Initiation, Propagation, and Stability of Detonation Waves in Tubes with U-Bends

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The objective of the research outlined in this paper is to provide experimental and computational data on initiation, propagation, and stability of gaseous fuel – air detonations in tubes with U-bends implying their use for design optimization of pulse detonation engines (PDEs). The first results with the U-bend of a fixed curvature indicate that, on the one hand, the U-bend of the tube promotes the shock-induced detonation initiation. On the other hand, the detonation wave propagating through the U-bend is subjected to temporary attenuation followed by the complete recovery in the straight tube section downstream from the U-bend.

Introduction

Tube bends and coils are the elements, which can be used for obtaining a compact design of PDEs and ensuring reliable deflagration-to-detonation transition (DDT). Surprisingly little work has been done on the DDT and detonation diffraction in such elements.[1, 2] Our recent research on a liquid-fueled air-breathing PDE[3–5] has unequivocally demonstrated that tube coils do promote DDT efficiently. It is anticipated that depending on the tube diameter, U-bend curvature, and the characteristic lengths of tube segments attached to the U-bends, different diffractions of initiating shock waves and developed detonations can result in various transient phenomena leading to shock-to-detonation transition or failure of a developed detonation.

The objective of the research outlined in this paper is to provide experimental and computational data on gaseous fuel – air detonations propagating in tubes with U-bends and to derive theoretical criteria for evaluating detonation initiation and stability conditions in terms of tube diameter, U-bend curvature, and characteristic lengths of tube segments between two U-bends. The main configuration to be studied at the first stage of the research is shown in Fig. 1.

Experimental Setup

Figure 1 shows the schematic of the experimental setup for the studies of detonation initiation and propagation in tubes with U-bends. The setup comprises the Shock Generator, two pieces of a straight tube 51 mm in inner diameter, and a U-bend made of the tube of the same diameter. The far end of the tube opposite to the Shock Generator is closed. The setup allows replacing the U-bends to study the effect of their curvature on detonation initiation and propagation. The internal radius of the U-bend shown in Fig. 1 is equal to tube diameter, i.e., 51 mm.

The Shock Generator is 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 is filled with a solid propellant (the mass up to 1.5 g). The propellant is ignited by an igniter 0.20 ± 0.02 g in mass. The maximal pressure in the chamber is 200 MPa. The strength of the shock wave formed depends on the nozzle diameter, diaphragm thickness, and thermodynamic parameters of combustion products in the Shock Generator.

Before each run, the detonation tube is evacuated and filled with the stoichiometric propane–air mixture at initial pressure of 0.1 MPa and initial temperature of 294 ± 2 K.

The measuring system includes piezoelectric pressure transducers, analog-to-digital converter, and a PC. The pressure transducers PT0, PT1, …, PT7 are mounted along the tube as shown in Fig. 1 by solid squares. The pressure transducer PT0 is used for triggering the measuring system.

The velocity of the shock wave was calculated using the formula $V = X / \Delta t$, where X is the length of the measuring segment and Δt is the time interval determined from the records of pressure transducers. The measuring segments PT0–PT1, PT1–P T2, …, PT6–PT7

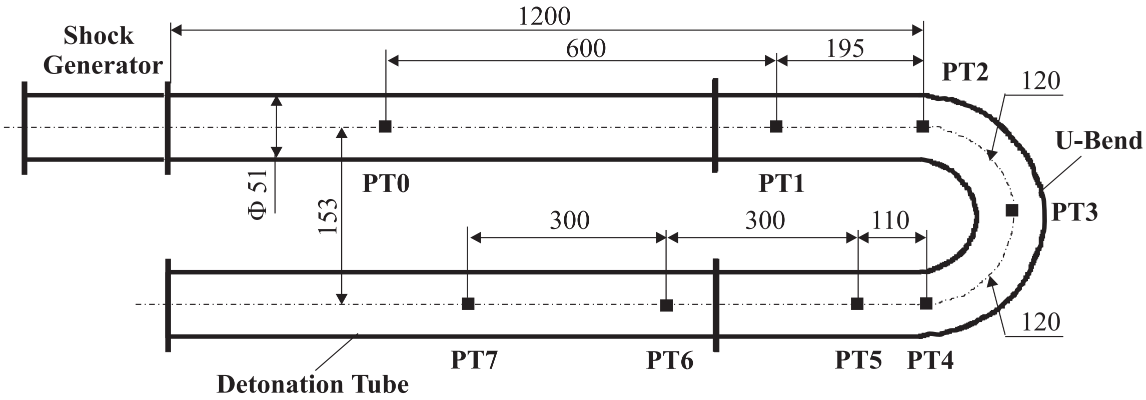

Figure 1: Schematic of the experimental setup for the studies of detonation initiation and propagation in tubes with U-bends. Dimensions are in mm

