transducers (Table 1)

Table 1: Measuring ports (in mm) in experiments with solid-propellant SG (Cases 1, 4, 5, and 7) and electric-discharge SG (Cases 2, 3, 6, 8, and 5).

Tube diameter 51 mm; U-bend curvature radius 10 mm										
Case	**PT0**	**PT1**	**PT2**	**PT3**	**PT4**	**PT5**	**PT6**	**PT7**	**PT8**	**PT9**
1	150	400	650	900	1140	1380	1816	2056	2296	2596
2	20	650	900	1140	1380	1816	2056	2296	2596	2896
3	0	850	1310	1810	2050	2726	2966	3206	3506	3806
Tube diameter 51 mm; U-bend curvature radius 51 mm										
4	405	1005	1200	1320	1440	1550	1850	2150	-	-
Tube diameter 41 mm; U-bend curvature radius 10 mm										
5	450	750	1050	1335	1590	1953	2241	2494	2794	3294
6	0	750	1050	1335	1590	1953	2241	2494	2794	3294
Tube diameter 41 mm; U-bend curvature radius 41 mm										
7	450	837	1117	1307	1553	1916	2172	2362	2614	3413
8	0	387	667	857	1103	1466	1722	1912	2164	2964
9	0	1060	1315	1505	1751	2114	2370	2560	2812	3612

earlier in [2–5, 8] and comprised three electrodes. The characteristic time of discharge was 20–40 μs. The tubes 51 and 41 mm in inner diameter had three straight sections and two U-bends, both in one plane. The internal radius of the U-bends was equal either to 10 mm or to the tube diameter. Each U-bend was fabricated by welding four curved segments. Up to nine piezoelectric pressure transducers (PT1 to PT9) were mounted along the tube axis (see Fig. 1 and Table 1). The total length of the tubes along the tube axis was up to 4 m. The internal tube walls in all Cases were smooth.

The accuracy of shock wave velocity measurements was estimated as 4%. The data acquisition system was triggered by pressure transducer PT0. To identify the detonation and deflagration in the experiments, two techniques were additionally used, namely photo-diode registration and smoked-foil footprints.

2. Experimental Results

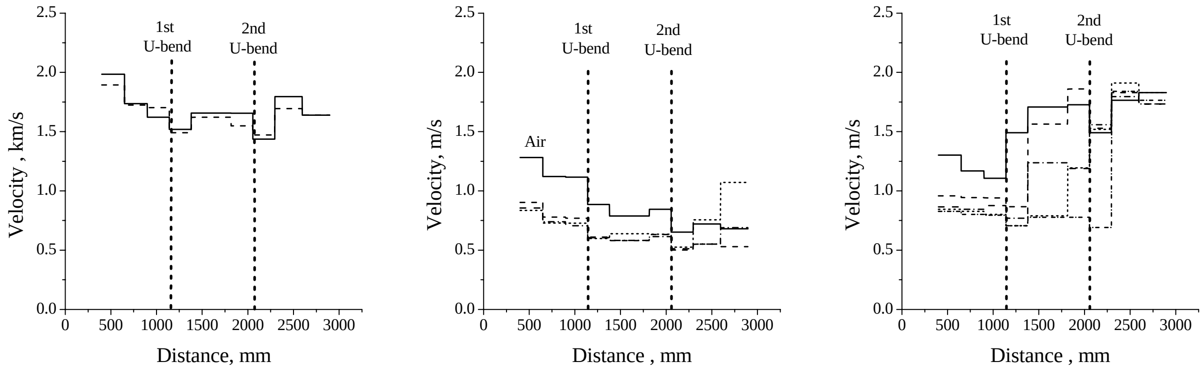
2.1 Solid-Propellant Shock Generator

The experiments with the solid-propellant SG are relevant to Cases 1, 4, 5, and 7. The results for Case 4 were partly reported earlier in [6, 7]. Figure 2 shows the measured dependencies of the shock and detonation wave velocities on the distance traveled along the 51-mm tube in some representative runs of Case 1. Two vertical dashed lines show the positions of the U-bends.

Shown in Fig. 2*a* is the variation of the mean shock velocity along the tube with two U-bends, when the solid-propellant SG generated an overdriven detonation at the first measuring segment (1800–2000 m/s) and the detonation wave transitioned successfully through the U-bends. The mean detonation velocity deficit in the regions behind the second U-bend attained the value of about 20%.

