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An experimental study of the propagation characteristics for a detonation wave of ethylene/oxygen in narrow gaps

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ABSTRACT

To investigate the propagation characteristics of a detonation wave in a narrow gap, the detonation processes of a stoichiometric ethylene-oxygen mixture were studied at different initial pressures in narrow gaps ranging 1.0–4.0 mm in height. Flame propagation through the narrow gap was observed with a high-speed camera, and the trajectories of triple points on the detonation waves were obtained using a soot-deposition plate. The results showed that both higher initial pressure p_0 and lower narrow gap height h could accelerate the deflagration-to-detonation transition process and determine how the detonation wave propagates, e.g., galloping detonation, stuttering detonation, and stable detonation. To attain unstable detonation propagation, the corresponding range of initial pressures increased with decreasing height of the narrow gap. A smaller height of the narrow gap led to a higher initial pressure threshold corresponding to the detonability limit. This could be determined by the range of h/λ; the onset of galloping detonation occurred when $0.17 < h/\lambda < 0.27$. Since the effect of the boundary layer on detonation propagation could not be neglected in narrow gaps, the velocity deficits were relatively large compared with those from a large scale channel. It was found that the velocity deficits were inversely proportional to the narrow gap height and initial pressure, and the relation between them was obtained by fitting the experimental data, i.e., $\Delta D = 0.65h^{-0.8}p_0^{-0.5}$.

1. Introduction

A detonation wave is an extreme combustion phenomenon that propagates close to an ideal one-dimensional Chapman-Jouguet (C-J) velocity (D_{CJ}) [1]. It can be considered as a reactive shock wave followed by a chemical reaction. The shock wave adiabatically compresses the mixture and ignites it. Energy is released through a chemical reaction, and in turn, supports the shock wave propagation. Detonation wave propagation in a small-scale (millimeter and below) channel appears to have different characteristics from those in a conventional large-scale channel [2], characteristics such as the deflagration-to-detonation transition (DDT) process [3,4], detonation propagation modes [5], detonability limit [6,7], and velocity deficits [8]. The differences are attributed to the significant effect of the boundary layer which is induced by the wall for the small confined space. This effect will be less important in a large-scale channel since the boundary layer is relatively thin compared to the channel size. In view of propulsive systems, the relevant research can provide theoretical support for designing the pre-detonator of detonation-based propulsion engines to enhance the DDT process [9,10]. On the other hand, since a detonation wave cannot propagate in a relatively narrow gap whose height is less than the cell size, the maximum safe gap in the detonation arrester [11,12] can be determined by better understand the mechanisms and limits for detonation propagation in a narrow gap to avoid hazardous phenomena in chemical plants. Hence, the study of detonation propagation in the narrow gap has important scientific and practical significance.

The characteristics of flame and detonation propagation in a small-scale channel have been studied using many numerical simulations and experiments. Ott et al. [13] simulated flame propagation in small channels and described a possible useful mechanism for the acceleration flame. Wu et al. [14] investigated flame propagation in capillary tubes with smooth circular cross-sections. Their results showed that tubes with larger diameters take longer to transition to detonation. Li et al. [15] used a parameter of the detonation initiation distance (DID) to determine the location of detonation onset, and indicated that the amount that the DID decreased was strongly dependent on the change in the initial pressure and gap size. The various detonation propagation modes can be achieved via reducing the channel size or decreasing the initial pressure. Manzhalei et al. [16] studied the detonation propagation mode of premixed acetylene/oxygen ($C_2H_2/2.5O_2$) gas in a

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Nomenclature

D_{CJ}	Chapman-Jouguet velocity (m/s)
D_{Str}	detonation velocity in the straight channel (m/s)
$\overline{D}_{Str}$	average detonation velocity in the straight channel (m/s)
h	height of narrow gap (mm)
l	width of narrow gap (mm)
L_{DID}	detonation induction distance (mm)
p_0	initial pressure (kPa)
u_1	velocity of the incoming mixture (m/s)
x	distance from the leading shock in the subsonic region (mm)

Greek symbols

δ^*	equivalent displacement thickness (mm)
ΔD	detonation velocity deficit
λ	detonation cell size (mm)
μ_e	viscosity of the gas in the combustion zone (g/(cm·s))
ρ_1	density of the incoming mixture (g/cm^3)

