Coupled Shock Cluster - Reaction Front Structures during Detonation Transition in Narrow Channels Filled with Ethylene/Oxygen Mixtures

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1. Introduction

Schlieren visualization of flame acceleration (FA) and detonation transition have been extensively performed to investigate deflagration-to-detonation transition (DDT) phenomena [1-6]. Dynamics of reaction and shock waves during FA and DDT in small channels particularly receive increasing interests recently due to their importance on fundamental combustion science as well as applications to explosion safety and micropropulsion [7]. Studies have shown that interactions between shock waves and reaction front are instrumental to both FA and detonation initiation. The generation of shock waves in the unburned gas region result in pre-heating and pre-compression of the mixture that lead to flame acceleration. Localized strong shock coupled to the flame has also been found to be the precursor of detonation initiation [8-14]. For detonation transition in small channels, further interactions among shocks, reaction front and boundary layers, which become more prominent in smaller confinements, add another layer of complexity to the phenomena. Various forms of shocks have been observed in our previous schlieren visualizations on the FA and DDT processes in miniature confinements, including channels, tubes, and gaps [15-18]. Strong influences of shock formations on reaction propagation dynamics were observed in the studies.

In a recent study, complete evolvements of reaction and shock waves in stoichiometric ethylene and oxygen mixture in a 1 mm × 1 mm channel were successfully resolved using high-speed schlieren technique [18]. The visualization revealed successive formations of three types of shock patterns in front of the reaction wave: leading shock, oblique shocks, and shock cluster. In addition, four reaction propagation stages prior to final detonation transition were classified. Transition between stages were associated with the formation of a shock pattern and the break of the acceleration rate as shown in Fig. 1. A leading shock developed ahead of the flame during the transition from 1st FA to 2nd FA stage. The flame was stretched in the 2nd FA stage, and oblique shocks began to develop in corners between reaction front and side walls. The appearance of a precursor shock and abrupt change of acceleration rate slope characterized the inception of 3rd FA. As the oblique shocks developed into a cluster of oblique shocks coupled with the reaction, the acceleration rate slope turned positive again, and the period thereafter was defined as the 4th FA stage. Local explosion drove the reaction front into detonation state at the end of the 4th FA stage, when the reaction propagation velocity reached ~ 1500 m/s.

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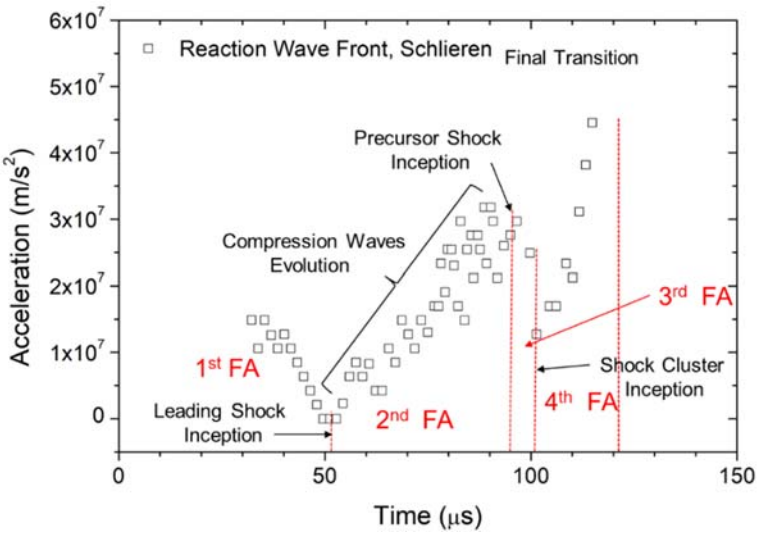

Fig. 1 Stages of Reaction Front Acceleration in a 1 mm channel filled with stoichiometric ethylene/oxygen mixture.

