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Fabrication of a helical detonation channel: Effect of initial pressure on the detonation propagation modes of ethylene/oxygen mixtures

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ABSTRACT

The effect of the initial gas mixture pressure on curved detonation propagation modes has been extensively investigated in the present study using a stoichiometric ethylene–oxygen mixture in a new experimental facility consisting of a straight channel section joined to a helical channel section. Flame propagation through the helical channel was observed by high-speed CCD camera, and the trajectories of triple points on the detonation waves were obtained using a soot-deposition plate. The results clearly identify three detonation propagation modes, namely, a stabilized propagation mode, critical mode, and non-stabilized propagation mode, that vary according to the ratio of the radius of curvature of the inside wall r_i to the normal detonation cell width λ. For the stabilized propagation mode ($r_i/\lambda > 27$), the detonation velocity at the inner wall in the curved section asymptotically approaches the detonation velocity in the straight section with increasing initial pressure due to competition between the weakening and strengthening effects characteristic of the curved channel geometry. A definite flame shape, which is perpendicular to the inner wall of the channel, is observed. For the critical mode ($16 \leq r_i/\lambda \leq 27$), the shape of the flame front is observed to be more irregular and unstable than that of the stabilized propagation mode. This mode can be considered as a transition zone, where the stabilized propagation mode transits to the non-stabilized propagation mode with decreasing initial pressure. For the non-stabilized propagation mode ($r_i/\lambda < 16$), two types of periodic detonation propagation behavior are observed. The first is analogous to single-headed spinning detonation in a circular tube, which is observed in an initial pressure range of 5.5–11 kPa. Soot-coated foil records show that the cellular structure has specific features of the periodic variation, such as re-generation, decrease, and partial disappearance of detonation near the inner wall. The angular interval of consecutive cycles for sinning-like detonation decreases with increasing initial pressure. The second is galloping detonation near the detonation propagation limit. In one cycle of galloping detonation, a change from multi-headed to single-headed cellular structure is observed. However, as the galloping detonation further decays to the low velocity phase of the galloping cycle, the cellular structure vanishes. The angular interval of consecutive cycles for galloping detonation is observed to be random. Although both spinning-like and galloping detonations periodically undergo the process of re-generation, decrease, and failure, they exhibit two different propagation behaviors. The former partially fails near the inner wall, and is re-initiated by transverse detonation from the outer wall, while the latter fails completely, and re-generates by local explosion at the outer wall.

1. Introduction

A detonation wave is an extreme combustion phenomenon that propagates close to an ideal one-dimensional Chapman–Jouguet (CJ) velocity (D_{CJ}) [1]. It can be considered as a reactive shock wave across which mixtures are adiabatically compressed, and thermodynamic states (e.g., pressure and temperature) sharply increase owing to the chemical reaction behind the wave. Compared with constant-pressure combustion, detonation waves have many advantages such as higher thermodynamic efficiency and a wider range of Mach numbers [2].

Owing to the remarkable features of detonation waves, the application of detonations for propulsion has received widespread attention. The rotating detonation engine (RDE), which has been experimentally and numerically obtained very promising thrust performances by Wolanski et al. [3], Bykovskii et al. [4,5], and Schwer

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et al. [6], is a recent example. The RDE requires only a single initiation to trigger the deflagration-to-detonation transition (DDT) process, whereupon the detonation wave continuously propagates in the azimuthal direction of a coaxial cylinder as long as propellant is supplied near the head-end of the combustion chamber. Thus, the RDE can generate high thrust due to the expansion of combustion products behind the detonation wave.

Note that, for detonation waves propagating in an RDE, the curved geometry can uninterruptedly present convergent/divergent effects. Hence, the detonation propagation in a curved channel is more complicated than that in a straight channel. Numerous researchers have investigated this issue for the application of RDEs. Sugiyama et al. [7] simulated detonation wave propagation in a curved channel with various channel widths in two types of the ratios of inner and outer radii using two-dimensional Euler equations and a two-step reaction model. The results show that two detonation modes are observed: one is marginal multicellular detonation mode and the other is stable multicellular detonation mode. Pan et al. [8] numerically and experimentally revealed a self-sustaining mechanism of gaseous detonation rotating in a curved channel. Due to the curvature of the channel, the size of the cellular pattern along the concave wall was found to be smaller than that along the convex wall. This implied that the detonation wave near the outer wall is convergent and therefore stronger than that near the divergent inner wall. Kudo et al. [9] experimentally demonstrated the occurrence of three types of detonation wave propagation modes in bent tubes: a stabilized propagation mode ($D_{\mathrm{In}}/D_{\mathrm{Str}} \geq 0.8$), critical mode ($0.6 \leq D_{\mathrm{In}}/D_{\mathrm{Str}} < 0.8$), and non-stabilized propagation mode ($D_{\mathrm{In}}/D_{\mathrm{Str}} < 0.6$), where D_{In} is the detonation velocity near the inner wall of the curved section and D_{Str} is the detonation velocity in the straight channel. Nakayama et al. [10] considered the stability of detonation wave propagation through curved channels as a basic element of an annular combustor. The researchers visually investigated detonation wave propagation through curved channels with five types of rectangular cross-sections having curvature characterized by different inner radii, and employed multi-frame short-time open-shutter photography (MSOP) to simultaneously observe the shape of the shock wave front and the trajectories of triple points on the detonation wave. The results indicated that new cells were generated smoothly during the stabilized propagation mode within the enlarged cells, which were affected by expansion waves originating from the divergent inner wall, and stabilized the propagation of the detonation wave front through the curved channels. Subsequently, Nakayama et al. [11] investigated detonation wave propagation in various curved channels owing to waves formed using various fuel mixtures such as ethylene–oxygen, hydrogen–oxygen, and acetylene–oxygen diluted by argon. It was concluded that the shapes of the shock wave fronts of stabilized curved detonation waves possessed the characteristic of self-similarity for equivalent values of r_i/λ, where r_i is the radius of curvature of the inside wall and λ is the normal detonation cell width, regardless of the curved channel and the test mixture gas employed. Recently, Nakagami et al. [12] used a disk-shaped rotating detonation combustor (RDC) to observe the structure of detonation waves. Their research revealed that several forward-tilting detonation waves propagated in both the counterclockwise and clockwise directions and explained why the detonation velocity differed so widely from the CJ value.

