Detonation Diffraction from Circular Tubes to Cones

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Abstract

An experimental study of the detonation diffraction from 26 and 52-mm inner diameter tubes to cones of various angles in stoichiometric acetylene/oxygen mixture allowed us to determine critical conditions and to reveal new details of the mechanisms involved. All soot-foil records show that critical transmission is due to super-detonation propagating transversally in shocked gas before the decoupled flame front. However, at large cone angles super-detonation originates at the axis of flow and propagates tangentially to the cone wall (this situation is close to detonation transmission to a half-space). On the opposite, at smaller angles super-detonation originates at cone wall and propagates towards the axis. In addition, at intermediate cone angles the soot plates often give some evidence that during escape of detonation products from the tube a Mach disk is formed at a distance of about one tube diameter from the tube exit. Numerical two-dimensional simulations of detonation diffraction favorably agree with the observations.

Introduction

G. Thomas et al. (1985) conducted a thorough study of critical transmission of detonation waves in two-dimensional channels with rectangular cross-section at different values of divergence angle and ratio of channel width to its thickness. They also analyzed results obtained by other teams involved in similar studies and demonstrated that near the critical conditions "explosion re-initiation occurs along the walls, which results in the formation of two transverse detonation fronts which propagate along the decoupled shock reaction front and collide at the centre along axis". The purpose of the present study is to extend the data obtained by G. Thomas et al. (1985, 2002) for rectangular channels and those obtained by Borisov et al. (1989) in tubes by the data corresponding to axisymmetric flows in acetylene/oxygen mixture and to analyze the observed trends numerically.

Experimental Study

We have studied detonation transition from a tube to a cone in a stoichiometric $C_2H_2+2.5O_2$ mixture at room temperature using the set-up sketched in Fig. 1. A 4-m long and 52-mm i.d. detonation tube was connected to a large 500-mm long and 380-mm i.d. chamber. The diameter of the final 140-mm long section of the tube was reduced to 26 mm by means of a cylindrical insert. Another series of experiments was performed with no insert, so that our results correspond to i.d. tubes of 26 and 52 mm. Conical pieces were fixed at the tube exit on the chamber wall. To analyze the detonation diffraction and determine critical conditions we have varied cone expansion angle α between 5° and 55° and for each value of α we have studied the effect of the initial pressure P_o. All the events related with detonation transmission were recorded on a smoked plate located at the axial plane. Detonation velocity before the outlet section of the tube was close to the CJ velocity within 1% as measured by ionization probes and pressure gauges.

Soot records in Fig. 2 show failure of transition at P_o=0.03 bar and divergence angle α=15°. Increase of initial pressure to 0.035 bar at the same divergence angle results in detonation transition (Fig.3). Thus, a critical transition pressure exists at a given α. In both cases detonation quenches during the initial stage of expansion of detonation products and front of the flame decouples from the shock front. Successful detonation re-initiation results from a few successive detonation onsets (and quenchings) in the layers of pre-compressed fresh mixture between the decoupled flame front and the diverging shock. These layers manifest themselves by very fine detonation cells at the periphery of the bubble of detonation products.

Figure 3 shows that the super-detonation arises at first at the cone wall at a large distance from the tube exit, about 2 tube diameters, and then it propagates in transversal direction to the axis along the narrow layer between the shock front and decoupled flame front. Until implosion takes place at the tube axis, the primary super-detonation is too weak to ignite the fresh mixture. After the implosion, the reinforced super-detonation continues its propagation to the opposite cone wall. Nevertheless, this super-detonation eventually dies out despite the subsequent impact against the opposite wall. Finally, detonation re-initiation takes place at the same cone wall where primary super-detonation was born but at a distance of about 3 tube diameters where thickness of the pre-shocked layer between the flame front and the shock front has become significantly larger than at the instant of birth of the primary super-detonation. Figure 3 shows a strong asymmetry of the flow pattern during detonation transition in agreement with earlier observations by Borisov et al. (1989). One can see that, at smaller divergence angles, the super-detonation originates at the wall and then propagates to the axis resulting in implosion (in contrast to detonation diffraction to a half-space, α=90°, where super-detonation originates at the axis of the flow and propagates tangentially to the flow of expanding products from the axis to the wall).