tube with inner diameters around 0.6 mm, and they classified reaction propagation scenarios such as high speed detonation, galloping, and low speed detonation. Wu et al. [14,17] obtained different propagation modes for stable Chapman–Jouguet (C–J) detonation: oscillating flame, galloping detonation, and stable detonation flame in a circular tube with inner diameters in the range 0.5–3 mm. The results indicated that only the detonation process occurring in the 0.5-mm channel exhibited a 5% detonation velocity deficit. However, the experiment could only be performed at atmospheric pressure, thus limiting the investigation of the effect of varying the initial pressure on the initiation and propagation of premixed gas. Gao et al. [6,18] studied the detonation propagation of stable and unstable premixed gas in five circular channels (1.5, 3.2, 12.7, 31.7, and 50.8 mm). Their results showed that, far away from the detonation limit, the detonation velocity was stable and the oscillation was small. When the limit condition was approached the detonation wave exhibited obvious velocity oscillation, in particular, the galloping detonation mode showed a certain periodicity. Lee [19] studied the near-limit propagation characteristics of a detonation wave in a circular channel. He pointed out that the detonation velocity decreased rapidly as the initial pressure approached the limit finally acquiring a single-headed spinning detonation indicating the limit was reached. Ishii et al. [20] studied the propagation characteristics of a detonation wave in narrow gaps with heights ranging from 1.2 to 2.0 mm. This study indicated that the velocity deficits strongly depend on the height of narrow gap. Ishii et al. [6] studied the propagation characteristics of the H_2/O_2 detonation wave in a narrow gap at an initial pressure of 39 kPa. They learned that the velocity deficit of the detonation wave was proportional to $h^{-0.8}$. However, they did not consider the effect of initial pressure on velocity deficits. Chao et al. [21] investigated the detonation velocity deficits of $H_2/O_2/Ar$ and $C_2H_2/O_2/Ar$ mixtures in a circular channel with heights of 2.2 mm and 6.9 mm, respectively, and they pointed out that extinguishing the stable premixed gas was mainly affected by the negative displacement of the boundary layer behind the detonation wave front. This conclusion is consistent with Fay's theory [22]. The detonation wave reaches the maximum velocity deficit (20–25% of the theoretical C–J value) at the near-limit condition.

In this study a high-speed camera and soot-deposition plate are used synchronously to observe detonation propagation in narrow gaps with a stoichiometric ethylene-oxygen mixture. The characteristics of detonation propagation in narrow gaps, such as the initiation process, propagation mode, and detonability limits, are described in detail. Furthermore, the quantitative relationship between detonation velocity deficits and initial pressure and narrow gap height is also provided.

2. Experimental system

Fig. 1 shows the experimental system, which consists of a combustor, an ignition system, a gas distribution system, and a measurement system. Experiments were conducted in a 1220-mm long $h \times 20$-mm rectangular cross-section straight narrow gap, where h = 1.0, 2.2, 2.9, 4.0 mm. The experiment channel was assembled using three types of materials. One side of the channel was equipped with a polycarbonate sheet as a wall for visualization so that the flame propagation process could be captured by high speed camera (OLYMPUS i-SPEED). On the other side an aluminum plate for soot deposition was used to characterize the detonation cell structure in the narrow gap. Copper gaskets were placed between the PC sheet and aluminum plate to form the narrow gaps with different heights. The installed error in the height of narrow gap was±50μm. A stoichiometric ethylene-oxygen mixture was used for studying the propagation characteristics of a detonation wave. First of all, the ethylene is a kind of industrial chemical suitable for the application in organic synthetic industry. The safety of pipeline transport for ethylene needs to be attended. Secondly, the choice of this mixture in the present study is motivated by the fact that its chemical reaction is susceptible to flow disturbance, and hence the cellular structure is highly irregular. For this unstable mixture, the feature of longitudinal oscillation can be observed, especially in near-limit conditions. Thus, it would be of interest to study the behavior of detonation propagation in narrow gaps based on a stoichiometric ethylene-oxygen mixture. For each test stoichiometric ethylene-oxygen mixtures were introduced into the pre-evacuated channel to the desired initial pressure p_0. An accurate digital vacuum gauge (OMEGA HHP 242-015A, 0–15 psi) was used to monitor p_0. The accuracy of the gauge was ±0.10% of its full scale. The gases were first mixed in a tank for at least 24 h via a partial pressure method to ensure homogeneity before being fed into the channel. At the start-up stage the mixture was ignited by a spark plug mounted at the head of the straight channel. The flame propagated from left to right and finally exited from the right end, which was sealed using 0.1-mm-thick aluminum diaphragm. The minimum rupture pressure for aluminum diaphragm is about 3 atm.

3. Results and discussion

To obtain photographs of flame propagation with high space resolution the frame rate of the high-speed camera was set at 75,000 fps, and the time interval between two adjacent photographs was 13.33 μs. Fig. 2(a) displays a sequence of the flame front propagation in the narrow gap with the cross section of 2.9×20 mm and with p_0 = 13 kPa. The propagation direction was from bottom to top. The velocity evolution of the flame front at different positions in the narrow gap is shown in Fig. 2(b). The local velocity of the flame front can be obtained from the ratio of the distance between positions in adjacent images to the interval time. The spatial resolution of the image is 1.5 mm/pixel; therefore, the measurement error is 112 m/s. The solid line in Fig. 2(b) represents the theoretical C–J detonation velocity, $D_{CJ,}$ under a given initial pressure. Its value can be calculated using the Gordon–McBrid