A Study of Detonation Transmission for Facilitating Detonation Initiation in Pulse Detonation Engines

Extended Abstract Submitted to
the 18th International Colloquium on the Dynamics of Explosions and Reactive Flows

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The pulse detonation engine (PDE) is a propulsion concept based on using the high pressure generated by repetitive detonation waves [1-4]. In the PDE operation, detonation waves are initiated repeatedly in the PDE tube and a fresh combustible mixture is introduced into the tube accordingly to provide fuel for the detonation. However, there are significant difficulties in initiating and sustaining a detonation in a PDE tube of practical sizes. One possible approach to overcome the initiation difficulty is to use a smaller tube (pre-detonator/initiator) in which detonation waves can be initiated relatively easily and, then, use this detonation to initiate detonation in the main PDE tube. Another approach is to initiate detonation in a more energetic mixture and, then, let this detonation travel into the less detonable, main mixture. In both approaches, the key issue is survivability of the detonation after the transition.

Detonation transition or diffraction from tubes of one size or geometry into another is a classical area of detonation research [5-10]. In the past, different detonation diffraction problems in the same mixture have been extensively studied. One of the major contributions of the past work on detonation transmission has been the development of the concept of the "critical tube diameter", d_c for detonation transmission from a circular tube. If a detonation is propagating in a tube that is smaller than d_c, then it will fail when it encounters a sudden expansion into an unconfined volume containing the same mixture [5]. Schlieren records of the detonation transmission phenomena can be found in the review of Oppenheim and Soloukhin [11]. Mitrofanov and Soloukhin [12] appear to be the first to propose that a minimum of 10-13 detonation cells are required in the primary tube for successful detonation transmission in oxygen-acetylene mixtures. Edwards et al. [13] and Edwards and Thomas [14] provided further evidence for the 13L (cell width) link between the cell size and the critical tube diameter. Since then, the universality of this empirical correlation has been confirmed for a variety of fuel-air mixtures [15-17]. Although a detailed theoretical or numerical justification has not been presented for the 13L correlation, heuristic arguments have been provided in the review of Lee [5]. If the cell width for hydrocarbon-air fuels is of the order of a cm, these results imply that the pre-detonator tube should be of the order of 10's of cm to ensure successful initiation in the larger detonation (or thrust chamber) tube. This would appear to be impractical for many air-breathing propulsion applications. However, it must be remembered that the previous studies have focused on detonation transmission between different geometries but both containing the same fuel-air mixture. An alternative that may be of greater significance for PDEs is the use of a more detonable mixture in the initiator or pre-detonator. It is not clear if the past correlation is valid when the mixtures are not the same in the two tubes. Furthermore, the concept of the critical tube diameter is for the case when the second tube is of a very large diameter, that is, it can be considered to be essentially unconfined. The confining walls of the main detonation tube could also have a beneficial effect in the PDE, since it is possible that the presence of the walls will enhance the transmission of the detonation. In fact, there is some experimental evidence [18] that the walls of a tube provide a favorable influence. Using noncircular tubes is another idea that has been proposed for successful detonation transmission for PDE applications. However, experiments have shown that the 13L correlation holds for noncircular tubes provided an effective diameter is used, except for slot-shaped tubes of large aspect ratios [19]. The same study showed that the critical number of L for successful detonation transmission was about 3 for a near two-dimensional slot.

However, studies of detonation transition problems between different mixtures have been sparse. In ref. 20, we observed the successful detonation transition from a 4cm, two-dimensional channel filled with an ethylene-oxygen mixture to a 14cm, two-dimensional channel filled with an ethylene-air mixture. In the current study, we will use time-accurate numerical simulations as a tool to further investigate detonation transition problems between different mixtures in channels of the same size and between channels of different sizes. In the transition process, the detonation structure is not only affected by the geometric change of the channel, but also, more importantly, strongly influenced by changes in the property and energy content of the mixtures. We will focus on the effect of interacting waves generated at the interface of different mixtures and at the change in the channel geometry on the detonation transition. It is expected that the understanding gained from this study will provide useful guidance to overcome the initiation difficulty in the pulse detonation engine.

The conservation equations for mass, momentum, energy, and individual species are solved in conjunction with an induction parameter model. Details of this model can be found in ref. 21. The convective part of the conservation equations is solved using the Flux-Corrected Transport algorithm (FCT). This algorithm is conservative, accurate, stable, and monotonic (positivity-preserving) where the monotonicity is achieved by introducing a diffusive flux and later correcting the calculated results with an antidiffusive flux modified by a flux limiter [22]. The code used in this study consists of separate convection and chemistry modules. These modules are coupled together by a time-step splitting technique. Diffusive transport processes such as thermal conduction, molecular diffusion, thermal diffusion and viscosity, and radiation transport are not included. For the time scales under consideration in this study, the contribution from these processes will be small when compared to the dominating effect of shock-induced combustion. In this study, we employ multiple computational domains to represent different parts of detonation channel. This approach allows us to easily simulate detonation waves propagating in channels of varying geometric shape. Using the FCT algorithm, the numerical solution for every spatial point at a particular time step depends on its neighboring five grid-points in each grid direction. Therefore, an overlapping region of ten grid points is used to assure completely transparent connection between different domains.