Figure 4 shows flow pattern drawn by detonation at the same divergence angle (α=15°) as in Fig.3 but at a higher initial pressure (P_o=0.04 bar). Apparently, the asymmetry of the flow becomes less important and the distance to a cross-section of formation of first super-detonation significantly shortens with increase of P_o. Figure 5 shows detonation quenching at P_o=0.04 bar due to further increase of divergence angle to 25°. Thus, critical transition pressure increases with divergence angle in agreement with earlier observations (Thomas et al., 1985).

Figure 3 to Fig.5 show some black areas near the tip of the extinction cone drawn by trajectories of the triple points. Hence, formation of these black areas occurs both at transmission and quenching. Finally, comparing, for example, Fig.2 and Fig.4 one can also see that the number of detonation cells in the undisturbed flow before the tube exit increases with initial pressure.

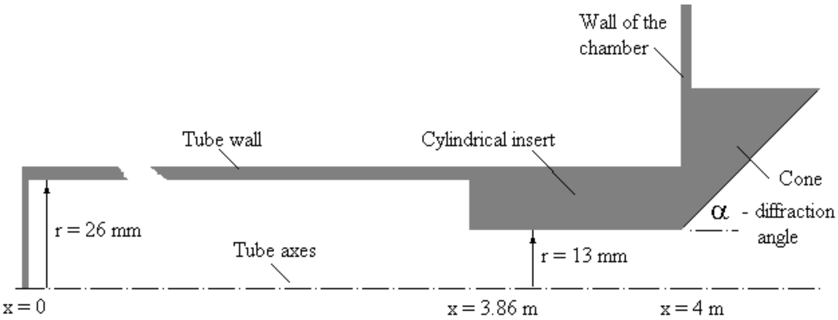

Figure 1. Scheme of experimental setup

Figure 6 summarizes experimental results on critical transition pressure at different values of divergence angle α for the case of 26-mm tube diameter. Experimental results corresponding to failure of transition ("no go") are shown by open circles while solid circles correspond to successful detonation transition ("go"). At a given α the detonation transition takes place above the solid curve, i.e. higher initial pressure favors transition. At initial pressures P_o above 0.07 bar and divergence angles above 40° the transition to detonation in the tested mixture occurs independently on P_o or α and is due to implosion at the axis. However, in rectangular channels the threshold value of α is closer to 55°, as found by Thomas et al. (1985), while Borisov et al. (1989) found that the threshold α is about 60°. Figure 7 presents our results for both tube diameters as a dependence of ratio of critical number of detonation cells on divergence angle. Thus, the detonation transmission in the considered mixture takes place regardless of the cone divergence angle and tube diameter if the number of cells in the tube is at least 12 (which is close to the famous critical ratio of critical tube diameter d_c to detonation cell thickness, i.e. d_c/λ =13, for detonation transition to a half-space).

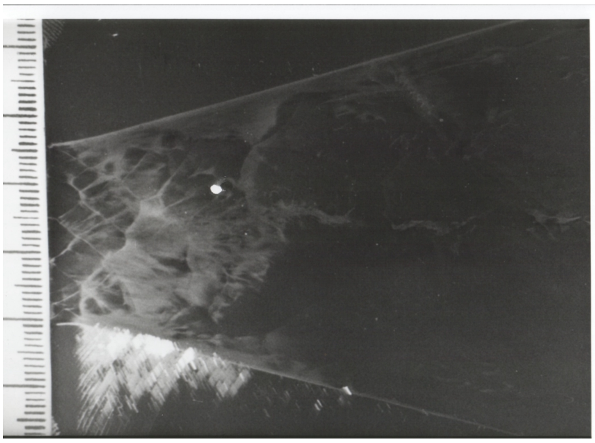

Figure 2. Soot-plate record after detonation extinction at P_o=0.03 bar and α=15°.