Through extensive experiments with various channel size and equivalence ratio, we have found that the coupled shock cluster – reaction front structure in 4th FA stage always appears before detonation transition for the ethylene/oxygen mixture. It seems to be a precursor pattern for final detonation transition. Purpose of the study is to further reveal characteristics of the coupled structure. The angle between the staggered oblique shocks and the side wall is found to be the key feature of the coupled structure. The influence of mixture equivalence ratio on the angle has been experimentally investigated. Correlations between the angle and DDT time are also discussed.

2. Experimental Setup

Reaction and shock waves patterns in the 1 mm × 1 mm cross-section, 750 mm long square channel as shown in Fig.2(a) were visualized via high-speed schlieren technique in the experiments. The channel was machined with electric discharge machining on stainless steel plate. Surface irregularities along the channel side walls were within 5 μm. Transparent glass windows are clamped onto the stainless steel plate to form the square channel. Holes were drilled near both ends and at the center of one window to allow gas feedthrough and accommodation of the igniter, respectively. Equivalence ratio of ethylene/oxygen mixture was metered using mass flow controllers (MKS Instruments, 1179A) that regulated ethylene and oxygen filling flow rates. In all experiments, the 1 mm channel was initially filled with ethylene/oxygen mixture at ambient temperature and pressure with equivalence ratio ranging from 0.6 to 1.7. Uncertainty of equivalence ratio is ±0.05.

Schlieren visualization system for the study was schematically shown in Fig. 2(b). A monochrome high-speed camera (Vision Research, Phantom v12.1) was used to capture the schlieren images. The light source was a high-speed laser (Cavitar, CAVILUX Smart UHS). Pulse duration of the laser was 50 ns. The very short illumination time period helped to minimize motion blur on the images, especially during final detonation transition when shock wave structures evolved rapidly. The frame rate of the recorded schlieren image sequences was 150,000 fps. The optical setup allowed an observation window of 25 mm wide; therefore, the channel had to be shifted along the longitudinal axis in order to visualize the fronts at different stages.

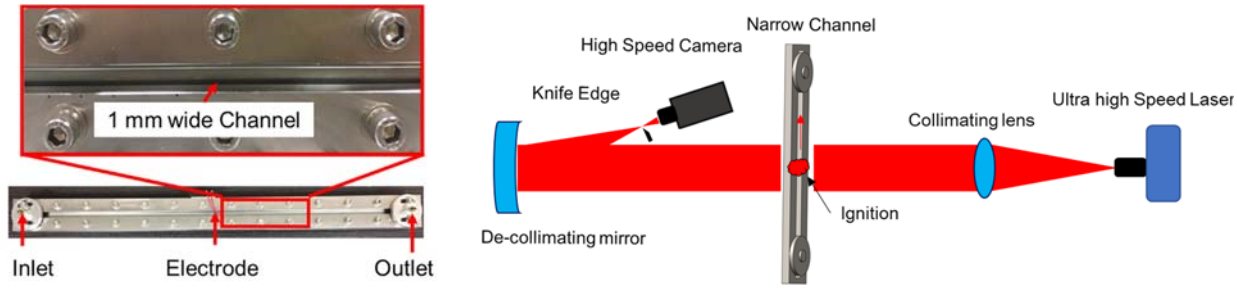

Fig. 2 Experimental setup.

3. Reaction and Shock Fronts

Figures 3 show the reaction and shock waves patterns observed at several key instants of the propagation process in stoichiometric ethylene/oxygen mixture. The reaction front propagates from left to right in the figures. In Fig. 3(a), a leading normal shock was observed ahead of the reaction front. The shock results from the choking of the induced flow ahead of the flame in the narrow channel. Boundary layers develop between the leading shock and the flame, which may lead to the stretching of the parabolic flame front. Compression waves in the corner between the stretched parabolic flame front and the side walls can be seen in Fig. 3(b). The waves were strengthened into oblique shocks and resulted in strong pressure gradient ahead, which appeared as a dark zone in Fig. 3(c). The dark zone later developed into a precursor shock as shown in Fig. 3(d), which is different from the leading shock formed early in the process (see Fig. 3(e)), but the two shocks may merge at a later moment before detonation transition. The front structure evolved into a coupled shock cluster – reaction front structure, in which the reaction front is interweaved with the shock cluster ahead, as shown in Figs. 3(d) and (e). Detonation structure was shown in Fig. 3(f).

