SHOCK-TO-DETONATION TRANSITION IN TUBES WITH U-BENDS

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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. Extensive experimental and computational studies with the tube 51 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 [1–5]. Recent research on deflagration-to-detonation transition (DDT) and shock-to-detonation transition (SDT) in curved tubes [2–6] 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], the experimental and computational results were reported for the SDT in a stoichiometric propane–air mixture in a tube with a single U-bend of the internal radius equal to tube diameter (51 mm). The results demonstrated a considerable effect of the U-bend on detonation initiation and propagation. On the one hand, the U-bend of the tube promoted the SDT: a shock wave entering the U-bend at a velocity exceeding 1100 m/s always transitioned to a detonation. On the other hand, the detonation wave propagating at a velocity of 1700–1800 m/s through the U-bend was subjected to temporary attenuation with the velocity drop of about 250 m/s (15%) followed by the recovery of the propagation velocity in the straight tube section downstream from the U-bend. Two-dimensional (2D) numerical simulations of detonation transition through the U-bend revealed salient features of transient phenomena in U-tubes. It was shown that different portions of the lead detonation front exhibited different behavior in the U-bend due to temporally and spatially shifted interaction with various compression and rarefaction waves and due to finite rate of chemical reaction. Both localized detonation decay and detonation reinitiation events were detected near the internal wall of the U-bend. In addition, large-scale unburned fuel pockets far behind the lead shock front were shown to form during detonation transition through the U-bend. After exiting from the U-bend, the detonation recovered at a distance of about 8–10 tube diameters attaining an established cellular structure.

The curvature of the U-bend, tube diameter, and compression phase duration of the initiating shock wave are expected to be 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 is mainly focused on the effect of U-tube curvature 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 explosive mixture was the stoichiometric propane–air. The mixture was prepared in the mixer at normal atmospheric conditions.

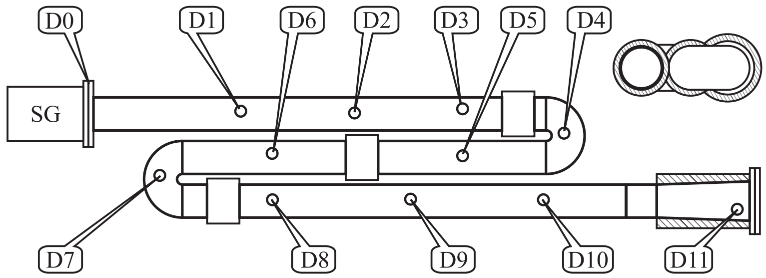

Figure 1 Schematic of the experimental setup. Dots indicate the positions of pressure transducers (see Table 1)

Table 1 Measuring ports in experiments with solid-propellant SG (Case 1) and electric-discharge SG (Cases 2 and 3). The distance is measured (in mm) from the position D0 in Fig. 1

Case	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
1	400	650	900	1140	1380	1816	2056	2296	2596	2896
2	650	900	1140	1380	1816	2056	2296	2596	2896	—
3	850	1310	1810	2050	2726	2966	3206	3506	3806	—

Remark: In Case 3, an elongated tube was used.

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 (Case 1 in Table 1) and electric-discharge SG (Cases 2 and 3 in Table 1).

The solid-propellant SG was a combustion chamber 22 cm^3 in volume equipped with a changeable nozzle of up to 14 mm in diameter closed with a bursting diaphragm. Before the run, the combustion chamber was filled with a solid propellant of a total mass up to 2.5 g. The propellant was ignited by an igniter 0.2 ± 0.02 g in mass. The maximal pressure in the chamber was up to 100 MPa. The strength of the shock wave formed depended on the nozzle diameter, diaphragm thickness, and thermodynamic parameters of combustion products in the SG.

The electric-discharge SG was the same as used earlier in [2–5] and comprised three electrodes. The distance between two main electrodes was 8 mm. The primary (breakdown) discharge gap was 3 mm. The primary discharge was of fixed (57 J) energy. It produced plasma to trigger the main discharge of considerably higher energy. The capacitance of the main discharge was 800 μF. Voltage was varied from 1.5 to 2.5 kV. The characteristic time of discharge was 20–40 μs.