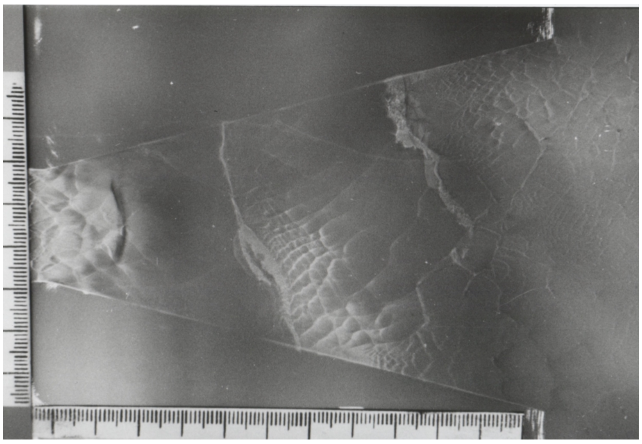

Figure 3. Soot-plate record after detonation transition at P_o=0.035 bar and divergence angle α=15°.

Figure 4. Soot-plate record demonstrating detonation transition at P_o=0.04 bar and α=15°.

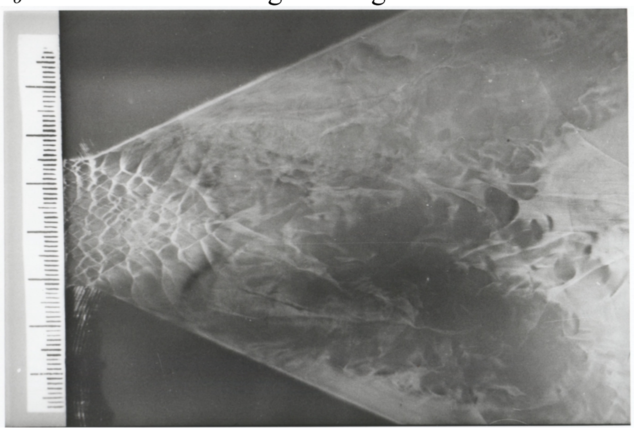

Figure 5. Soot-plate record showing detonation extinction at P_o=0.04 bar but higher α=25°.

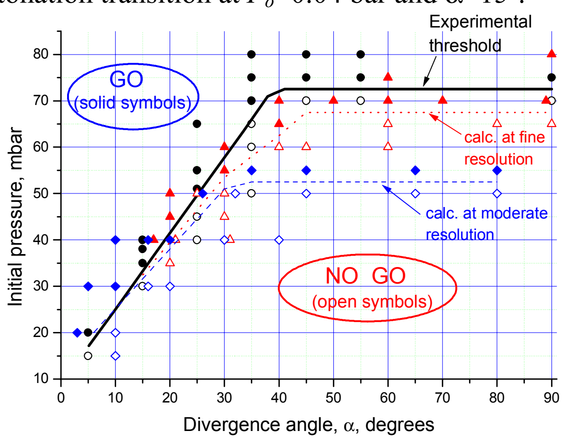

Figure 6. Dependence of critical pressure on divergence angle for 26-mm diameter tube. Triangles and diamonds show numerical results.

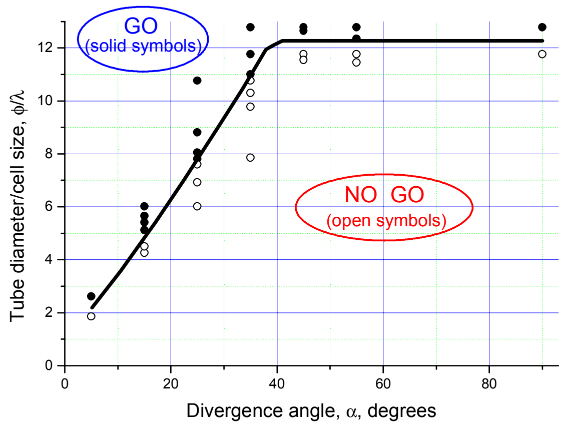

Figure 7. Dependence of ratio of tube diameter to critical detonation cell size for both 26- and 52-mm diameter tubes.