It is well known that a detonation wave continuously propagates around an annular channel. This is analogous to detonation wave propagation along an infinitely long channel, and some detonation propagation modes have been obtained and clarified in straight tubes, such as stable detonation, spinning/stuttering detonation, galloping detonation, and fast flame waves [13]. While stabilized, critical, and non-stabilized propagation modes occur in curved channels, only the stabilized propagation mode has the front shock behavior and the detonation propagation mechanism in curved channels been revealed in detail [8–12]. However, the characteristics of detonation wave propagation in curved channels for the critical and non-stabilized propagation modes have not been described clearly due to a lack of sufficient length to support detonation propagation, such as periodic variation near the inner wall, or galloping detonation near limit conditions. Moreover, the mechanism of transition of propagation modes is not well understood. The present study therefore employed a new experimental facility having a sufficient curved region to describe detonation wave propagation phenomena in detail. To this end, a helical channel, having a curved region consisting of $\theta = 1620^{\circ}$ in the circumferential direction, was fabricated. The research is mainly focused on transitions between different detonation propagation modes as a function of varying initial pressures of the gas mixture. The evolution of cellular structures and the measured local detonation velocities are used for describing the characteristics of the detonation propagation modes in the helical channel. Furthermore, the mechanism of each detonation propagation mode is also revealed.

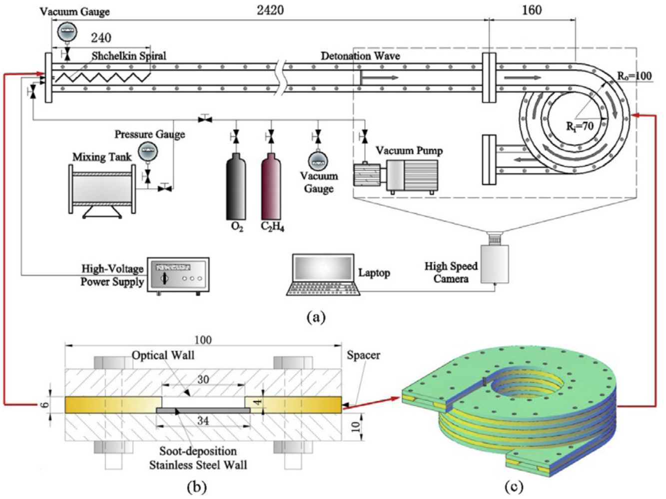

Fig. 1. Schematic of experimental system: (a) experimental setup; (b) rectangular cross-section of the combustor; (c) detailed schematic of helical channel.

2. Experimental details

2.1. Experimental rig

A schematic of the experimental system employed for studying detonation propagation in a curved channel is shown in Fig. 1. The system mainly consists of a combustor, an ignition system, a gas distribution system, and a measurement system. As shown in Fig. 1(a), experiments were conducted in a 2420 mm long 4 × 30 mm rectangular cross-section straight channel followed by a test section consisting of an equivalent rectangular cross-section curved channel with an inner radius of 70 mm and an outer radius of 100 mm. As shown in Fig. 1(b), the combustor is composed of a pair of polycarbonate sheets that are 100 mm wide, which serve as annular plates forming an optical wall and a soot-deposition wall, respectively, and two polycarbonate spacers that are 6 mm thick and 35 mm wide. The spacers were cut by a computer numeric control (CNC) machine to form a 2 × 2 mm step at both inner edges of the sheets for creating an experimental channel with a T-shaped cross-section. A stainless-steel plate for soot deposition was inserted into the 2 × 34 mm rectangular cross-section of the T-shaped channel for characterizing the detonation cell structure, which reduced the detonation propagation channel to a 4 × 30 mm