The tube 51 mm in inner diameter had three straight sections and two U-bends, both in one plane, as shown in Fig. 1. The internal radius of the U-bends was 11 mm while the axial curvature radius was 37 mm. Each U-bend was fabricated by welding four curved segments. Up to ten piezoelectric pressure transducers (D1 to D10) were mounted along the tube axis (see Fig. 1 and Table 1). In Cases 1 and 2 of Table 1, the lengths of the straight tube sections were 1005 to 1200 mm each and the total length of the tube, when measured along the tube axis, was 3330 mm. In Case 3, the setup had a straight-tube extension 850 mm long attached to the SG. The internal tube walls were smooth.

The accuracy of shock wave velocity measurements was estimated as 4%. The data acquisition system was triggered by pressure transducer D1. The measuring segments at the straight tube sections were 240, 250, and 300 mm long. The measuring segments in the U-bends were 250 mm long when measured along the U-bend axis and 232 mm long when measured along the straight line connecting the neighboring measuring ports. For calculating the shock wave propagation velocity in the U-bends, the corresponding measuring segments were taken to be 240 mm long (the shortest distance between the neighboring measuring ports if measured inside the tube). To identify the detonation and deflagration in the experiments, two techniques were additionally used, namely, coupled photodiode and pressure registration in the same tube cross section and smoked-foil footprints.

2 Experimental Results

2.1 Solid-Propellant Shock Generator

The first experimental series (Case 1) was performed with the solid-propellant SG. Figure 2 shows the measured dependencies of the shock and detonation wave velocities on the distance traveled along the tube in some representative runs. 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

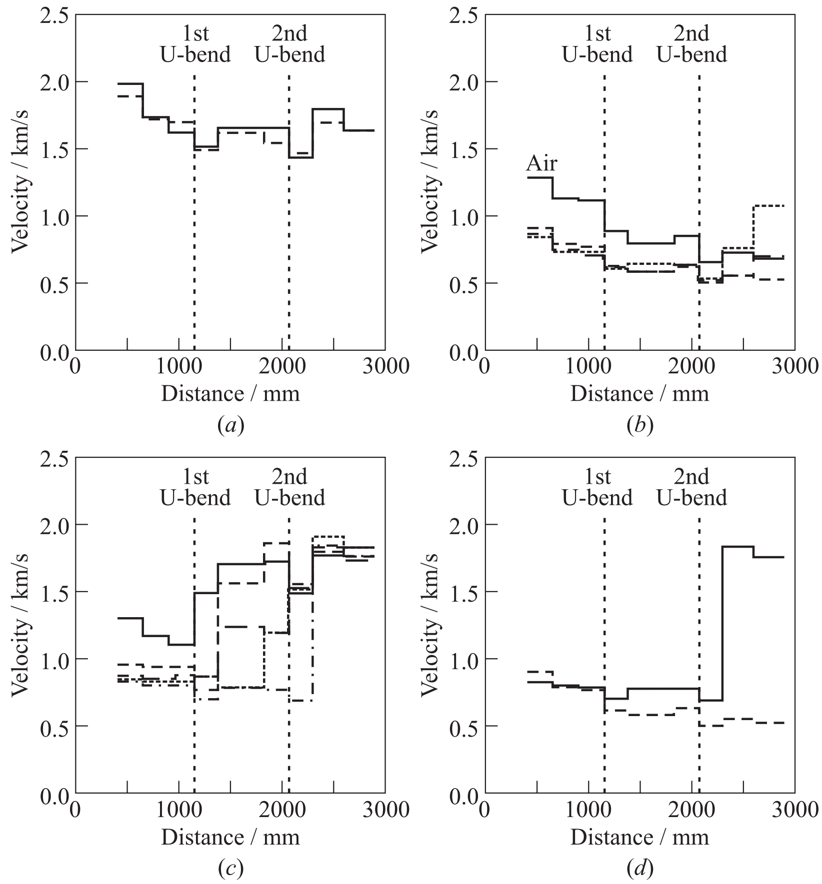

Figure 2 Mean shock wave velocities at different measuring segments of the tube with two U-bends (shown by vertical lines) in runs of Case 1: (*a*) transition of detonation through two U-bends, (*b*) transition of shock waves through two U-bends without detonation onset, (*c*) transition of shock waves through two U-bends with detonation onset, and (*d*) hysteretic phenomena in the vicinity of the critical primary shock intensity