Table 1: Measured shock wave velocities (in m/s) at different measuring segments of the tube with the U-bend of Fig. 1

Measuring segment	Run 1	Run 2	Run 3	Run 4	Run 5
PT0–PT1	602 ± 6	862 ± 9	1007 ± 10	1117 ± 11	1750 ± 18
PT1–PT2	575 ± 12	805 ± 16	1083 ± 22	1242 ± 25	1741 ± 35
PT2–PT3	585 ± 20	800 ± 25	1052 ± 32	1071 ± 35	1739 ± 50
PT3–PT4	588 ± 20	759 ± 25	1071 ± 33	1263 ± 40	1690 ± 50
PT4–PT5	544 ± 17	769 ± 25	1038 ± 32	1310 ± 40	1507 ± 45
PT5–PT6	534 ± 15	696 ± 18	1215 ± 30	1754 ± 45	1744 ± 45
PT6–PT7	517 ± 13	—	2027 ± 50	1785 ± 45	—

correspond to the segments between the pressure transducers PT0 and PT1, PT1 and PT2, …, PT6 and PT7, respectively. The error in determining X is ± 0.5 mm which gives about 0.45% error for the shortest measuring segment (PT4–PT5) 110 mm long. The time interval Δt is determined at the half-amplitude levels of pressure-transducer signals. Because of the finite dimensions of the sensitive elements of the transducers, the duration of the shock (and detonation) front registration is no less than 3 μs. The characteristic sampling time of each measuring channel is 1.2 μs, which allows the resolution of the wave front with two to three samples. Thus the time interval Δt was determined with an uncertainty of ± 2.4 μs. The detonation velocity in the stoichiometric propane–air mixture is at the level of 1800 m/s. The time interval taken for the detonation wave to pass the shortest measuring segment PT4–PT5 is about 61 μs. Hence the maximal error in determining the time interval Δt is ± 4%, and the corresponding error of determining the shock and detonation wave velocity does not exceed 4.45%. The lengths of the measuring segments PT2–PT3 and PT3–PT4 in the U-bend are measured along the arc and are equal to 120 mm.

First Experimental Results

Table 1 and Fig. 2 show the shock wave velocities measured at different measuring segments of the tube in 5 representative runs: Run 1, Run 2, …, and Run 5. Note that these runs are well reproducible at similar initial conditions. Figures 3*a* to 3*d* and Fig. 4 show the pressure records registered by the pressure transducers PT1 to PT7 in these runs.

In Run 1, the mean shock wave velocity at the entrance to the U-bend (measuring segment PT1–PT2) is about 575 m/s. The velocity of the shock wave decreases

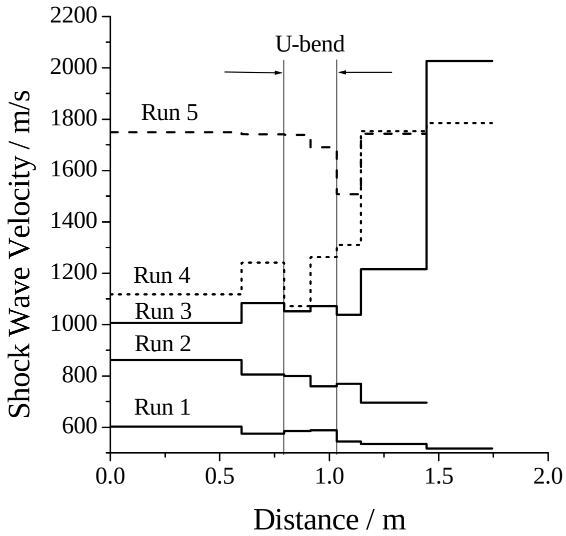

Figure 2: Mean shock wave velocities at different measuring segments of the tube with the U-bend in 5 representative runs

gradually with the distance traveled, although in the U-bend it is nearly constant (~580 m/s), see Fig. 2.

In Run 2, the mean shock wave velocity at the entrance to the U-bend is somewhat higher (about 805 m/s) than in Run 1. Nevertheless the qualitative behavior of the shock wave is similar to that in Run 1 (see Fig. 2) except for the indication of the secondary explosion on the record of PT6 at $t \approx 2200$ μs (see Fig. 3*b*). Also, at $t \approx 3400$ μs one can see the reflected blast wave appearance on the record of PT6. This blast wave propagates upstream at a velocity of 1740 m/s at the measuring segment PT5–PT6, 1530 m/s at PT4–PT5, 1580 m/s at PT3-PT4, 1645 m/s at PT2-PT3, and 1670 m/s at PT1-PT2, i.e., the reflected blast wave resembles a detonation wave in terms of its propagation velocity if one takes into account that this wave propagates upstream. Note that in the straight tube of the same length neither a secondary explosion nor a reflected, detonation-like wave were observed, other conditions being similar.