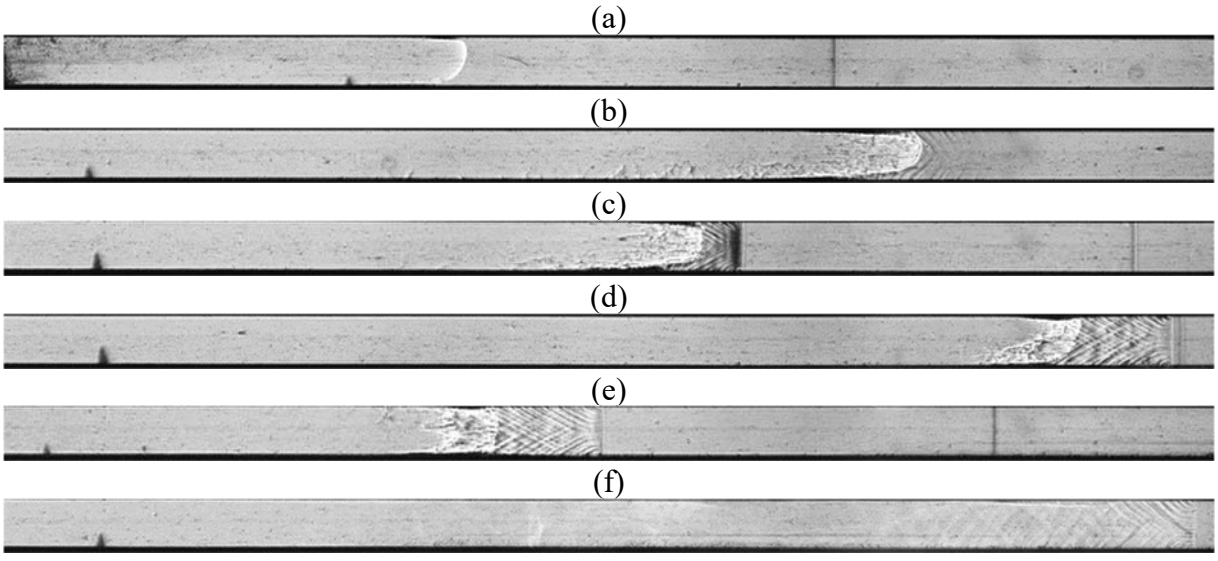

Fig.3 (a) leading shock, (b) compression waves between the reaction front and side walls, (c) oblique and precursor shocks, (d) and (e) coupled shock cluster – reaction front structures, (f) detonation front sturcutre in the 1 mm channel filled with stoichiometric ethylene/oxygen mixture. The markers on the bottom left in the figures correspond to 10, 20, 30, 40, 60, and 70 mm from the ignition point.

