# Numerical and Experimental Investigation of Detonation Initiation in Profiled Tubes

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## 1 Introduction

Shaping of tube walls – is the novel way of shock-induced detonation initiation without additional energy input. Such a way of detonation initiation is promising for advanced propulsion systems operating on pulse detonations.

It has been shown numerically and experimentally [1] that proper shaping of regular obstacles in the rectangular channel filled with a gaseous explosive mixture can significantly decrease shock-to-detonation transition (SDT) time and distance. The numerical investigation of SDT was continued in [2]. The mechanism of SDT in a round tube with a localized parabolic contraction of the cross section followed by the conic expansion with smooth walls was analyzed qualitatively and quantitatively. Three stages of SDT phenomenon have been identified, namely, (1) double Mach reflection of the lead shock wave (SW) from the curved wall, (2) local explosion(s) due to the cumulation of Mach stem or (and) reflected SW, and (3) detonation reinitiation due to interactions of the blast waves from the local explosions with the conic expansion.

To validate the numerical findings of [2], a set of experiments has been performed. This paper presents the results of these experiments as well as the results of further numerical studies aimed at optimizing the cone expansion part of wall profile.

## 2 Computational study

The round tube of diameter $D$ comprised three sections: Section 1 with constant cross-section, Section 2 with a shaped contraction-expansion, and outlet Section 3 with constant cross-section (Fig. 1). Initially, the tube is filled with the homogeneous, quiescent, stoichiometric mixture of propane, oxygen, and nitrogen under normal conditions. The wall profile in Section 2 is given by the parabolic curve $z(r)$. The parabolic shape $z(r)$ was chosen to meet the following constrains: (i) the focus of the parabola should lie in the free flow at the tube symmetry axis, (ii) the blockage ratio of contraction, $BR = 1 - (d/D)^2$, should not exceed a certain maximum value; and (iii) angle $\varphi$ should not also exceed a certain limiting value. Twelve different values of angle $\varphi$ ranging from 5° to 90° and three values of $BR$ were investigated. At time zero, the incident shock wave (ISW) of Mach number $M$ and constant post-shock flow was assumed to enter the computational domain through the inlet.

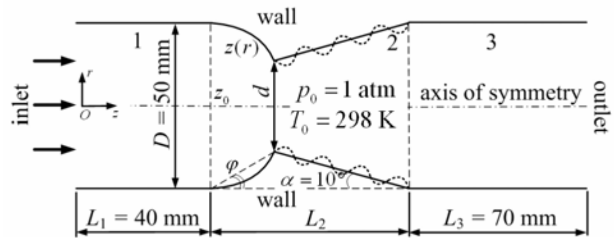


Figure 1 – Statement of the problem.

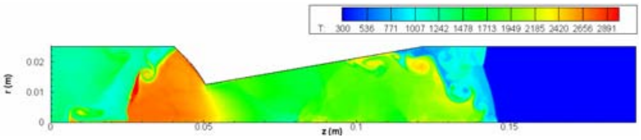


Figure 3 – Detonation initiation failure in a tube with parabolic contraction and smooth conic expansion at $M$ = 2.7, $\varphi$ = 50°, $BR$ = 0.75. Predicted field of temperature (in K). Time 137 μs.

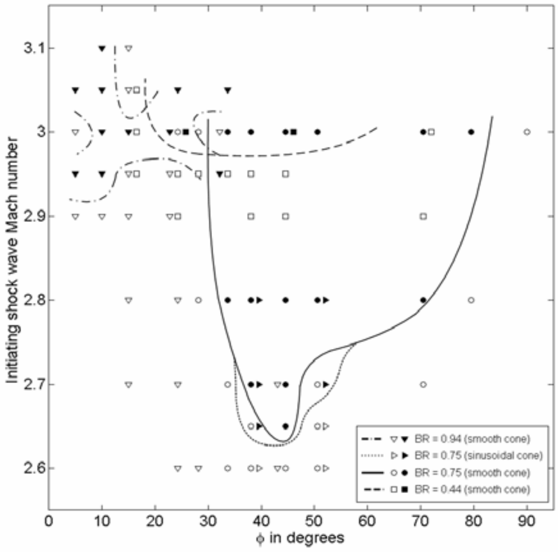


Figure 2 – "Detonation curves": open symbols – SDT "no go", closed symbols – SDT "go" conditions.