Numerical Study

Using the LCPFCT technique developed by Oran and Boris (1987) we have performed 2D axially symmetric numerical simulation of critical detonation transmission from a tube to a cone in the same way as we have simulated transition from a tube to a half-space through an annular orifice in stoichiometric C_2H_2/O_2 mixture (Khasainov et al., 2001). Figure 8 and Fig.9 show calculated traces of maximum pressure at P_o=0.03 bar and α=15° and 10° respectively. One can see that the shape of the diverging shock is very complicated and that smaller divergence angle favors formation of triple points at the cone wall and transition to detonation.

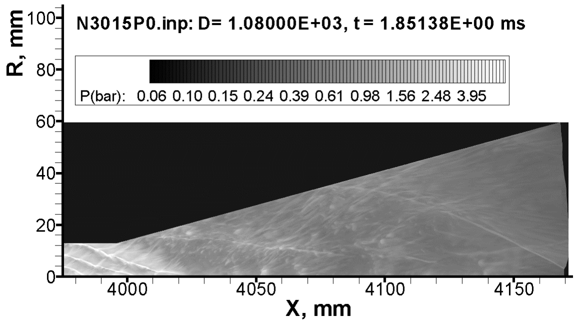

Figure 8. Calculated traces of maximum pressure at P_o=0.03 bar and divergence angle α=15° (t=1.851 ms).

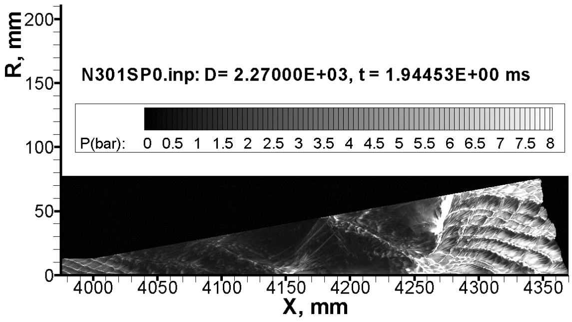

Figure 9. Calculated traces of maximum pressure at P_o=0.03 bar and α=10° (t=1.944 ms).

Comparison of Fig. 10 with Fig. 9 shows that an increase of initial pressure from 0.03 to 0.04 bar at α=15° results in detonation transition (note that P_{cj}=1.2 bar at P_o=0.04 bar).

Comparison of pressure distributions in Fig. 11a and Fig. 11b separated by 4 μs shows, in agreement with observations by Thomas et al. (1985), that super-detonation propagates from the wall to the axis of the flow. Indeed, super-detonation displays itself as a zone of high pressure coupled with fast reaction manifested by a sharp transition between the white and black color at distributions of reaction product concentration. On the contrary, surface of flame front decoupled from the shock is very irregular and transition from fresh mixture to products occurs in a much thicker zone. In addition, one can see the Mach disk near the tube exit and its position and shape reasonably correspond to those of "black" zones observed on soot records. Thus, it seems that formation of these zones is due to sharp flow deceleration at the Mach disk formed during escape of the products from the detonation tube.

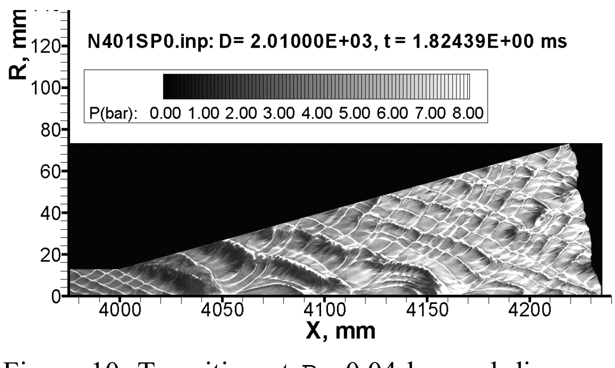

Figure 10. Transition at P_o=0.04 bar and divergence angle 15° (t=1.824 ms).

