Effects of Nitrogen Dilution on Detonation Transmission across a Sudden Expansion in a Millimeter-scale Channel

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1 Introduction

Detonation wave transmission across a sudden expansion in a millimeter-scale channel was experimentally studied using high-speed cinematography and soot film visualization. The effects of nitrogen dilution on detonation transmission were characterized. Three detonation transmission modes were observed in stoichiometric ethylene/oxygen-enriched-air mixtures as the nitrogen dilution ratio varied.

Studies related to detonation transmission in millimeter or sub-millimeter scale channels are relatively few in the literature, but the topic is not only intriguing from fundamental combustion perspective but also important to micro/meso scale combustion and propulsion applications [1, 2]. Deflagration-to-detonation transition (DDT) is a preferred detonation initiation approach in pulsed detonation engines (PDEs) due to the lower ignition energy required [3]. A considerable distance is nonetheless necessary for the development of detonation wave from slow deflagrative flame. Recent studies have shown that DDT distance reduced with decreasing diameter in millimeter-scale tubes [4, 5]. Therefore, a pre-detonator featuring a millimeter-scale channel with a sudden expansion can potentially be the ignition source that are able to simultaneously meet the requirements in output thrust, size and ignition energy of a mesoscale PDE. Obtaining designs that ensure reliable transmission of detonation wave through the sudden expansion is crucial.

Detonation transmission in larger channels and tubes has been intensive studied [6-13]. Detonation diffraction through sudden expansion is known to be influence by the tube geometry, expansion ratio, mixture reactivity, initial pressure, etc. The ratio between tube diameter, d, and detonation cell size, λ, is known to be the key parameter deciding the transmission scenario. For d/λ larger than a critical value, detonation wave transmits across a sudden expansion without extinction. Certain run-up distance would be required for the re-initiation of detonation wave in the expanded section in cases with smaller d/λ. Three re-ignition mechanisms have been proposed in the literature [13]. However, d/λ occurred in the present study is on the order of 1, which were not within the values discussed in Ref. [13].

2 Experiment setup

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The channel assembly for the present study is shown in Fig. 1. The assembly consists of a 1 mm thick metal plate, two transparent borosilicate windows, and a pair of aluminum holders. The slot for reaction propagation is fabricated on the metal plate using electro-discharge machining (EDM). In the assembly, the plate was sandwiched between the glass windows, and further clamped between the holders. Through-holes were drilled on the two ends of the glass such that reaction gas can be fed into the channel through the adapters on the holders. The overall length of the channel is 930 mm. Ignition electrodes are installed at the center of the channel to create an adiabatic boundary condition on the symmetric plane. Width of the channel for the central section is 1 mm, and 3 mm for the outer section. The 90^o sudden expansions locate 250 mm from the ignition spot.

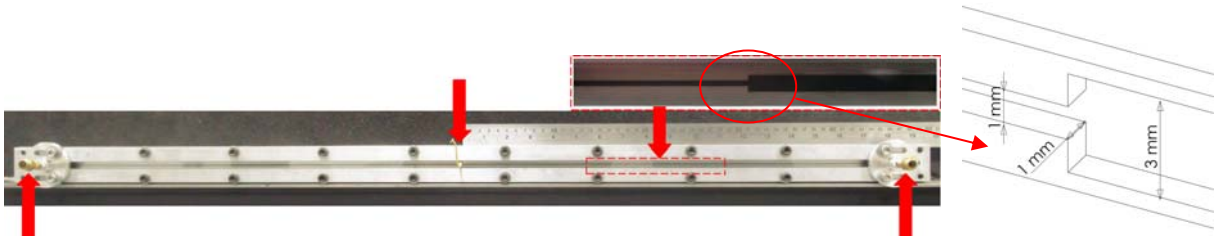

Figure 1. The channel assembly and schematic of the sudden expansion.