In this study, we will simulate the detonation transition from the ethylene-oxygen mixture to the ethylene-air mixture in channels of varying geometry. Examples of geometric and mixture configurations to be studied are shown in Fig. 1. Figure 1(a) shows a straight channel filled with two different mixtures. This configuration represents the experimental setup used at the Stanford University [23], where a small amount of the ethylene-oxygen mixture is distributed near the closed end of the detonation tube to facilitate the detonation in the rest of the tube filled with the ethylene-air mixture. Figure 2 shows the detonation transition process from the ethylene-oxygen mixture to the ethylene-air mixture in this configuration from our preliminary results. It is evident that the detonation survives the transition and there are complex pressure waves generated at the interface between the two different mixtures. Configuration shown in fig. 1(b) consists of a small tube filled with the ethylene-oxygen mixture and a large tube filled with the ethylene-air mixture, representing the concept of the pre-detonator or detonation initiator used in the experiments at the Naval Post Graduate School [24]. Other configurations are also considered in this study. Detailed results will be presented at the meeting and reported in the final paper.

References

1. Nicholls, J.A., Wilkinson, H.R. and Morrison, R.B., *Jet Propulsion*, 27:534-541 (1957).
2. Eidelman, S., and Grossmann, W., "Pulse Detonation Engine: Experimental and Theoretical Review," AIAA 92-3168, July 1992.
3. Bussing, T. and Pappas, G., "An Introduction to Pulse Detonation Engines", AIAA 94-0263, Jan. 1994.
4. Kailasanath, K., "Applications of Detonations to Propulsion: A Review", AIAA 99-1067, Jan. 1999.
5. Strehlow, R.A., and Salm, R.J., *Acta Astronautica*, 3:983-994 (1976).
6. Moen, I.O., Murray, S.B., Bjerketvedt, D., Rinnan, A., Knystautas, R., Lee, J.H., *Proc. Combust. Inst*. 19: 635-645 (1982).
7. Rinnan, A., *Proceedings of the International Conference on Fuel-Air Explosions*, University of Waterloo Press, Ontario, Canada, 1982, pp. 553-564.
8. Murray, S.B., and Lee, J.H., *Combust. Flame* 52:269-289 (1983).
9. Lee, J.H.S., *Ann. Rev. Fluid Mech.*, 16:311-336 (1984).
10. Jones. D.A., Kemister, G., Tonello, N.A., Oran, E.S., and Sichel M. *Shock Waves,* 10:33-41 (2000)
11. Oppenheim, A.K., Soloukhin, R.I., *Ann. Rev. Fluid Mech.*, 5:31-58 (1973).
12. Mitrofanov, V.V., and Soloukhin, R.I., *Sov. Phys.-Dokl.* 9:1055 (1965).
13. Edwards, D.H., Thomas, G.O., Nettleton, M.A., J. Fluid Mech., 95:79-96 (1979).
14. Edwards, D.H., and Thomas, G.O., *Prog. Astro. Aero*, 75:341-357 (1981).
15. Knystautas, R., Lee, J.H.S., and Guirao, C., *Combust. Flame* 48:63-83 (1982).
16. Lee, J.H.S., Knystautas, R., and Guirao, C., Proceedings of the International Conference on Fuel-Air Explosions, University of Waterloo Press, Ontario, Canada, 1982, pp. 157-187.
17. Moen, I. O., Funk, J.W., Ward, S.A., and Rude, G.M., *Prog. Astro. Aero*, 94:55-79 (1984).
18. Dupre, G., Knystautas, R., and Lee, J.H.S., *Prog. Astro. Aero*, 106:244-259 (1986).
19. Liu, Y.K., Lee, J.H, and Knystautas, R. *Comb. & Flame,* 56:215-226 (1984).
20. Li, C, and Kailasanath, K, to appear, *Proc. Combust. Inst*. 28:(2000).
21. Li, C, Kailasanath, K., and Oran, E.S., *Phy. Fluids*, 6:1600-1610 (1994)
22. Boris, J.P. and Book, D.L., *J. Computational Physics*, 11:38-59, (1973).
23. Hanson, R. K., *Private Communication*, January, 2001.
24. Brophy, C. *Private Communication*, January, 2001