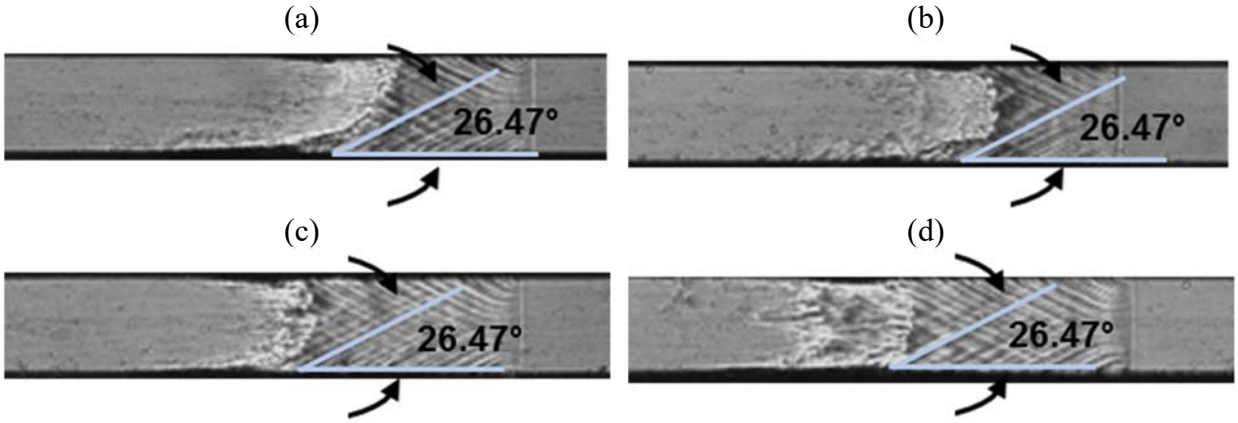

Fig. 4 Coupled shock cluster - reaction front structures of Φ = 1 ethlyene/oxygen mixture at (a)112.82 μs, (b) 126.19 μs, (c) 141.93 μs, (d) 148.96 μs from ignition timing in the 1 mm channel

Within the coupled shock cluster – reaction front structure, oblique shock waves staggered from each side of the wall are parallel to each other and form a checker pattern. Estimating the wave speed using the 50 ns illumination time and the length of the shock cluster, it can be concluded that the observed cluster is resulting from accumulated motion of a single or a few shocks. The pattern in the image is indeed the instantaneous structure of coupled shock cluster and reaction waves.

Figures 4 further show the evolvement of the coupled shock cluster - reaction front structure at four different timings, 112.82 μs, 126.19 μs, 141.93 μs and 148.96 μs. An ω-angle is defined as the angle between the oblique shock waves in the coupled wave structure and the channel wall to characterize the coupled wave structure. Interestingly, we find that ω-angle is invariant with distance and time as reaction wave propagates in the 1 mm channel filled with stoichiometric ethylene/oxygen mixture.

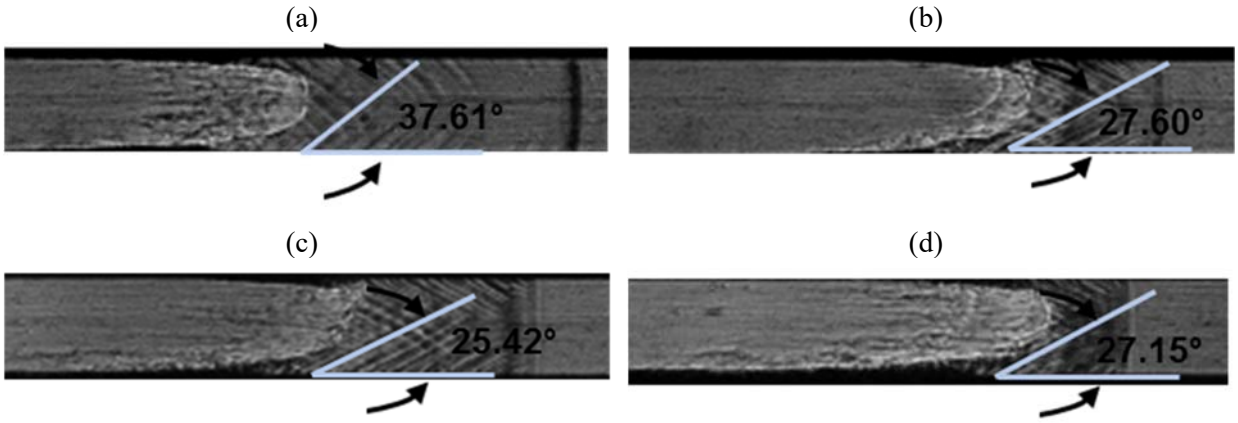

Fig.5 Shock cluster structure in mixture with Φ equals to (a) 0.6, (b) 0.9, (c) 1.2, and (d) 1.5.