Premixed ethylene/oxygen/nitrogen mixtures were fed from one of the outlet adapter shown in Fig. 1. High-speed reaction wave visualizations were performed using a IDT Motionscope X3 high speed camera. For soot film visualization, kerosene soot was smoked on the inside surface of one of the glass window.

3 Results and Discussions

In the present study, the dilution ratio, δ, is defined as volumetric concentration of nitrogen in the oxidizer stream. The oxidizer stream consists of nitrogen and oxygen, so it can be considered as oxygen-enriched-air. Since the oxidizer was prepared by regulating volumetric flow rates of oxygen and nitrogen streams, dilution ratio could be calculated using the following relationship:

$$\delta = \frac{\dot{V}_{N_2}}{\dot{V}_{N_2} + \dot{V}_{O_2}} \times 100\% \qquad (1)$$

where $\dot{V}_{N2}$ is the volume flow rate of nitrogen, and $\dot{V}_{O2}$ is the volume flow rate of oxygen. It was experimentally found that DDT could only be initiated in the narrow channel for cases with δ smaller than 45 %, and deflagrative flames were observed in larger dilution ratios. But even deflagrative flame would be quenched in mixtures with δ greater than 65 %. When δ < 10%, the glass window cracked due to the excessive detonation pressure, such that no reliable data could be obtained.

High-speed visualizations of detonation wave propagation and the corresponding velocity evolutions are shown in Figs. 2(a) and (b), respectively. Velocity evolutions in Fig. 2(b) show that the reaction fronts accelerate exponentially for the first 60 mm in the narrow section. The gradient of reaction front velocity lessens as the propagation speed reaches the sonic speed of burned gas, but will eventually accelerate into DDT at 100 mm from the ignition spot in the narrow section. The overshoot in the velocity trace is a consequence of DDT. The detonation wave propagates at a velocity of approximately 2250 m/s for the remaining narrow section after the transition. This velocity is very close to the Chapman-Jouguet (C-J) velocity of 2280.4 m/s. Abrupt decrease in propagating velocity was observed as the reaction wave transmit across the sudden expansion; the reaction front decelerates to ~ 1400 m/s before re-accelerates back to a near C-J velocity in the expanded section. We define the minimum velocity measured during the transmission phase as the stall velocity, and the location where stall velocity is found as re-ignition point. The propagation velocity of the detonation wave in the

expanded section was 2318 m/s, 3 % higher than the velocity in the narrow section. The difference underscores the velocity deficit typically observed for detonation waves propagating in small channels. Fig. 2(b) also shows that the distance required for the reaction front velocity to reach C-J velocity after the sudden expansion was approximately 40 mm.

(a) (b)

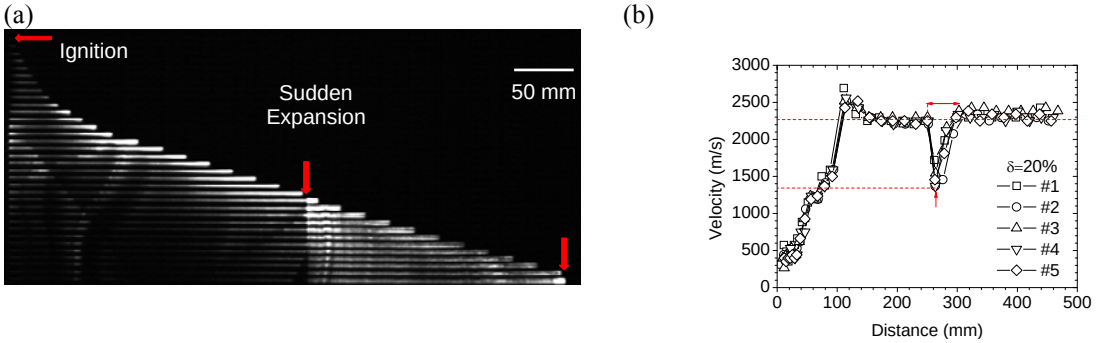

Figure 2. (a) High-speed visualization of reaction propagation in mixtures, and (b) Velocity to position chart of ethylene/oxygen flame at 20% dilution ratio. Δt between consecutive frames in part (a) was 8.6 μs.