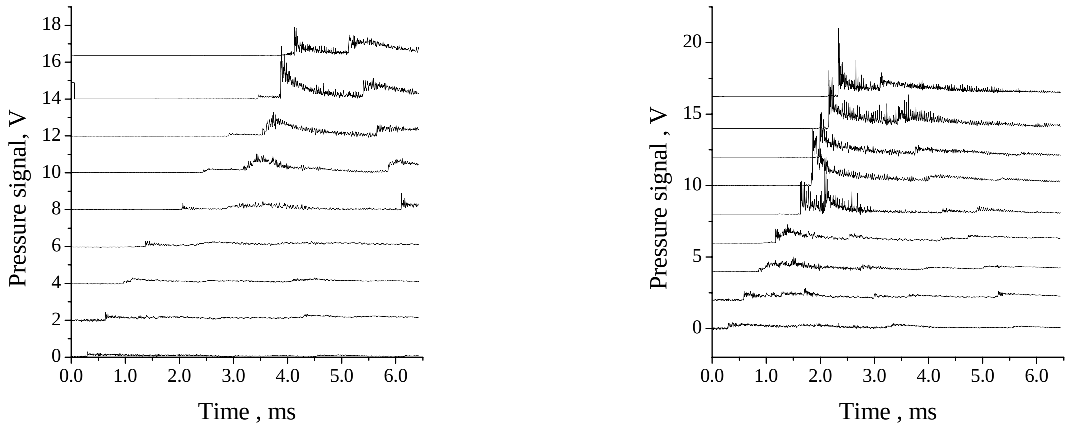
Figure 2*b* shows the variation of the mean shock wave velocity along the tube, when the SG generated a shock wave with the velocity of 800–900 m/s at the first measuring segment. Due to attenuation in the straight section upstream the first U-bend, the shock waves entered the first U-bend at a mean velocity of 700–750 m/s in this experimental series. After passing the U-bends, such shock waves decelerated to about 500 m/s. There were indications of shock wave acceleration downstream the second U-bend up to 1100 m/s in some runs, however the total length of the tube was insufficient for determining whether such waves were capable of transitioning to a detonation. For the sake of comparison, Figure 2*b* also shows the attenuation of a shock wave of initial velocity of 1300 m/s in pure air.

Figure 2*c* shows the variation of the mean shock wave velocity along the tube with the initial shock wave velocities in the range from 850 to 1300 m/s at the first measuring segment. In this experimental series, the shock waves transitioned to detonations after passing either the first U-bend, or the second U-bend, i.e., the



(a) (b) (c)

Figure 2: Mean shock wave velocities at different measuring segments of the tube 51 mm in diameter with two U-bends (shown by vertical lines) in some representative runs: (*a*) transition of detonation through two U-bends, (*b*) transition of shock waves through two U-bends without detonation onset, and (*c*) transition of shock waves through two U-bends with detonation onset



(*a*) (*b*)

Figure 3: Pressure records: (*a*) shock wave with a strong pressure wave in the wake, and (*b*) SDT

SDT phenomenon was detected. The lowest mean velocity of the primary shock wave entering the first U-bend and leading to the detonation onset behind the second U-bend was about 800 m/s. This velocity value should be treated as the critical condition for the setup of Case 1. Remind that in the experiments with a U-bend of smaller curvature (Case 4 [6, 7]), the critical shock wave velocity was about 1100 m/s. It is seen from Fig. 2*c* that the higher the primary shock velocity the faster is the onset of detonation.

Figure 3 shows the pressure records relevant to some runs of Fig. 2. Remind that pressure transducers PT4 and PT7 were positioned in the first and the second U-bends. Figure 3*a* shows the pressure records relevant to the phenomena observed in the experimental series of Fig. 2*b*. Starting from the record of PT4, one can see the formation of a strong secondary pressure wave in the wake of the primary shock wave. At the record of PT9, the secondary shock wave has not yet caught up with the primary shock wave. The third wave evident in Fig. 3*a* corresponds to the shock wave reflected from the closed

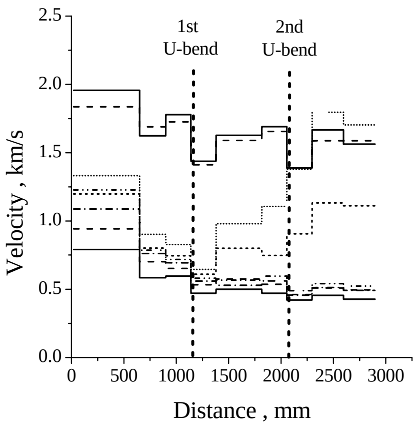


Figure 4: Mean shock wave velocities at different measuring segments of the tube 51 mm in diameter with two U-bends (shown by vertical lines) in some representative runs with electric-discharge SG

end of the tube. Pressure records in Fig. 3*b* correspond to the experimental series of Fig. 2*c*. The formation of a secondary pressure wave is clearly seen at the record of PT4. The detonation arose in the intermediate straight tube section between pressure transducers PT4 and PT7 after the secondary shock wave caught up with the primary shock wave.