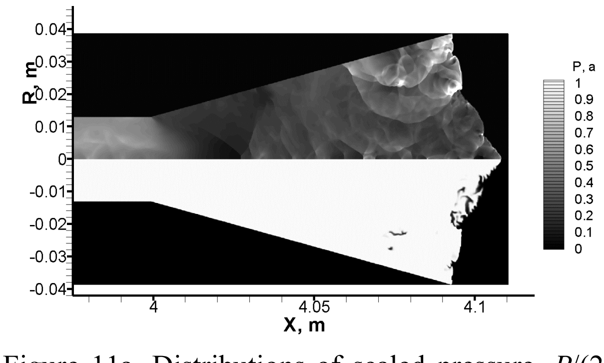

Figure 11a. Distributions of scaled pressure, P/(2 bar), (at R>0) and reaction product concentration a (at R<0) at P_o=0.04 bar, α=15°, t=1.769 ms.

Figure 12 displays, in agreement with our observations, that at high divergence angles the mechanism of transition to detonation changes to that corresponding to detonation diffraction to a half-space, when super-detonation propagates first from the axes to the wall (Khasainov, 2001).

In general, an agreement between numerical simulations and observations is good concerning flow pattern during transition and effect of divergence angle on critical transition pressure. However, since detonation cell size decreases with increase of initial pressure, namely, λ(mm)=0.1P(bar)$^{-1.2}$, and since number of numerical meshes describing each detonation cell must be approximately constant, one needs to improve resolution with increase of ambient pressure to provide acceptable agreement with observations – compare dash and dot lines in Figure 6 which correspond to mesh size of $dx=dy$=0.1 mm and 0.05 mm respectively.

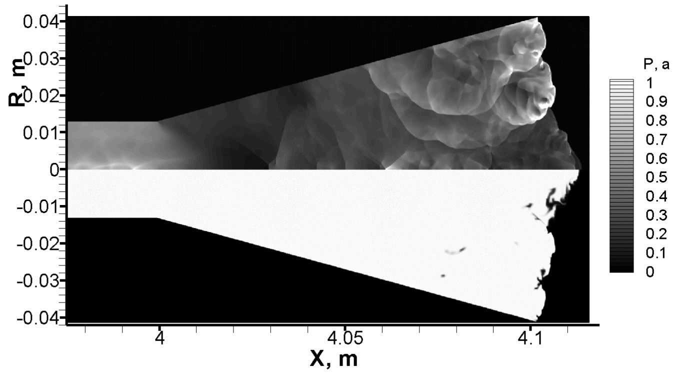

Figure 11b. Continuation of Fig.11a but at t=1.773 ms

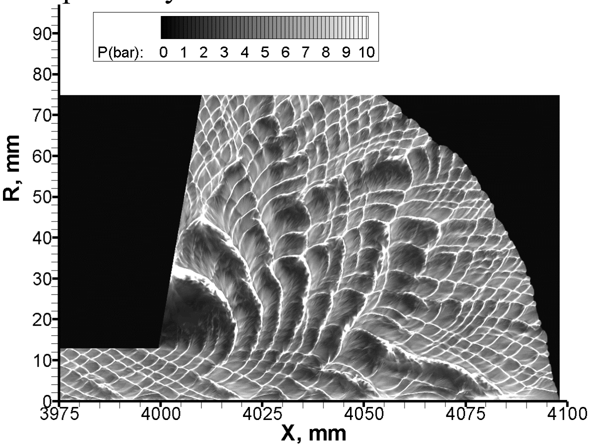

Figure 12. Transition at P_o=0.07 bar and divergence angle 70° (t=1.729 ms)

Conclusions

A study of detonation transmission in stoichiometric C_2H_2/O_2 mixture from tubes to different diverging cones allowed us to establish an empirical dependence of critical number of detonation cells on divergence angle. The soot-plate records of detonation transition improve existing knowledge of mechanism of detonation transition. All soot-foil records show that critical transmission is due to super-detonation transversally propagating in shocked gas before the flame front. At smaller angles the super-detonation originates at cone wall and propagates towards the axis. On the opposite, at large divergence angles the super-detonation originates at the axis of flow and propagates transversally to the cone wall (this situation is close to detonation transmission to a half-space). In addition, at intermediate cone angles the soot plates often give some evidence that during escape of detonation products from the tube a Mach disk is formed at a distance of about one tube diameter from the tube exit. Results of numerical modeling reasonably agree with experimental data and display all the aforementioned features.

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