(a) (b)

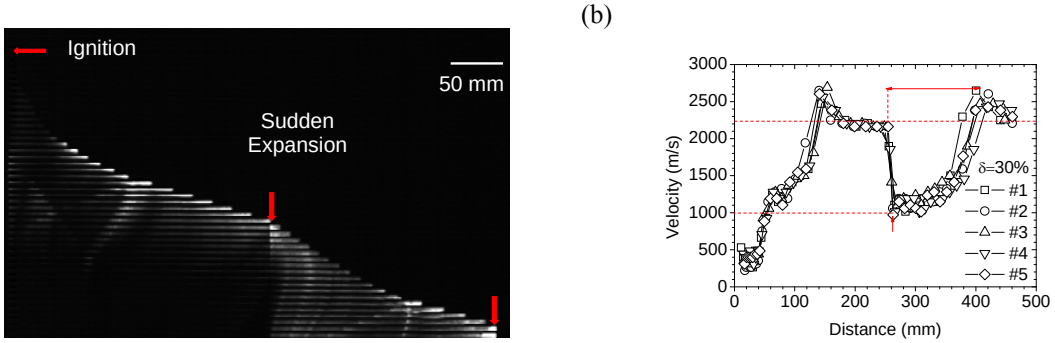

Figure 3. (a) High-speed visualization of reaction propagation in mixtures, and (b) Velocity to position chart of ethylene/oxygen flame at 30% dilution ratio. Δt between consecutive frames in part (a) was 8.6 μs.

(a) (b)

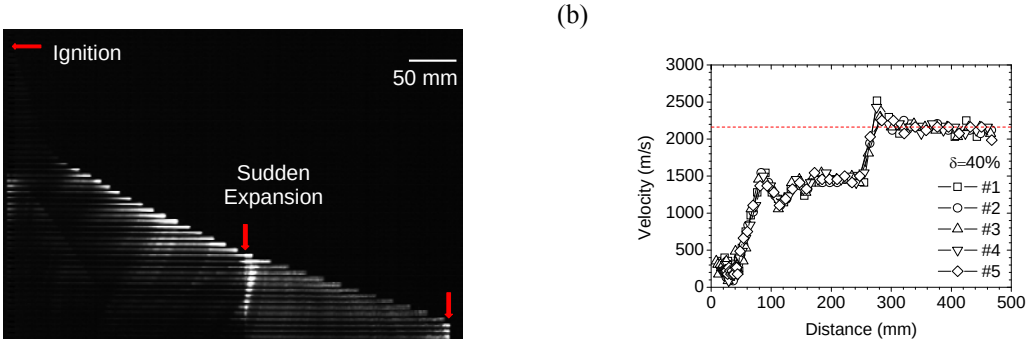

Figure 4. (a) High-speed visualization of reaction propagation in mixtures, and (b) Velocity to position chart of ethylene/oxygen flame at 40% dilution ratio. Δt between consecutive frames in part (a) was 8.6 μs.

Results of high-speed visualization and propagation velocity characterization for the case with 30% N_2 dilution in the oxidizer were shown in Fig. 3(a) and (b). Comparing Fig. 3(b) and Fig. 2(b), the most significant differences are the recovery distance and the existence of velocity overshoot in the expanded section. The propagation velocity of the detonation wave in the δ = 30 % mixture stalls to a velocity of approximately 1000 m/s in a few mm downstream of the sudden expansion; follows by re-acceleration. The re-acceleration process is milder than the case with lower dilution ratio; however, the

terminal velocity before the reaction front reaching the channel exit can still exceed C-J velocity. Velocity overshoot typically appeared in the velocity evolution of DDT process can be found at 150 mm downstream of the sudden expansion (400 mm from the ignition spot). It is likely that when the weaker detonation wave transmitted through the sudden expansion, the energy of detonation wave was not enough for direct initiation of detonation in the wider channel; the detonation wave was instead fomented through gradual pressure accumulation caused by the wall effects, and eventually resulted in DDT. Consequently, the recovery distance was 4 times longer than the $\delta = 20\%$ case.