Since ω-angle is constant during the process, it can be a characteristic parameter for the coupled waves structure. We therefore further investigate influence of mixture equivalence ratio, Φ, on ω-angles. Fig. 5 shows the shock cluster – reaction front structures in Φ = 0.6, 0.9, 1.2 and 1.5 ethylene/oxygen mixtures. The visualizations show that ω-angle changes with mixture equivalence ratio. The angle is the smallest in Φ = 1.2 mixture and becomes larger in both smaller and larger equivalence ratio mixtures. It is worth noting

that clarity of the patterns in the schlieren images is also the highest for Φ = 1.2 mixture. Experimental results show that the reaction does not evolve into near Chapman-Jouguet (C-J) detonation eventually; the final state of the propagation is low-speed detonation mode instead. Correspondingly, oblique shocks ahead of the reaction looks blurrier in images of Φ = 0.6 mixture (Fig. 5(a)), and

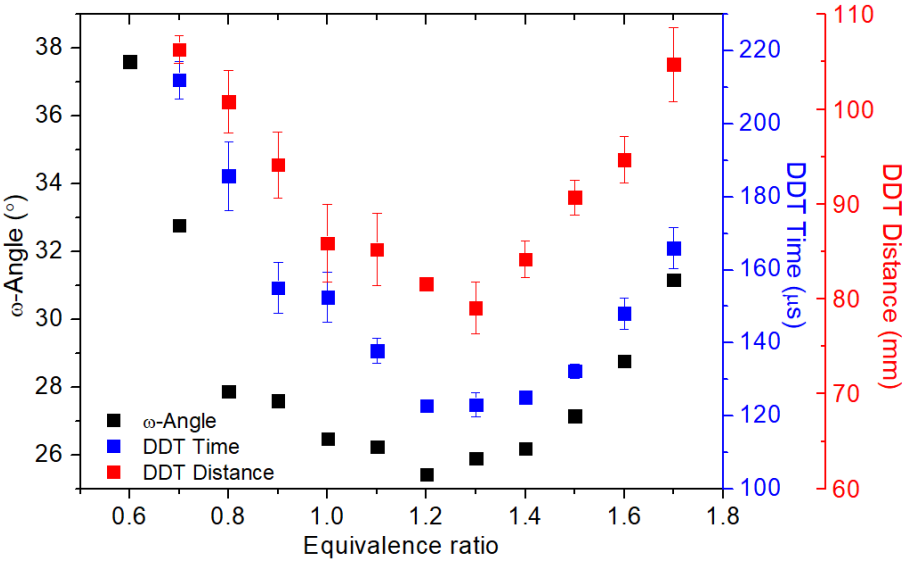

Fig.6 Variation of ω–angle, DDT time and distance with respect to Φ

Figure 6 shows the variation of ω-angles in mixtures with equivalence ratio between 0.6 and 1.7. Experimentally derived DDT induction time and distance were also plotted in the figure for comparison. It is found that variations of ω-angle, DDT time and distance follow similar trend. Minima of DDT time, distance, and ω-angle occur at mixtures with Φ between 1.2 and 1.3; DDT distance, time and ω-angle all become longer or larger in leaner or richer mixtures. Further studies will be made to understand the origin of the ω-angle and causes of the observed trends.

4. Conclusion

Experiments show that a coupled shock cluster – reaction front structure emerges prior to detonation transition in ethylene/oxygen mixture in small channels. The structure features checkered oblique shock pattern between a precursor normal shock and reaction front interweaved with the oblique shock structure. It is found that the angle between the parallel oblique shocks in the structure and the side wall, defined as ω-angle, does not change over time for a specific mixture. However, the angle does vary with mixture equivalence ratio. Minimum ω-angle is observed in Φ = 1.2 mixture, which is identical to the equivalence ratio at which DDT time and distance are the shortest. Shock cluster structure in the leanest Φ = 0.6 case is not as clear as the other cases. Tests show that the final state of the reaction wave is low-speed detonation instead of near C-J detonation.

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