SG generated an overdriven detonation at the first measuring segment (1800–2000 m/s) and the detonation wave transitioned through the U-bends. The detonation wave decelerated to 1510 m/s after the first U-bend, accelerated to 1660–1720 m/s in the intermediate straight tube section, decelerated again to 1430–1480 m/s after the second U-bend, and then recovered and propagated at 1650–1800 m/s. 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 first U-bend, such shock waves propagated at a nearly constant velocity of 600–650 m/s along the intermediate straight tube section and decelerated to about 500 m/s after the second U-bend. 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 concluding whether such waves were capable of transitioning to a detonation or not. For the sake of comparison, Fig. 2*b* 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 these experiments, the shock waves transitioned to detonations after passing either the first or the second U-bend, i.e., the 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 [2], 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 the onset of detonation. However, in the vicinity of the critical velocity value, some hysteretic behavior of shock waves was observed. This kind of behavior is demonstrated in Fig. 2*d*.

Figure 3 shows the pressure records relevant to some runs of Fig. 2. Remind that pressure transducers D4 and D7 are positioned in the first

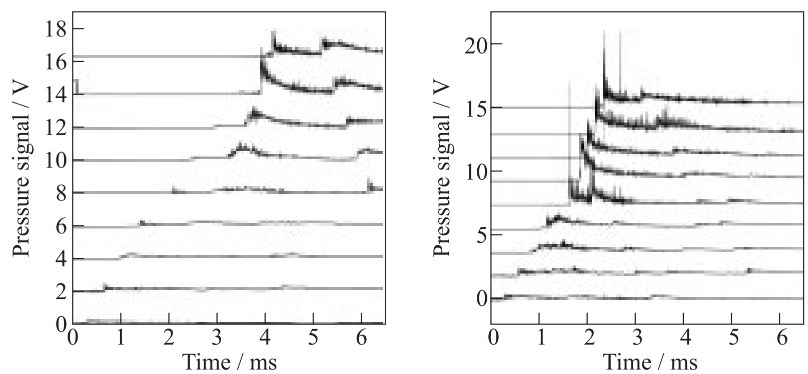

Figure 3 Records of pressure transducers D1 to D9: (*a*) shock wave with a strong pressure wave in the wake, and (*b*) SDT

and the second U-bends. Figure 3*a* shows the pressure records relevant to the phenomena observed in the experiments of Fig. 2*b*. Starting from the record of D4, one can see the formation of a strong secondary pressure wave in the wake of the primary shock. At the record of D9, the secondary shock wave has not yet caught up with the primary shock. Note that the third wave evident in Fig. 3*a* corresponds to the shock wave reflected from the closed end of the tube.

Pressure records in Fig. 3*b* correspond to one of the experiments of Fig. 2*c*. The formation of a secondary pressure wave is clearly seen at the record of D4. The detonation arose in the intermediate straight tube section between pressure transducers D4 and D7 after the secondary shock wave caught up with the primary shock.

2.2 Electric-Discharge Shock Generator

The second experimental series (Case 2) was conducted with the electric-discharge SG. 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 tube in some representative runs. Again, the vertical dashed lines show the positions of the U-bends.