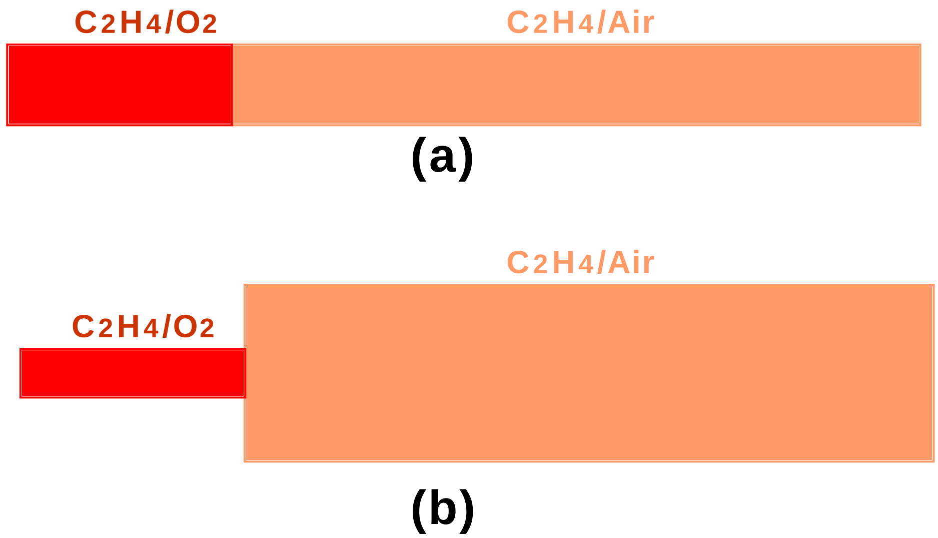

Figure 1. Examples of geometric and mixture configurations used in the study.

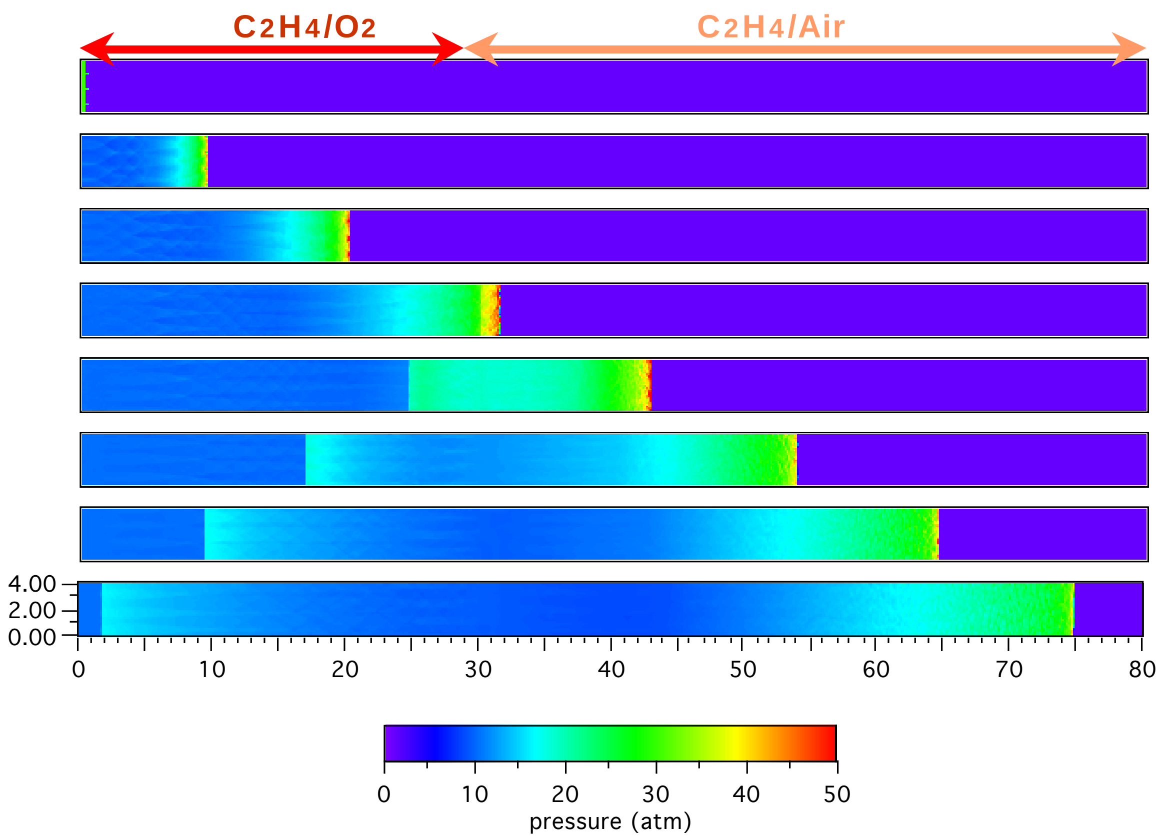

Figure 2. Detonation transition from the ethylene-oxygen mixture to the ethylene-air mixture in a 4cm, straight tube.