In the tube 41 mm in diameter, the characteristic features of the studied phenomena were similar except for a somewhat lower detonation propagation velocity (1600–1650 m/s) and a larger critical shock wave velocity (about 850 m/s for the U-bends of larger curvature (Case 5) and 1200 m/s for the U-bends of smaller curvature (Case 7)). The principal new finding for the 41-mm tube was the observation of occasional detonation decay in the configuration with small U-bend curvature (Case 7).

2.2 Electric-Discharge Shock Generator

The second experimental series (Cases 2 and 8) was conducted with the electric-discharge SG and relatively short straight tube sections at the initiation side. The main specific feature of this SG was that it generated the shock waves of shorter compression phase duration. Figure 4 shows the measured dependencies of the shock and detonation wave velocities on the distance traveled along the 51-mm tube in some representative runs. Again, the vertical dashed lines show the positions of the U-bends. Similar to the experiments described in Section 2.1, the detonation wave, when passing through the U-bends, exhibited deep drops in the mean propagation velocity, but nevertheless recovered after the second U-bend. Clearly, due to a short compression phase duration, the primary shock waves attenuated much stronger than in Case 1. For example, the primary shock wave with the mean velocity of about 1350 m/s at the first measuring segment attenuated to the velocity of about 800 m/s at the entrance to the first U-bend. A similar initial shock wave in the Case 1 attenuated to about 1150 m/s. Nevertheless, the critical velocity value for the shock wave entering the first U-bend, required for detonation initiation, appeared to be also about 800 m/s, i.e. close to that found in Section 2.1.

In the 41-mm tube, the critical velocity value for the shock wave entering the first U-bend, required for detonation initiation, appeared to be about 850 m/s for 10-mm curvature radius and 1200 m/s for 41-mm curvature radius. With the electric-discharge SG, detonation decay behind either first or second U-bend was also observed.

2.3 Electric-Discharge Shock Generator with Extension

The third experimental series (Cases 3, 6, and 9) was conducted with the electric-discharge SG and with extension tubes at the initiation side. The extension tubes were used to vary the intensity of the primary shock wave at the entrance to the first U-bend. Figure 5 shows some measured dependencies of the shock and detonation wave velocities on the distance traveled along the 51-mm tube. In this experimental series, the phenomenon of detonation decay in the U-bend was also observed in the 51-mm tube. One of the curves in Fig. 5 shows the event of detonation decay after it passes through the first U-bend. Due to the limited length of the tube in the setup of Fig. 1, it was not possible to judge whether the detonation was capable to recover after passing the second U-bend. The other important finding in this experimental series is that the critical velocity value for the shock wave entering the first U-bend to transition to detonation was also close to 800 m/s for the 51-mm tube. One of the solid lines corresponds to the run with the shock wave entering the first U-bend at the mean velocity of 790 m/s, decaying to 440 m/s in the

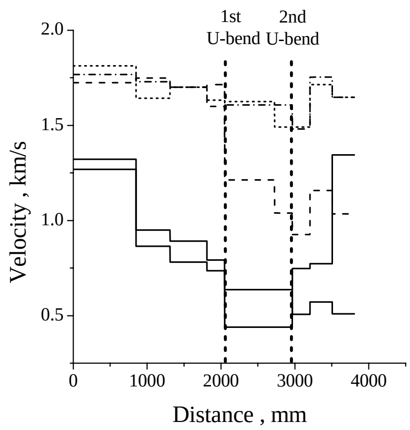


Figure 5: Mean shock wave velocities at different measuring segments of the tube 51 mm in diameter with two U-bends (shown by vertical lines) in representative runs

intermediate tube section, and accelerating up to 1340 m/s behind the second U-bend. Inspection of the corresponding pressure records made it possible to assume that the detonation would likely occur in the longer tube.

For the 41-mm tube, the critical velocity value for the shock wave entering the first U-bend and required for detonation initiation was again about 850 m/s and 1200 m/s for the U-bends of larger and smaller curvatures, respectively.

3. Computational Analysis

The mathematical model was based on the standard two-dimensional Euler equations, energy conservation equation with a chemical source term, and equation of chemical kinetics. The kinetics of propane oxidation was modeled by a single-stage overall reaction [7]. The rate constant was obtained by fitting the calculated ignition delays with the experimental data on ignition of the stoichiometric propane–air mixture behind reflected shock waves.

For numerical solution of governing equations a method of splitting by physical processes was used. At each time step, only convective fluxes and pressure work were taken into account at the first stage. This stage of integration was solved by the second-order Godunov–Kolgan method. Mass, momentum, and energy fluxes through faces of a computational mesh were found from the exact solutions of the Riemann problem. At the second stage, the chemical reaction was taken into account. A fully implicit method was used for integrating the reaction kinetic equation. A more detailed description of the numerical procedure is available in [7].