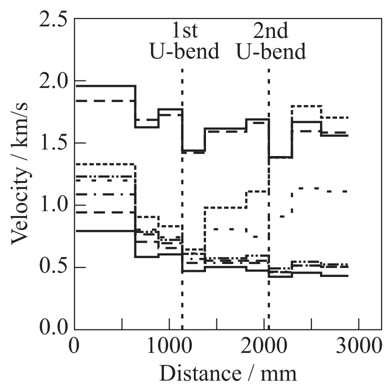

Figure 4 Mean shock wave velocities at different measuring segments of the tube with two U-bends (shown by vertical lines) in some representative runs with the electric-discharge SG

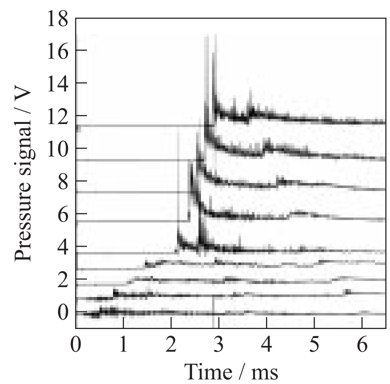

Figure 5 Pressure records at SDT

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 in Case 2 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. In Case 1, a similar initial shock wave 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. Figure 5 shows pressure records in the run relevant to SDT.

2.3 Electric-Discharge Shock Generator with Extension

The third experimental series (Case 3) was conducted with the electric-discharge SG and with the extension tube at the initiation side. The

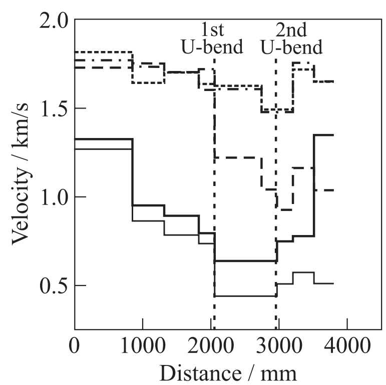

Figure 6 Mean shock wave velocities at different measuring segments of the tube with two U-bends (shown by vertical lines) in representative runs

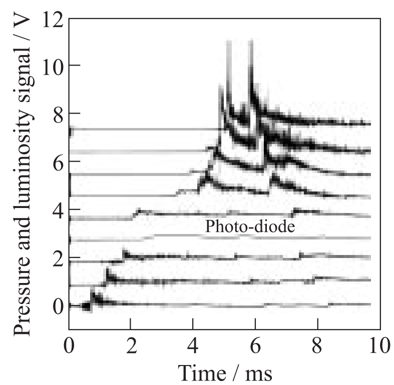

Figure 7 Representative pressure and luminosity records for the case when no SDT occurs

extension tube was used to vary the intensity of the primary shock wave at the entrance to the first U-bend. Figure 6 shows some measured dependencies of the shock and detonation wave velocities on the distance traveled along the tube. In these experiments, the phenomenon of detonation decay in the U-bend was observed. One of the curves in Fig. 6 shows the event of detonation decay after it passed through the first U-bend. Due to the limited length of the tube in the setup of Fig. 1, it was not possible to conclude whether the detonation was capable to recover or not after passing the second U-bend. The critical velocity value for the shock wave entering the first U-bend to transition to detonation was also close to 800 m/s in these experiments. 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 640 m/s in the 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 example, Fig. 7 shows the pressure records in the run relevant to possible SDT. It follows from Fig. 7 that a strong secondary shock wave has nearly caught up with the decaying primary shock wave at pressure transducer D9 (the upper trace).

3 Computational Analysis

The mathematical model was based on the standard 2D 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

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

The heat effect of the reaction entering the energy conservation equation was taken equal to 46.6 MJ/kg. The expression for a bimolecular reaction rate $w = k[C_3H_8][O_2]$ was used to calculate the rate of reaction, where $k = 7{\cdot}10^{14}p^{-0.2264}\exp(-E/RT)$ $cm^3/(mol{\cdot}s)$ is the rate constant, T is the temperature, R is the gas constant, $E = 45\,460$ kcal/mole is the activation energy, and p is pressure in atm. 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 [6].

For numerical solution of governing equations, a method of splitting by physical processes was used. A more detailed description of the numerical procedure is available elsewhere [6].