Fig. 4 shows the high-speed visualizations and reaction front velocities for mixtures with 40% dilution ratio. The mixture was not sensitive enough for the reaction wave to reach C-J detonation in the narrow section. The detonation wave dwelled at a steady low-speed detonation mode after initial acceleration. The propagation velocity of the low-speed detonation mode was ~ 1500 m/s; interestingly, the propagation velocity increased to near C-J velocity after the reaction wave passing through the sudden expansion (Fig. 4(b)). The step increase in propagation velocity at the sudden expansion happened almost instantaneously, which took less than 15 mm (~10 μs) to accomplish.

Effects of dilution ratio on stall velocity and recovery distance are shown in Fig. 6(a) and (b), respectively. For $\delta \leq 20$ %, the stall velocity is approximately 1300 m/s, and evolutions of detonation wave transmission resemble the case shown in Fig. 2. Stall velocity for mixtures with δ between 25 % and 35 % is approximately 1000 m/s, and the reaction fronts propagate in the mode shown in Fig. 3. These two modes of detonation recovery owing to the difference in dilution ratio can be more clearly identified as recovery distances are compared in Fig. 6(b). Recovery distance is defined as the distance between the location of sudden expansion and where the reaction front re-accelerates back to near C-J velocity. With mixtures having less N_2 dilution, it takes only 40 mm for the reaction wave to reach C-J velocity after stalling at the sudden expansion; however, in mixtures with δ greater than 25%, the recovery distance increases to 160 mm. For mixtures with more than 35% N_2 in the oxidizer, the reaction wave propagates in a mode as shown in Fig. 4. Velocity stall is not observed in this mode; hence, characterizations of stall velocity and recovery distance are not possible.

(a) (b)

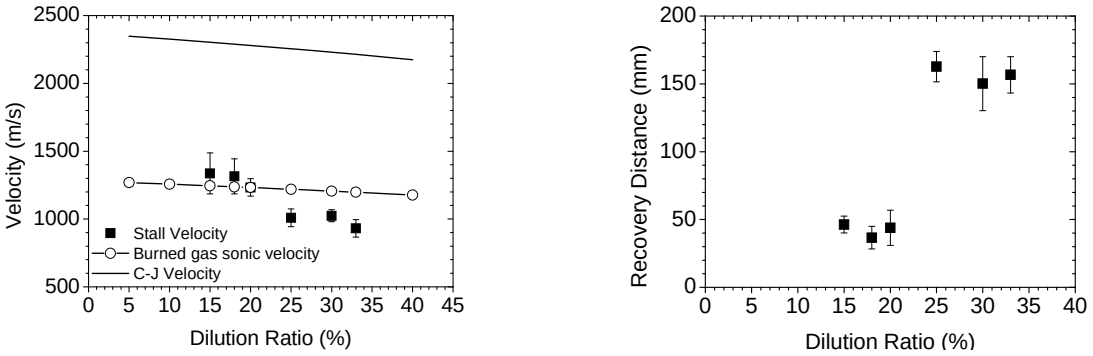

Figure 5. (a) C-J velocity to stall velocity chart with different dilution ratio, and (b) Recovery distance to dilution ratio chart.

Soot film visualizations were also performed to characterize cell structures. Images showing extinction cone downstream of the sudden expansion and the development of detonation cells in the expanded section for the $\delta = 20$ % case is presented in Figs. 6. Corresponding soot film visualization for the $\delta = 30$ % case is shown in Figs. 7. A large cone structure can be seen on the expanded side of the sudden expansion (Fig. 6(a)). The length of cone is between 4 - 5 mm long. Tips of the extinction cones locate at where the stall velocities occur in Fig. 2(b). Figs. 6(c) and (d) are the images showing the soot film structures further downstream of the expanded section. Mesh-like cell structures resulting from multi-

head detonation wave propagation are observed. Initial detonation cell size is smaller than 1 mm, and it grows to approximately 1.5 mm.

