Direct observation of the critical initiation state of transition from deflagration to detonation

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Dear Editor,

Conventional engines (e.g., gasoline/diesel engines and gas turbines) rely primarily on deflagration, a subsonic combustion process with practical thermal efficiency typically less than 45% due to thermodynamic and mechanical constraints. Moreover, they become ineffective for hypersonic propulsion because of insufficient air compression at such speeds. As the demand for higher energy conversion efficiency increases, deflagration-based systems approach their performance limits. In contrast, detonation combustion enables near-constant-volume self-pressurized combustion, with theoretical thermal efficiency gains of 10–25% over conventional cycles.[1] While significant engineering challenges remain, this approach may open new frontiers in efficient energy utilization.

Deflagration-to-detonation transition (DDT) is a fundamental challenge in detonation combustion research.[2] Detonation sustains a self-sustaining wave speed, surpassing deflagration by 2–4 orders of magnitude, thus enabling rapid energy release. The observation and quantitative study of the DDT process provide an experimental foundation for understanding the transition between two fundamentally distinct combustion modes and their characteristic correlations.[3,4] In recent years, significant progress has been made in the study of DDT, which has focused mainly on flame acceleration mechanisms, turbulence effects, and shock-flame interactions.[5,6] Experiments and numerical simulations revealed the important role of turbulence in the obstructed channel in flame acceleration and presented a correlation between the DDT onset distance and flame acceleration up to the 1/2 Chapman-Jouguet (CJ) detonation velocity (V_{CJ}).[7] However, although existing studies provide an important basis for understanding the DDT process, quantitative information analyzing the state of the shock and flame during flame acceleration and DDT is still lacking, and the core of the DDT initiation mechanism has not yet been fully revealed.

At present, DDT research faces challenges due to the complexity, stochasticity, and instantaneity of the process, which complicate experimental capture of the critical transition state. In this work, we designed a narrow rectangular channel (cross section: 10 mm × 150 mm) and employed argon dilution to reduce the reactivity of the combustible gas, enabling controllable DDT triggering. We also developed a flow field diagnostic system, which includes a high-speed schlieren system with an ultrashort exposure time (< 50 ns) and an open shutter shooting system with a relatively long exposure time (120 μs). To the best of our knowledge, this system yields relatively high-quality images of the DDT process to date. However, it should be noted that detonation propagation behavior would be influenced by channel geometry. Square tubes promote more shock-shock interactions at the corners compared to round tubes,[8] while narrow channels may amplify viscous boundary layer effects. These can lead to attenuation of the CJ detonation velocity and increase the likelihood of wall-initiated DDT.

Figure 1A presents a schlieren visualization of the precursor shock waves (PSW1 and PSW2) and the trailing deflagration flame front. Figure 1B quantitatively tracks their velocity evolution, revealing distinct dynamic behaviors. PSW1 maintains an initial steady velocity of approximately 670 m/s, whereas the flame-proximal PSW2 propagates at approximately 1505 m/s. This substantial velocity differential causes PSW2 to overtake and merge with PSW1 at 170 μs, resulting in a post-collision velocity peak of 1650 m/s for PSW1 and the degeneration of PSW2 into a mere density discontinuity. Contrary to conventional DDT understanding, where flame acceleration leads to shock-flame coupling, our observations demonstrate an alternative scenario: the deflagration flame experiences continuous deceleration (from 1392 m/s upon window entry to approximately 1039 m/s at exit) due to interaction with the reverse rarefaction wave generated during the PSWs fusion moment.

Analysis of the average preheating zone thickness (δ) in Figure 1C shows that its growth rate $d\delta/dt$ is 0.195 mm/μs before catching up with PSW1, but increases sharply to 0.413 mm/μs after PSW fusion. This result challenges conventional DDT mechanisms by uncovering a previously unnoticed deceleration phase prior to detonation onset. Specifically, the flame speed does not always accelerate during DDT. It actually slows due to the reverse rarefaction wave generated by PSWs interaction. Notably, this deceleration does not prevent DDT, as shock merging enhances thermodynamic conditions (higher temperature and pressure) that facilitate detonation initiation. The measured combustion wave velocity (above $0.5V_{CJ}$, where V_{CJ} = 1928 m/s) confirms the system remains above the CJ deflagration threshold, retaining full potential for transition to detonation.

