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Accelerative expansion and DDT of stoichiometric ethylene/oxygen flame rings in micro-gaps

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Abstract

Acceleration and transition to detonation of expanding flame rings ignited at the center of 260 μm and 120 μm gaps between parallel flat pates were experimentally studied. The micro-spacing was initially filled with stoichiometric ethylene/oxygen mixtures at ambient pressure and temperature. Visualizations showed that the outward propagating reaction wave was initially smooth and circular, but petal-like wrinkles quickly developed on the flame ring. Flame wrinkles appeared earlier and closer to the ignition point as the gap width became smaller. The flame underwent fast acceleration during the onset of flame wrinkling, but the acceleration was relatively mild as the wrinkled flame ring continued to expand. Time exponents for the accelerative growth of corrugated flame rings were identical in the two highly confined gaps. The flame ring underwent deflagration-to-detonation transition as the propagation velocities abruptly surged from 1000 m/s to over 2000 m/s. The arc-shaped detonation waves initiated from local explosion spots on the flame ring were propagating at near Chapman–Jouguet velocities. The induction distance and time for detonation transition were both shorter in the smaller gap. Detonation cell patterns and the initiation locations were also clearly recorded through soot film visualizations.

Keywords: DDT; Flame acceleration; Wrinkled flame; Micro-gap; Micro-detonation

1. Introduction

Since the exact mechanism responsible for detonation transition in small confinements is still far from clear, flame acceleration and deflagration-to-detonation transition (DDT) in very small tubes and channels have drawn intense research interest [1–8]. Understanding DDT in highly confined spaces is also crucial for combustion safety and may lead to potential applications in micro-scale propulsion and power devices [9,10]. A new configuration for investigating the characteristics of flame acceleration and DDT in small confinements using micro-gaps has been proposed in a brief communication recently published [11]. Outward propagating flame ring was ignited at the center of a 260 μm gap between parallel flat plates in the experiments. Preliminary visualizations have shown that although the gap width approaches the quenching limit, the reaction front still undergoes accelerative planar expansion and eventually runs up to detonation.

A freely expanding flame becomes wrinkled and self-accelerates under the influence of hydrodynamic instability [12–18]. Time evolutions of

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effective flame radius generally correlate with the power law formula, $r(t) = a + bt^c$, where $r(t)$ is the radius of the flame at instant t; a, b, and c are empirical constants. Analyses have shown that the time exponent, c, for an outwardly free propagating spherical flame falls between 1.25 and 1.5. In a recent theoretical analysis, Akkerman et al. [12] further suggest that self-accelerating wrinkled flame could eventually lead to deflagration-to-detonation if the length and time scales are large. Detonation is triggered by the induced compression wave ahead of the accelerating flame. They also point out that unconfined DDT in terrestrial conditions is unlikely. However, the compression wave can be generated and even be enhanced by very small confinements. Previous studies on flame propagation in small tubes have shown that a smaller tube diameter can expedite flame acceleration and deflagration-to-detonation [1–3,8,19,20]. The reduced cross-sectional area of the tube obstructs the induced flow ahead of the accelerating flame from free flowing, which leads to pre-compression of the unburned mixture. As flame propagates into the compressed unburned gas, mass burning rate is increased, which further strengthened the pre-compression effect. Final run up into detonation occurs when the compression wave eventually triggers local explosion. Lee et al. [21] have investigated the expansion of a cylindrical flame ignited from the center of a 30 mm thick cylindrical chamber. The interaction between reflected shock from the cylinder wall and the flame was considered to be the cause for the formation of wrinkled flame pattern and subsequent explosion as the flame approached the end wall. Wrinkles were observed on the stoichiometric ethylene/oxygen flame ring at ~45 μs in the 260 μm gap, and local explosions occurred in less than 150 μs after ignition [11]; both time scales are much shorter than the time required for a precursor shock to reach the perimeter of the micro-gap. Disruptions of the expanding flame by reflected shock as described in Ref. [21] are eliminated in the present micro-gap experiments.

The objectives of the paper are to reveal the characteristics of the accelerative flame ring expansion and DDT in the sub-millimeter gap, and investigate the effects of gap size. High-speed cinematography was first utilized to obtain the velocity evolutions in a reduced region of interest along the horizontal axis. The repeatability of reaction front evolutions was also found to be adequate for the implementation of delayed-single shot approach to resolve the detailed structures of flame ring at different instants. Growth rates of the expanding wrinkled flame ring were derived using image sequences from the delayed single-shot approach. Soot foil visualization was utilized to investigate cell structures of the detonation waves. Effects of gap width on expansion rate, DDT time, and DDT distance were also discussed.

2. Experimental setup

Custom-made thin copper shims were clamped between two parallel Plexiglas plates to create a micro-gap of the same width as the shim thickness. The pair 300 mm × 300 mm transparent Plexiglas plates were each 7.5 mm thick. The whole fixture was compressed by the eight equally spaced bolts and nuts around the plate perimeter. Sets of 260 μm and 120 μm thick shims were made for the present study. The uncertainty of the gap width for the thicker gap was ±10 μm. Schematic of the assembly for creating the micro-gap and a picture of the whole fixture are shown in Fig. 1. The planar gap space is open to atmosphere circumferentially except at where the bolts locate. A 0.7 mm diameter hole was drilled at the center of the back plate for installing a two-hole ceramic tube, which shielded a pair of electrodes for ignition spark generation. Spark ignition of the mixture was accomplished through a high-voltage circuit. The energy released by the capacitor during the voltage breakdown was ~1.6 mJ, and actual energy being deposited into the gaseous mixture for ignition would be even smaller. The spark energy is far less than energy for direct detonation initiation in ethylene/oxygen mixture [22].

Another 0.7 mm diameter hole was drilled 10 mm away from the center hole on the same plate. Stainless steel hypodermic tubing with 0.63 mm O.D. and 0.33 mm I.D. was inserted in the off-center drill for injecting the combustible mixture. The clearances between the tubings and the holes were sealed with epoxy. Stoichiometric ethylene/oxygen mixtures (gas purity > 99.9%) was premixed before being fed into the gap. The mixture equivalence ratio was regulated by electronic mass controller system (1179A, MKS). Uncertainty of the equivalence ratio was ±0.05.

Both high-speed cinematography and delayed single-shot visualization techniques were utilized. A high-speed camera (MotionPro X3, IDT) was used to capture the reaction front evolutions along a rectangular region-of-interest (ROI) window enclosing the ignition spot. Due to the insufficient frame rate of the high-speed camera

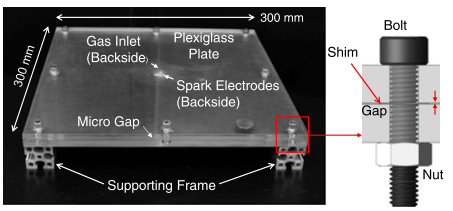

Fig. 1. Schematics of the micro-gap assembly.