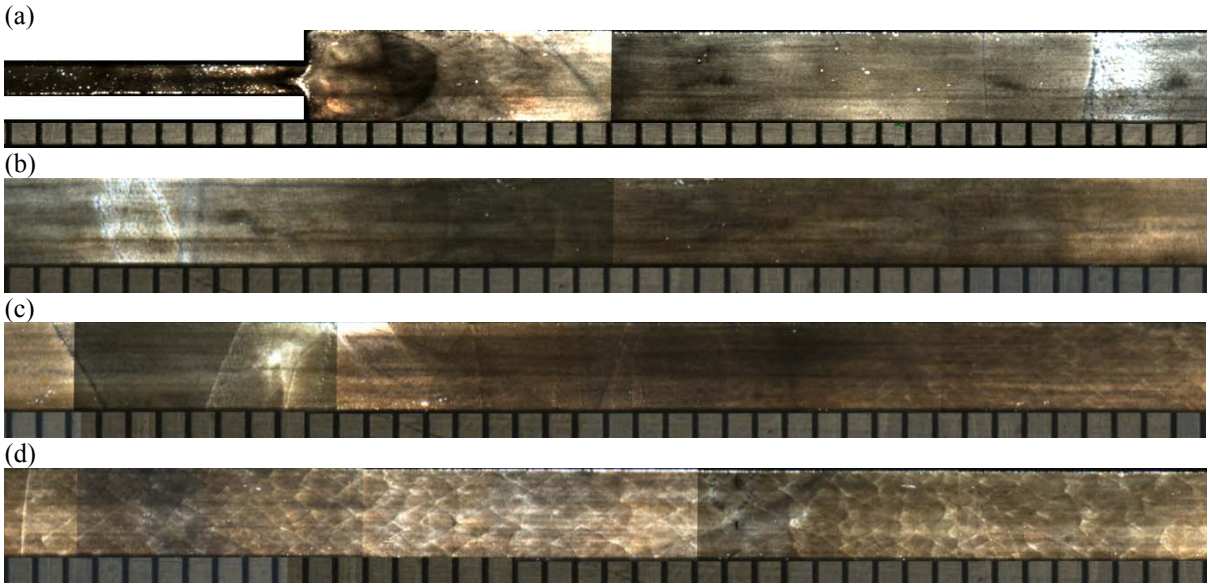

Figure 6. Soot film visualization of stoichiometric ethylene/oxygen, δ=20% in a channel with sudden expansion, flame propagates from left to right. Left edge of the image is at (a)240 mm, (b)280mm, (c)320mm, (d)360mm, from the ignition point; distance between ruler marks below each picture is 1 mm.