Figure 1D illustrates the DDT process at the upper wall of a pipe. A precursor shock wave initially decouples from the flame. After the flame catches up, a hot spot forms at the upper wall (t = 100 μs), followed by a detonation bubble. By 120 μs, three distinct regimes are observed: ① a detonation wave marked by the bubble; ② a deflagration wave composed of a slow shock and fast flame, similar to Figure 1A; and ③ a quasi-detonation wave with a rapidly accelerating wavefront separating from the unburned gas. Due to its slower speed, regime ② is gradually overtaken by the upper and lower waves. Detonation wave heads emerge at 130 μs, and two distinct waves (D1 and D2) are visible at 140 μs. These subsequently merge into a single detonation wave, rapidly consuming the remaining unburned gas.

Figure 1E② shows a synchronously captured open-shutter image. A broad luminous band exists in Zone I, indicating the propagation trajectory of the detonation formed by the hot spot. Zones II and III display condensed cellular structures, suggesting the detonation is still overdriven and in its early stage. Initiation near the wall is attributed to reduced flow velocity in the boundary layer, where viscous dissipation and thermal conduction cause localized heating. Wall turbulence further enhances mixing and heat transfer, promoting high-temperature zones.

Figure 1F illustrates the DDT phenomenon in the channel. At 60 μs, the flame front couples with the shock wave. After 10 μs, a clear acceleration of the wavefront is visible, followed by the formation of a hot spot at the arrow-marked location at 90 μs, which is consistent with the hot spot captured in Figure 1E③. At 100 μs, two detonation waves (D1 and D2) emerge, with D2 initially exhibiting a smaller wavefront that subsequently expands. At 130 μs, both detonation waves are distinctly observed.

Figure 1G presents the propagation characteristics of overdriven detonation immediately following the DDT process. At 20 μs, D1, which initiated earlier, appears in the viewing window as a fully developed detonation wave. In contrast, D2, having initiated later, remains in an overdriven state at this stage, as indicated by its notably smaller transverse waves and higher propagation velocity compared to D1. The velocity evolution of both detonation waves is presented in Figure 1H. D1 maintains a constant velocity of 1975.9 m/s (101.5% V_{CJ}), whereas D2 gradually decelerates from 2298.3 m/s to 2118.0 m/s, although it consistently maintains a higher speed than D1. Ultimately, the two detonation waves merge into a single curved detonation front propagating downstream. Further evidence of their distinct states is visible in Figure 1E④, which reveals two clearly differentiated regions in the detonation cellular structure. Region I displays relatively large cells, while Region II exhibits much finer cellular patterns

This study presents two key findings regarding the DDT process in narrow channels. First, before deflagration fully transitions into detonation, the merging and collision of precursor shock waves lead to an expanded preheating zone and a reduced flame speed, thereby delaying local hot spot formation. Second, we identified two distinct DDT initiation modes in confined geometries: 1. Wall-initiated detonation. This occurs at low initial pressures, where the mixture exhibits slow reaction kinetics. However, heat accumulation and turbulence effects near the wall boundary layer can generate local hotspots. When the temperature and pressure at this location reach the spontaneous ignition threshold, rapid chemical reactions are triggered, initiating localized detonation. 2. In-channel detonation. This is the more prevalent mode under normal conditions. Here, shock-flame coupling leads to a positive feedback