The problem was solved for the lower part of the tube (see Fig. 1) using symmetry conditions at the upper boundary (symmetry axis), slip condition at the lower boundary, and zero-gradient outflow condition at the right boundary.

The mathematical statement of the problem was based on the set of equations for the axisymmetric, two-dimensional, transient flow of inviscid, compressible, multicomponent, explosive gaseous mixture. Propane oxidation was modeled by a single-stage overall reaction. The numerical procedure for solving Euler equations was based on the principle of splitting various physical processes and the finite volume approach with the explicit time integration scheme and second-order Godunov scheme for fluxes. The numerical algorithm for parallel computing was used [3].

As a result of numerical simulation of shock wave transition through the contraction with various values of $\varphi$, blockage ratio, and ISW Mach number in the case with smooth cone expansion, the "detonation curves" shown in Fig. 2 were plotted. At $BR$ = 0.75, the curve exhibits a pronounced minimum at $M$ = 2.65 and $\varphi$ = 45°. The grater $M$, the broader the interval of $\varphi$ where SDT was observed in the calculations. In view of the fact that at $\varphi$ = 45° SDT is always obtained at $M$ > 2.65, this shape will be referred to as «optimal» for $BR$ = 0.75. This shape has been chosen for experimental validation.

To optimize the shape of the wall profile, the conic expansion with wavy (sinusoidal) wall was considered (dotted curve in Fig. 1). Such wall pattern is determined by the number of sine periods on the expansion length and sine amplitude.

Figure 3 shows the failure of detonation initiation in a tube with the smooth-walled conic expansion. The sinusoidal shaping of the conical expansion wall leads to detonation initiation, other conditions being equal (Fig. 4b). In the latter case, the mechanism of SDT is as follows. The first and the second deepening of the sinusoidal conic surface appear to get filled with the preheated explosive mixture before the blast wave from the local explosion on the tube axis reaches the conic surface. This preheating is caused by the reflection of the lead SW from the sinusoidal wall. Therefore, successive autoignitions occur in the first two deepenings followed by further local explosions in the deepenings located downstream (Fig. 4a) in the course of blast wave propagation along the wall. This stage-by-stage blast wave amplification results in the SDT. Thus the sine-shaped conic expansion provides the results somewhat similar to those obtained experimentally with traveling ignition pulses [4]: a local explosion in each subsequent deepening plays the role of a successive igniter.

Note that the limits of SDT for the wall profile with the sinusoidal conic expansion were always wider than those for the smoothed-walled conical expansion (see Fig. 2).

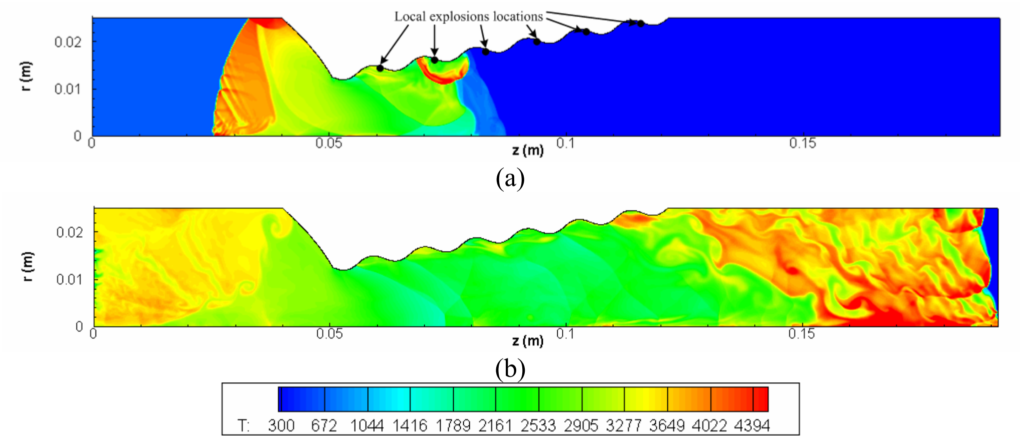


Figure 4 – Detonation initiation in a tube with parabolic contraction and sinusoidal conic expansion under conditions similar to those in Fig. 3. Predicted fields of temperature (in K). The upper snapshot corresponds to time 90 μs, the lower to 140 μs.