Figure 8 shows the comparison of calculations of SDT in a tube 51 mm in diameter with the U-bends of different curvature at identical initial conditions. Figure 8*a* corresponds to the study of [2] with the U-bend curvature radius equal to the tube diameter. Figure 8*b* corresponds to the 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 with a pressure of 18 MPa and temperature of 298 K. 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. 8*b*), while shock wave deceleration was detected in the tube with smaller curvature (Fig. 8*a*). These results correspond well with the experimental findings. Note that the tube diameter (51 mm)

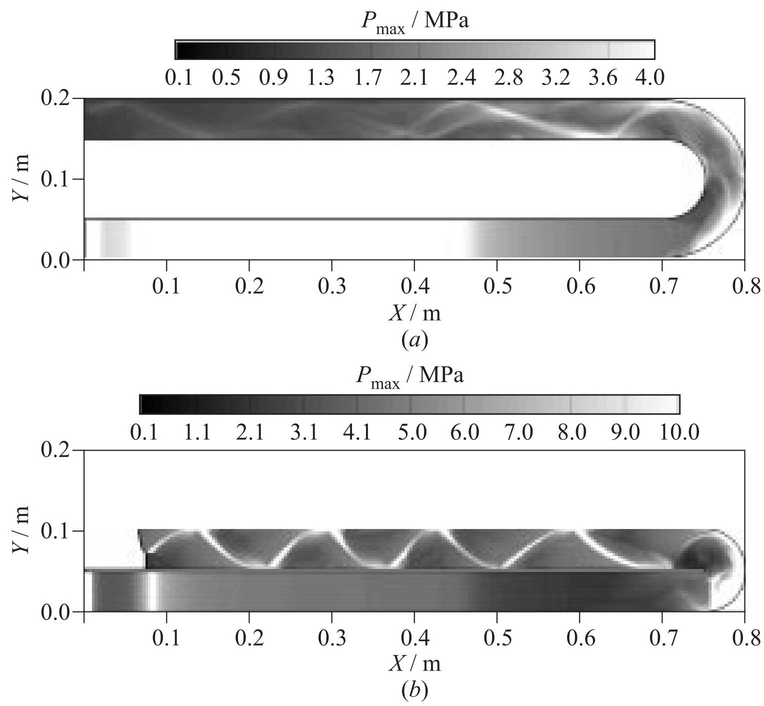

Figure 8 Predicted fields of maximal pressure at identical conditions of shock wave generation in tubes with different U-bend curvature: (*a*) no detonation, and (*b*) detonation

is close to the transverse size of a detonation cell for the stoichiometric propane–air mixture (about 50 mm). Therefore, experimental and computational results obtained herein deal with marginal detonations. It could be expected that in tubes of larger diameter, the critical phenomena like those shown in Fig. 8 will be less pronounced.

Concluding Remarks

New experimental and computational results were obtained for shock and detonation transition through U-bends in curved tubes filled with the stoichiometric propane–air mixture. The experiments demonstrated a considerable effect of the U-bend on detonation initiation and propagation and supplemented the observations reported earlier for the U-bends of smaller curvature. On the one hand, the U-bend of the tube was 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 the primary shock wave entering the first U-bend should exceed the value of about 800 m/s regardless the type of the shock wave generator used. In the tube of smaller curvature [2] (see Fig. 8*a*), the critical value of the primary shock wave velocity was at a level of 1100 m/s. On the other hand, the detonation wave propagating through the U-bend was shown to be subjected to temporary attenuation with a considerable velocity drop, followed by the recovery of the propagation velocity in the straight tube section downstream from the U-bend, or complete decay. The detonation decay was found to occur more likely in tubes with U-bends of larger curvature. The computational studies substantiated the effects observed experimentally.

The future work will be concentrated on experimental studies of the U-tubes of other diameters and the development of the physical criteria describing the shock and detonation transition in terms of U-bend curvature, tube diameter, and shock wave compression phase duration.

Acknowledgments

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