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Methane–oxygen detonation characteristics near their propagation limits in ducts

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HIGHLIGHTS

- New detonation cellular structures of CH_4–O_2 mixtures near the limits are reported.
- Detonation cell sizes for CH_4–O_2 mixtures are experimentally measured.
- Pressure range for the occurrence of single-headed spinning detonation is explored.
- Detonation velocity deficits in different channels are determined.

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ABSTRACT

In this study, the near-limit behavior of gaseous detonations in three methane–oxygen mixtures (CH_4–$2O_2$, CH_4–$1.5O_2$ and CH_4–$4O_2$) is investigated experimentally. A 36-mm diameter circular tube and three annular channel gaps ($w = 2$ mm, 4.5 mm and 7 mm) were used to look at the effect of different geometries on the detonation limits phenomenon. Photodiodes and smoked foils were employed to measure the time-of-arrival of the detonation wave and record the cellular detonation structure, respectively. As the detonation propagates within the limits, the velocity is steady with only a few percent deficit. By decreasing the initial pressure and, hence, reducing the sensitivity of the mixture, the detonation velocity deficit increases gradually. When the initial pressure is approaching the detonation limits, no steady detonation velocity can be realized, and failure occurs. With decreasing initial pressure, the smoked foil records indicate clearly that the cellular detonation evolves from a multi-headed to double-headed and eventually to a single-head spin as the limits approaches. The single-headed spinning detonations for CH_4–$2O_2$, CH_4–$1.5O_2$ and CH_4–$4O_2$ mixtures in the 36-mm round tube occurs from $p_0 = 3$–7 kPa, 4–10 kPa and 7–16 kPa, respectively. Using different annular channel widths, it is observed that the detonation velocity decreases as the channel gap is reduced.

1. Introduction

Methane (CH_4), is the main component of Natural Gas and produces less carbon dioxide for each unit of heat released, but more heat per mass unit than other complex hydrocarbons, it is thus considered as an environmental-friendly fuel [1]. However, the explosion and detonation accidents regarding methane mixture often occur and result in casualty and severe loss of property at industrial facilities, it received considerable attention in recent years in connection with the safety aspects of large-scale transport and underground coal mines, numerous previous researchers have contributed in discovering the phenomena and the mechanism of explosions and detonations [2–9].

A detonation wave is a supersonic combustion wave across which the thermodynamic states (e.g., pressure and temperature) increase sharply. It can be considered as a reacting shock wave where reactants transform into products, accompanied by an energy release across it [10]. Detonation limits refer to the conditions outside of which a self-sustained detonation wave can no

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longer propagate [10]. For a given explosive mixture, the detonation limits are approached by adding amounts of inert diluent, changing the composition of fuel/oxidizer, lowering initial pressure, or reducing the tube diameter. Well within the limits, the detonation propagates at a steady velocity close to the theoretical Chapman–Jouguet (CJ) value. Near the limits, the propagation phenomenon is generally unsteady and complex [11], and the detonation velocity fluctuates from 40 to 150% of the CJ value [12,13]. Haloua et al. [14] proposed four propagation modes to describe the near-limit phenomena, i.e., stable detonation, stuttering mode, galloping mode, and fast flame.

The study of the propagation limits behavior in narrow gaps is important from the aspect of safety assessment for methane–oxygen mixtures, because the maximum safe gap determined from experiment is an important parameter for deflagration or detonation hazard assessments [15]. Therefore, near limits behavior of detonation has been investigated in recent years. For example, Gao et al. [16], and Fischer et al. [17] measured the minimum tube diameter for steady detonation propagation in various hydrocarbon fuel–oxygen combustible mixtures and in different diameter tubes. The results they obtained confirm the criterion that the minimum tube diameter before detonation failure (i.e., critical condition of detonation limits) equals $\lambda/3$ (λ is the detonation cell size). This criterion was first proposed by Lee [18].

Toward the limits, some general features were also explored. For instance, as the velocity progressively decreases, there exists a maximum deficit when an eigenvalue detonation velocity can no longer be found, considered as the onset of the detonability limits [19]. The investigations of velocity deficit and detonation structure were performed by Gao et al. [12,13], and Lee et al. [9]. Ishii et al. [20–22] studied the propagation behavior of detonation waves for hydrogen/oxygen/argon mixtures in narrow gaps and at low pressures. Near the limits, galloping detonations were observed for unstable mixtures in small diameter tubes, but not for highly argon diluted, stable mixtures. The authors concluded that a strong reaction sensitivity or instability of the combustible mixture is one of the key factors for the existence of the galloping detonations [13]. Although velocity deficit have been extensively investigated near the limits, a quantitative criterion or theory is lacking for predicting the limits. Therefore, more experimental investigations need to be carried out to focus on the detonation near-limit behavior.