## 3 Experimental study

Figure 5 shows the experimental setup. Experiments were performed in a straight tube 3870 mm long and 52 mm in internal diameter with the stoichiometric propane – air mixture. Before each experiment the tube was evacuated and filled with the mixture. In all experiments, the initial mixture pressure and temperature were 1 bar and 295 ± 2 K. Shock waves were generated by a solid-propellant gas generator (GG) installed at one end of the tube. The other end of the tube was closed.

The GG was a cylindrical chamber 22 cm$^3$ in volume. It was equipped with a changeable exhaust nozzle with an orifice of 5 to 14 mm in diameter closed with a bursting diaphragm made of copper foil. The detailed description of GG can be found elsewhere [5]. A low-frequency piezoelectric pressure transducer of T6000 type was installed in the GG (transducer PT1 in Fig. 5).

At a distance 2113 mm from the GG orifice, an axisymmetric obstacle of "optimal" shape (with $\varphi$ and $\alpha$ equal to 45° and 10° respectively) was installed in the tube. To register wave phenomena in the tube and to determine the mean shock wave velocity at different measuring segments, high-frequency piezoelectric pressure transducers PT2 to PT9 of LKh600 type were used. Signals of all pressure transducers were registered using a PC and analog-to-digital converter L-Card L-783. The registration system in all experiments was triggered when the signal voltage at pressure transducer PT1 attained a certain preset value. Before each experiment, the GG was filled with a grained cotton powder of the mass ranging from 2 to 3 g. The powder was ignited using a primer igniter 0.3 g in mass. The maximal pressure in the chamber was 50 to 150 MPa. The strength of the SW formed depended on the nozzle diameter, diaphragm thickness, and thermodynamic parameters of combustion products in the shock generator.

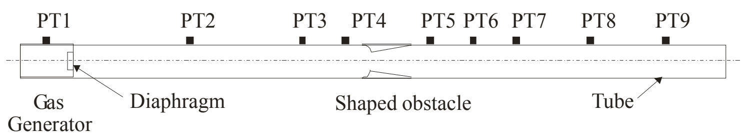


Figure 5 – Experimental setup.

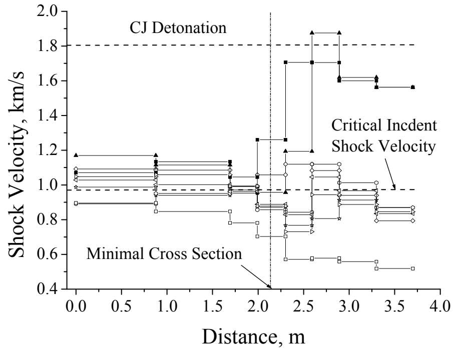


Figure 6 – Mean SW velocity at different measuring segments vs. distance.

Figure 6 shows the lead SW velocity at different measuring segments 0–PT2, PT2–PT3, PT3–PT4, PT4–PT5, PT5–PT6, PT6–PT7, PT7–PT8 and PT8–PT9 in 8 representative experiments. The measuring segment 0–PT2 corresponded to the distance between GG nozzle exit and PT2 transducer (877 mm). The dashed vertical line (distance 2130 mm) in Fig. 6 corresponds to the minimal cross section of the obstacle. The dashed horizontal line corresponds to the Chapman-Jouguet detonation velocity of 1804 m/s. The mean SW velocity at each measuring segment was determined based on the distance between the pressure transducers and the time taken for the SW to traverse this distance. The error of determining the SW velocity is estimated as 3%. Figure 6 shows that the SDT occurs when the ISW velocity exceeds a certain minimal (critical) velocity value. For the 52-mm tube, this critical velocity is equal to $970 \pm 30$ м/с. For the stoichiometric propane – air mixture this velocity corresponds to the SW Mach number of $M \approx 2.85$. This value is close to that predicted by the numerical simulation ($M \approx 2.65$). Note that at $M < 2.85$, the pressure histories at transducers PT5 – PT8 indicate the existence of strong secondary blast waves behind the lead SW. The detonation arising behind the wall profile seems to decay due to relatively sharp conical expansion. Further calculations and experiments are planned to show the effect of the cone expansion angle.

# 4 Concluding remarks

The computational and experimental studies of SDT in a round tube with profiled wall have been performed. Proper shaping of wall profile was shown to promote SDT.

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