In Run 3, the mean shock wave velocity at the entrance to the U-bend is about 1083 m/s (see Fig. 2), i.e., higher than in Run 2. The shock wave traverses the U-bend at a nearly constant velocity of about 1060 m/s but suddenly accelerates to 1215 m/s at the measuring segment PT5–PT6 and to 2027 m/s at the measuring segment PT6–PT7. The latter value of the shock wave velocity corresponds to the overdriven detonation wave. The reflected blast wave appearing at $t \approx 2300$ μs on the record of PT7 (see Fig. 3*c*) propagates upstream at the velocity of 1176 m/s at the measuring segment PT6–PT7, 1235 m/s at PT5–PT6, 1295 m/s at PT4–PT5, 1165 m/s at PT3–PT4, 1481 m/s at PT2–PT3, and 1234 m/s at PT1–PT2. This wave propagates in a partially reacted mixture as indicated by the records of pressure transducers PT2 to PT5 exhibiting secondary explosions and pressure humps. Therefore its propagation velocity is lower than in Run 2.

In Run 4, the mean shock wave velocity at the entrance to the U-bend is about 1242 m/s (see Fig. 2), i.e., higher than in Run 3. When entering the U-bend, the shock wave first decelerates to 1071 m/s at the measuring segment PT2–PT3 and then accelerates to 1263 m/s at the measuring segment PT3-PT4. This acceleration is most probably caused by the secondary explosion clearly seen on the record of the pressure transducer PT3 in Fig. 3*d*. After passing the U-bend, the shock wave continues accelerating and transitions to a detonation wave propagating at a mean velocity of 1750–1800 m/s at the measuring segments PT5–PT6 and PT6–PT7. The reflected blast wave appearing at $t \approx 2100$ μs on the record of PT7 (see Fig. 3*d*) propagates upstream at the velocity of 1167 m/s at the measuring segment PT6–PT7, 1162 m/s at PT5–PT6, 1294 m/s at PT4–PT5, 1212 m/s at PT3–PT4, 1364 m/s at PT2–PT3, and 1274 m/s at PT1–PT2. This wave propagates at nearly the same velocity as in Run 3.

In Run 5, the mean shock wave velocity at the entrance to the U-bend, i.e., at the measuring segment PT1–PT2, is about 1741 m/s (see Fig. 2). At the measuring segment PT0–PT1 its velocity is about 1750 m/s. This propagation velocity is close to the Chapman–Jouguet detonation velocity for the stoichiometric propane–air mixture at normal conditions. When traversing the U-bend, the detonation wave decelerates to 1690 m/s at the measuring segment PT3–PT4 and then to 1507 m/s at the measuring segment PT4–PT5 after exiting from the U-bend. However, it accelerates again to 1744 m/s at the measuring segment PT5–PT6. The reflected blast wave appearing at $t \approx$