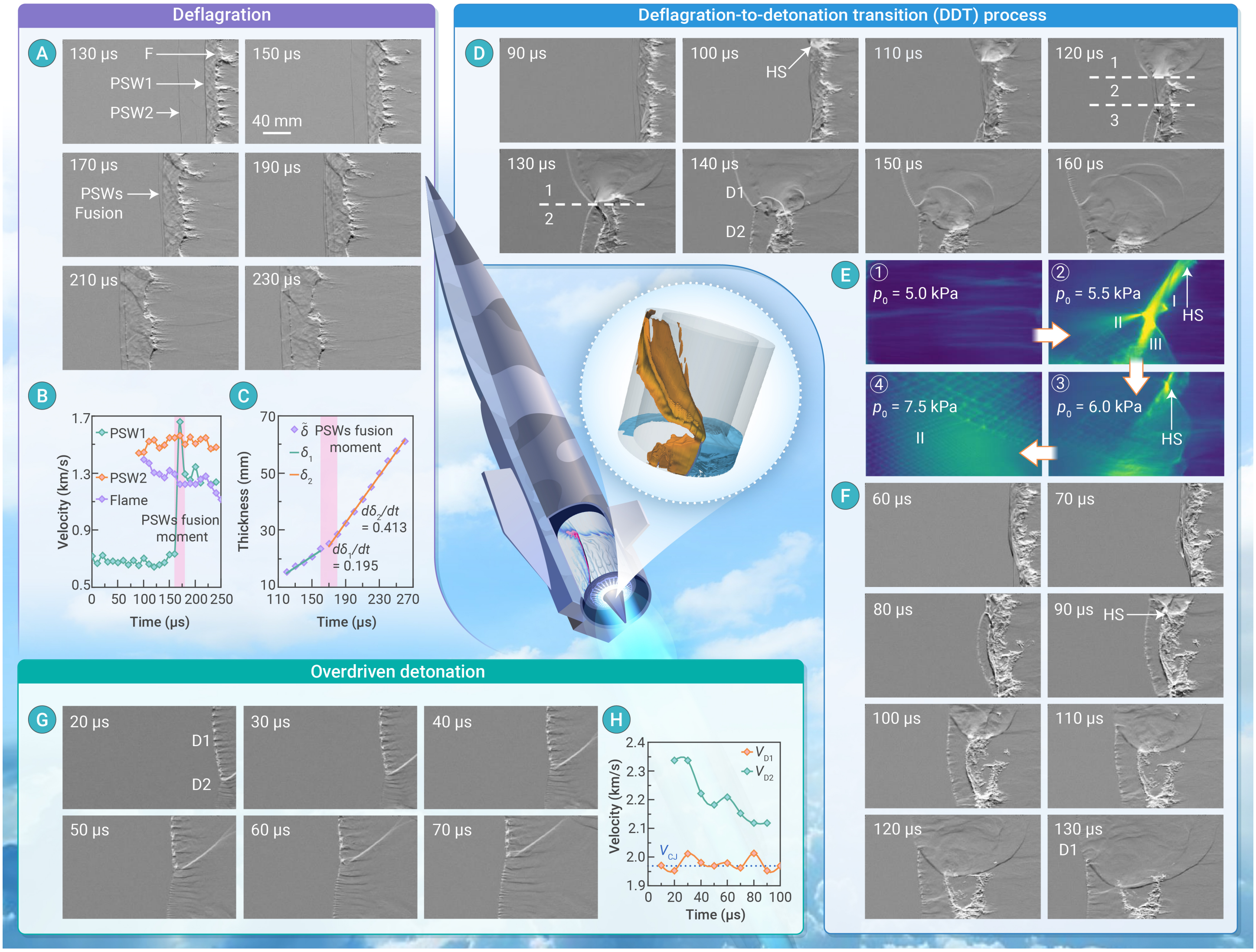

Figure 1. Experimental results of the critical state of DDT (A) Development process of the deflagration wave, the initial pressure p_0 = 5 kPa. (B) Velocity variations of the precursor shocks and flame front. (C) Average thickness variation of the preheating zone δ with time. (D) DDT onset from the sidewall, p_0 = 5.5 kPa; (E) Open-shutter images, ① deflagration (corresponding to Fig. 1A), ② wall-initiated detonation (corresponding to Fig. 1D), ③ in-channel detonation (corresponding to Fig. 1F), and ④ overdriven detonation (corresponding to Fig. 1G). (F) DDT onset in the channel, p_0 = 6 kPa. (G) Formation of overdriven detonation just after the DDT process, p_0 = 7.5 kPa. (H) Velocity variations of the two detonation wavefront surfaces (D1 and D2). Note: The detonation wave propagates from the right to the left. The moment of 0 μs is set as the moment when the precursor shock propagates into the view window. Symbol abbreviations: F: flame front, PSW: precursor shock wave, HS: hot spot, D1: first detonation front, D2: second detonation front.

mechanism: the combustion energy release strengthens the precursor shock (evidenced by shock acceleration). The shock-induced high-temperature, high-pressure conditions further accelerate flame propagation. This mutual reinforcement enables the combustion wave to self-sustain, continuously accelerate, and ultimately transition into detonation.

The experiments were conducted in a 2-meter-long rectangular channel with a width of 10 mm equipped with a 250 mm × 150 mm optical window. Owing to the detonation cell length being comparable to the channel width, the detonation wave structure exhibited quasi-two-dimensional characteristics. A custom-designed ion probe was employed to detect detonation wave propagation and trigger a synchronized imaging system, integrating high-speed schlieren visualization and open-shutter photography. By combining these two imaging techniques, both the transient flow structure and the full wave trajectory could be simultaneously resolved. The test mixture consisted of stoichiometric ethylene-oxygen, which was diluted with 40% argon to reduce the detonation sensitivity and enable controlled DDT triggering.

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DECLARATION OF INTERESTS

The authors declare no competing interests.