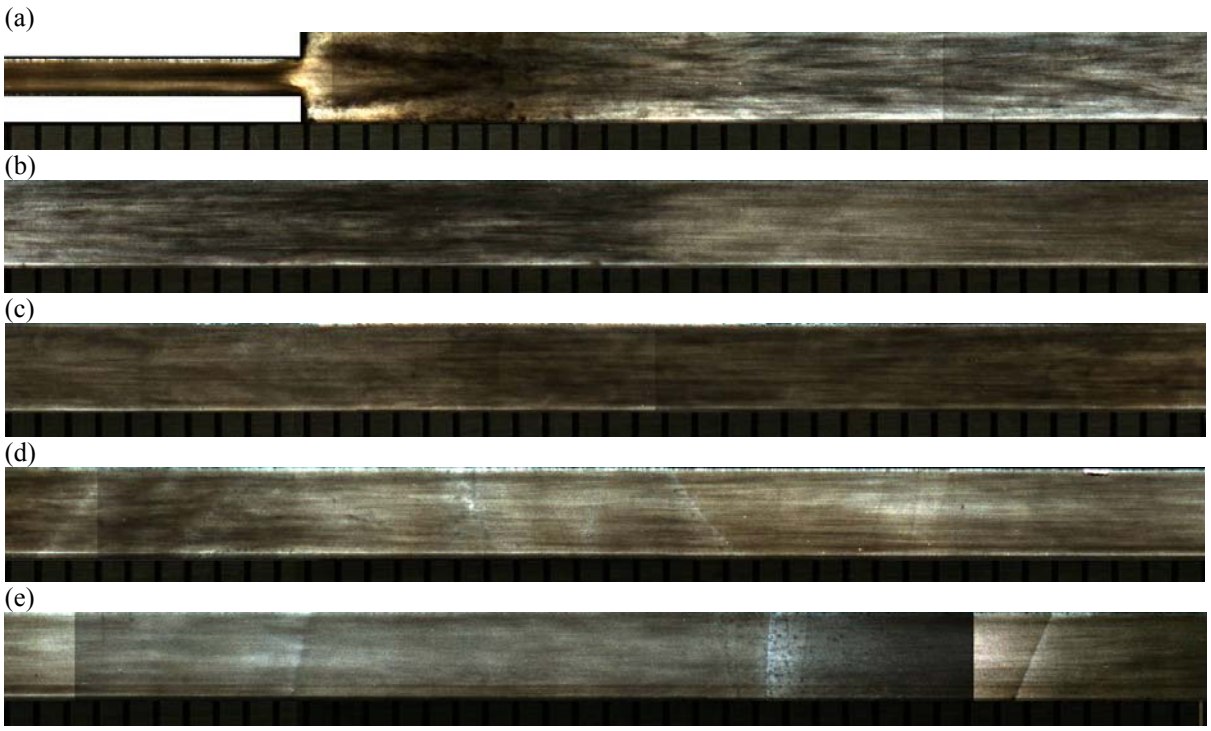

Figure 7. Soot film visualization of stoichiometric ethylene/oxygen, δ=30% in a channel with sudden expansion, flame propagates from left to right. Left edge of the image is at (a)240 mm, (b)280mm, (c)320mm, (d)360mm, (e)400 mm from the ignition point; distance between ruler marks below each picture is 1 mm.

We also apply the soot film visualization to mixtures with 30% dilution (Fig. 7). Similar cone-shaped structures are observed at the sudden expansion, but the length of the cone is longer, about 6 mm to 7 mm long. And in the 40% dilution case, the detonation wave is too weak to carve a pattern on the film.

4 Conclusion

Detonation transmission of stoichiometric ethylene/oxygen-enriched-air across a 1 mm to 3 mm wide 2D sudden expansion in a 1 mm deep channel was experimentally characterized under various degree of nitrogen dilution. Three transmission modes were identified. When the dilution ratio was between 15% and 20%, the reaction wave re-accelerated back to a near C-J velocity within 40 mm downstream of the sudden expansion after stalling at the sudden expansion, and then stably propagated at the near C-J velocity until the end of the channel. For mixtures with dilution ratios between 25% to 33%, the detonation wave also stall and re-accelerate to C-J detonation like first mode, but the stall velocity is lower, and recovery distance is 4 times longer. In mixtures with higher dilution ratios (37% - 40%), C-J detonation could not be sustained in the narrow section. Instead, there existed a low-speed detonation mode with a propagation velocity of approximately 1500 m/s. As the low-speed detonation wave headed into the sudden expansion, it immediately accelerated to C-J detonation in the expanded section. Soot film visualizations revealed extinction cones in both δ=20 % and 30 % cases. Lengths of extinction cones were longer for mixtures with higher dilution ratio. Cell size was approximately 1 mm for δ = 20% mixture ($C_2H_4+3O_2+0.75N_2$).

5 Reference

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