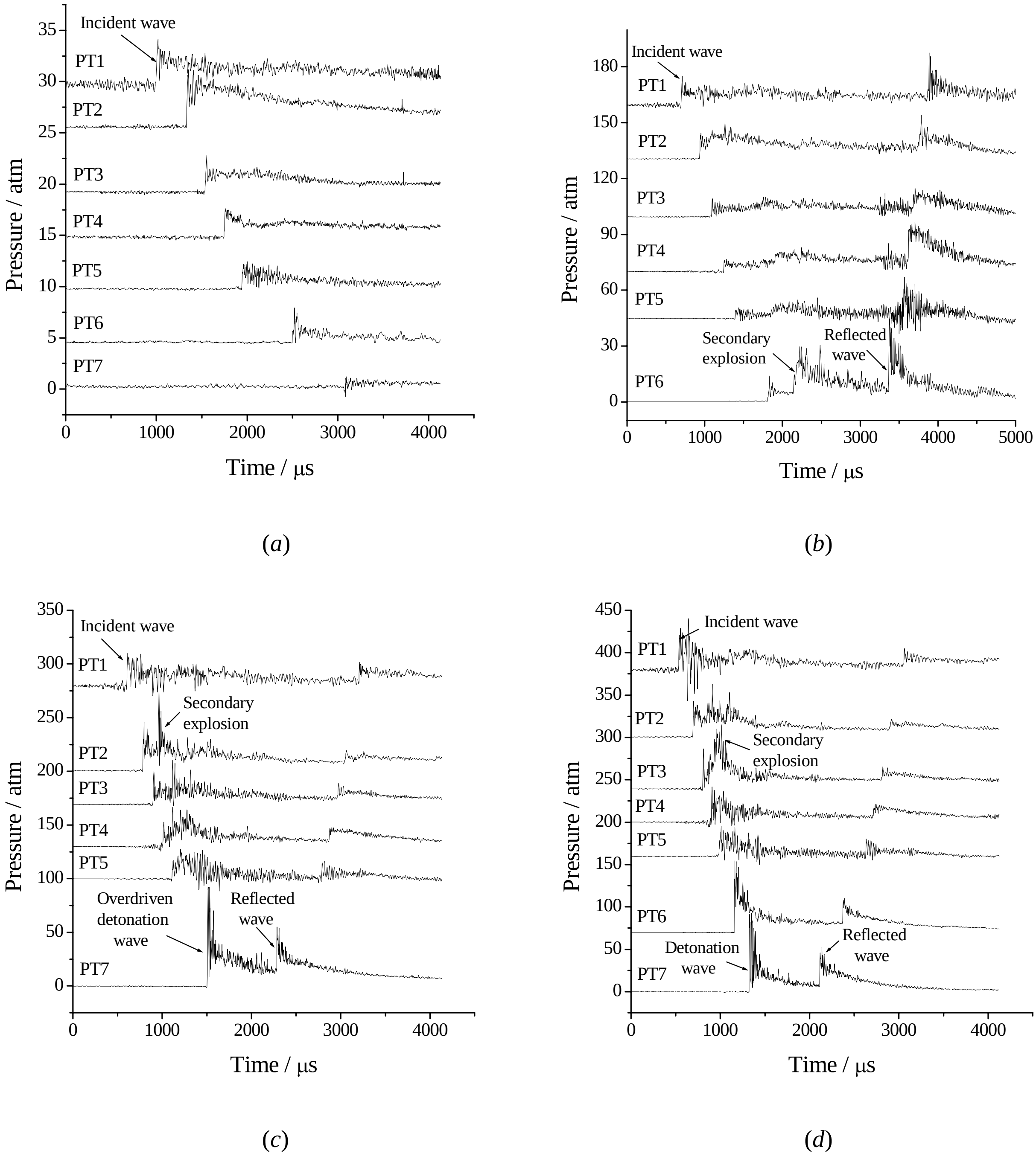

Figure 3: Pressure records registered by the pressure transducers PT1 to PT7 in Runs 1 to 4 with different mean shock wave velocities at the entrance to the U-bend (measuring segment PT1–PT2): (*a*) Run 1, V = 575 m/s; (*b*) Run 2, V = 805 m/s; (*c*) Run 3, V = 1083 m/s; and (*d*) Run 4, V = 1242 m/s

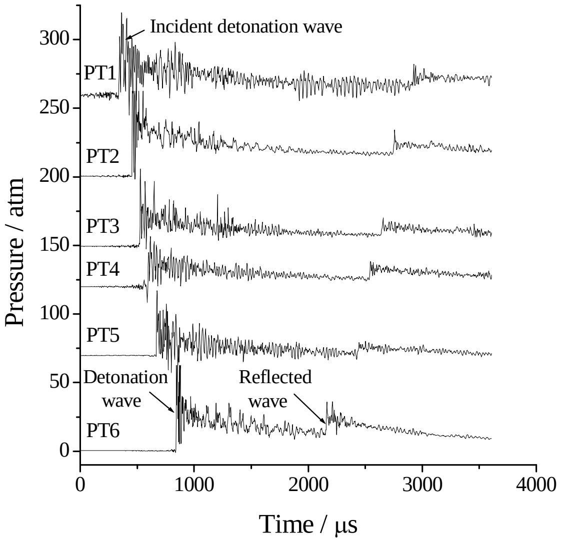

Figure 4: Pressure records registered by the pressure transducers PT1 to PT6 in Run 5 with the detonation wave at the entrance to the U-bend (measuring segment PT1–PT2), $V = 1741$ m/s

2160 μs on the record of PT6 (see Fig. 4) propagates upstream at the velocity of 1063 m/s at the measuring segment PT5–PT6, 1089 m/s at PT4–PT5, 1121 m/s at PT3–PT4, 1154 m/s at PT2–PT3, and 1174 m/s at PT1–PT2. This velocity is somewhat higher than the sound speed in the detonation products of the stoichiometric propane–air mixture (~990 m/s).

Concluding Remarks

Thus, the first experimental results obtained in a tube with a U-bend demonstrate a considerable effect of the U-bend on detonation initiation and propagation. On the one hand, the U-bend of the tube promotes the shock-induced detonation initiation as shown in Runs 2 to 4. On the other hand, the detonation wave propagating through the U-bend is subjected to temporary attenuation with the velocity drop of about 250 m/s (15% in terms of the initial propagation velocity) followed by the recovery of the propagation velocity in the straight tube section downstream from the U-bend, as shown in Run 5. The curvature of the U-bend and tube diameter are expected to be the most important governing parameter of the problem which determine the evolution of the initiating shock wave or a developed detonation wave in such a system. The future work will be concentrated on further experimental and computational studies of the encountered phenomena aimed at elaboration of the quantitative criteria to predict relevant critical conditions.

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