Furthermore, it has been established that the failure of detonations is due to the suppression of cellular instability and the wall loss, both causing velocity deficits and eventually failure [19]. Evidence that cellular instability is essential for the self-sustained propagation of detonations is available from experimental [23–27] and numerical investigations [28–36]. Instabilities thus play an important role in the detonation limits. In this study, systematic investigations on the near detonation limits behavior of methane–oxygen mixtures are carried out, typical unstable mixtures with irregular cell pattern, CH_4–$2O_2$, CH_4–$1.5O_2$ and CH_4–$4O_2$, are used, corresponding to equivalence ratios of 1, 1.33 and 0.5, respectively. The propagation of detonations are investigated in a round tube with a 36-mm inner diameter, and also in thin annular channels with different scales ($w = 2$ mm, 4.5 mm and 7 mm). The heights of the channel are small compared to the radius of the annulus so that radial curvature effects are negligible and it can be considered as a two-dimensional geometry.

2. Experimental section

The experimental apparatus consists of a 1.2-m long, 68-mm inner diameter steel driver section followed by a steel test section $L = 2.5$ m in length and an inner diameter of $d = 36$ mm, shown in Fig. 1(a), which is the same one that used in our previous studies [37,38]. Note that in this setup $L/d = 69.4$, too short to observe the galloping or stuttering propagation modes near the detonation limits, and we therefore only focus on whether detonations can sustain a steady velocity over this distance. The annular channel test section is created by inserting smaller diameter tubes supported by fins into the end of the detonation test section. Smaller tubes are used to create three annular channel gaps: $w = 2$ mm, 4.5 mm and 7 mm, shown schematically in Fig. 1(b) and (c). Experiments are also conducted in the 36-mm diameter circular tube without an inserted tube for comparison.

Fiber optics 2.2-mm in diameter and connected to a photodiode (IF-95OC) were spaced periodically along the entire length of the driver and test section. Three optical probes with interval distances of 20 cm were located in the driver section to verify that a CJ detonation was created prior to its transmission to the test section. Twenty optical probes spaced 10 cm apart were mounted on the test section to measure the time-of-arrival of the combustion wave. Typical optical probe traces are shown in Fig. 2. These diagnostics provide the time-of-arrival of the combustion wave determining the trajectory of the detonation. The detonation velocity is obtained by taking the slope of the trajectory.

Three explosive mixtures of methane–oxygen, i.e., CH_4–$2O_2$, CH_4–$1.5O_2$ and CH_4–$4O_2$, with different equivalence ratio were used, the mixtures are “unstable” with highly irregular cell patterns. The reason that those three mixtures were chosen is because we try to find out the different detonation near-limit behavior at fuel-lean, stoichiometric and fuel-rich conditions for CH_4–O_2 mixtures and furthermore, it is attempted to investigate the influence of the equivalence ratio on the detonation limits behavior. The mixtures were allowed to mix in a 20-L bottle by diffusion for at least 24 h in order to ensure homogeneity prior to being used. For any given experiment, the detonation tube was evacuated to at least 100 Pa. The tube was then filled to the desired initial pressure. The initial pressure was monitored by an accurate digital manometer model OMEGA HHP242-030A (0–30 psi) with an accuracy of ±0.10% full scale (i.e., ±0.2 kPa).

Smoked foils were also used to obtain the structure of the detonation in the 36-mm diameter circular tubes. The smoked foils were made of a thin (0.2 mm) plastic sheet uniformly covered with soot and carefully inserted into the test circular tube before each shot.

3. Results and discussions

3.1. Steady and unsteady velocity determination

Fig. 3 shows typical trajectories of the detonation wave at different initial pressures in a 36-mm diameter round tube. The x-axis is the position of the combustion wave at the various optical probes, and the y-axis is the time-of-arrival of the wave. At an initial pressure of $p_0 = 10$ kPa, the detonation velocity is found to be 2189 m/s, 98% CJ value. The CJ detonation velocity is calculated using the one-dimension ideal ZND model and CHEMKIN package. As the initial pressure decreased to $p_0 = 4.6$ kPa, the detonation still can propagate at a steady velocity, but the value is of 0.90 V_{CJ}. Whereas, with the initial pressure further decreases to a lower value, i.e., $p_0 = 2.5$ kPa, there is no steady velocity can be realized, thus, at this initial pressure, detonation fails due to outside its limits. Therefore, the unsteady velocity can be considered as the detonation approaches its limits.

3.2. Round tube

Fig. 4 shows the variation of the steady detonation velocity normalized with CJ value as a function of initial pressure in 36-mm