Figure 6 shows the comparison of calculations of SDT in a 51-mm tube with the U-bends of different curvature at identical initial conditions. Figure 6*a* corresponds to the study of [6, 7] with the U-bend curvature radius equal to the tube diameter. Figure 6*b* corresponds to the 51-mm tube with the U-bend studied herein. In both computational runs, the primary shock wave was generated by a high-pressure domain in a lower left end of the tube. The resulting shock wave entering the U-bend had a velocity of about 1000 m/s. It can be seen that a single-head detonation was initiated by such a shock wave in the tube with larger curvature (Fig. 6*b*), while shock wave deceleration was detected in the tube with smaller curvature (Fig. 6*a*). These results correspond well with the experimental findings.

The effect of compression phase duration in the primary shock wave is illustrated by Figs. 7*a* and 7*b*. In both cases, the primary shock wave velocity was 1460 m/s. The compression phase duration in the primary shock waves of Figs. 7*a* and 7*b* was 30 and 50 μs, respectively. It is seen that the longer-duration shock wave transitions first to a single-head detonation and then to a multihead detonation, i.e., exhibits SDT, whereas a shorter-duration shock wave does not. The effect of compression phase duration in the primary shock on the SDT was not observed experimentally so far. Probably, the reason is that this parameter was not varied in a sufficiently wide range.

Concluding Remarks

New experimental and computational results were obtained for shock and detonation transition through U-bends in curved tubes filled with a stoichiometric propane–air mixture. The experiments demonstrated a considerable effect of the U-bends on detonation initiation and propagation.

On the one hand, the U-bends of the tube were shown to promote SDT considerably. Moreover, the tubes with the larger curvature promoted SDT more efficiently than those of smaller curvature. Thus, it was proved experimentally that for the SDT in the tube with two U-bends of nearly limiting curvature the velocity of

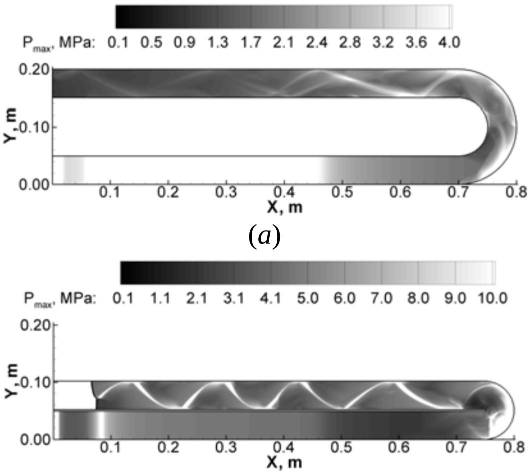


Figure 6: Predicted fields of maximal pressure at identical conditions of shock wave generation in tubes with different U-bend curvature: (*a*) no detonation, and (*b*) detonation

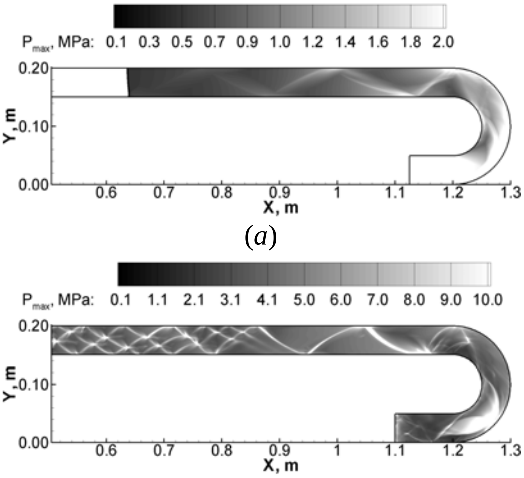


Fig. 7: Predicted maximal pressure field in the course of shock wave propagation in the tube with U-bend. Initial shock velocity is 1460 m/s; compression phase duration is 30 (*a*) and 50 μs (*b*).

the primary shock wave entering the first U-bend should exceed the value of about 800 m/s for the 51-mm tube and 850 m/s for the 41-mm tube regardless the type of SG. In the tubes with the curvature radius equal to tube diameter, the critical value of the primary shock wave velocity was at the level of 1100 m/s for the 51-mm tube and 1200 m/s for the 41-mm tube.

On the other hand, the detonation wave propagating through the U-bend was shown to be subject to temporary attenuation with a considerable velocity drop, followed by the detonation recovery in the straight tube section downstream from the U-bend, or complete detonation decay. The detonation decay was found to occur more likely in tubes with U-bends of smaller diameter.

The computational studies revealed the important effect of compression phase duration in the primary shock wave on the SDT.

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