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The effects of large scale perturbation-generating obstacles on the propagation of detonation filled with methane–oxygen mixture

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ABSTRACT

Orifice plates with large blockage ratios ($BR=0.691$, 0.826, 0.923 and 0.962) are placed in the entrance of the detonation transmission to investigate the artificially large-scale perturbations on the detonation propagation mechanism. Obstacles create large perturbations, thereby generating flow instability to affect the detonation transmission. In this study, stoichiometric methane–oxygen is examined because it has a wide application in the industry; therefore, its safety concerns must be addressed. Furthermore, the methane–oxygen mixture is characterized by a highly irregular cellular detonation front, and it is the representative of those potentially combustible mixtures used in practical aerospace application. Velocity behaviors after the detonation passes through the obstacles with different BR near the critical condition are analyzed; particular attention is paid to the cases for which BR is larger than 0.9 (i.e., 0.923 and 0.962), and the results are also compared with relatively smaller BR cases ($BR=0.691$ and 0.826). The effect of the diffraction, shock reflection and detonation instability on the propagation of detonation is examined. Finally, the analysis of critical length scale between the cell size (λ/d) and BR when the detonation fails or succeeds as it passes the obstacles is also performed, this work aims to explore the mechanism of critical perturbation scale on the detonation propagation.

1. Introduction

Methane (CH_4), which is the main component of natural gas, has a wide range of applications in the fields of heating, cooking, and electricity generation. Methane is also the major component in combustible gas in underground mining. It is well known that methane is flammable and always presents a fire and explosion hazard, and mine gas explosions cause a significant loss of life; a detailed list of coal mine disasters related to gas explosions during 1970–2010 in the U.S. was summarized by Cheng et al. [1]. Recently, fundamental investigations regarding methane explosion have been performed by many researchers, e.g., Zhang and Li [2], Nie et al. [3,4], Shen et al. [5],Wang et al. [6,7] and Zhang et al. [8,9].

After ignition, the combustion wave in methane–oxygen/air mixture develops into deflagration and even detonation in partially confined geometries under the effect of boundary conditions. Detonation is a type of combustion involving a supersonic exothermic front accelerating through a medium that eventually drives a shock front propagating directly in front of it. Over the past several decades, the repeated obstacles were artificially mounted in the path of flame propagation in tubes or channels to study the effect of perturbation or turbulence generated from obstacles on the flame acceleration and deflagration-to-detonation transition (DDT) [10–19]. Valiev et al. [20] provided details of the theory and numerical modeling of the flame acceleration in channels with obstacles during DDT; they also demonstrated the possibility of DDT in the geometry of obstructed channels using numerical methods. Goodwin et al. [21] studied the effect of decreasing the blockage ratio on DDT in small channels with obstacles. They concluded that for $BR=0.35$–0.5, detonation occurred via the creation of a hot spot in a gradient of reactivity that forms behind a Mach reflection. However, for a high blockage ratio ($BR=0.8$), the failure of detonation was mainly due to insufficient reactants for the detonation front to traverse past the upstream obstacles.

The instabilities may also have influences on detonation propagation, as has been proposed by the early work of Lee [22], in which it was argued that the onset of detonation in a smooth tube at the critical state is associated with the instability mechanisms in reactive media. The consequence of the instability is the formation of discrete localized explosion centers, which then leads to the

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development of the detonation wave. However, during the period in which the detonation transmits through obstacles, the competing effects of high blockage ratios that are associated with instabilities and diffracting has not been examined yet and is still open for discussion. Recently, evidence has been found to support the argument that obstacles have a significant effect on the detonation propagation. For example, Teodorczyk [23] performed an experimental study of the effect of obstacles (blockage ratio, *BR* = 50%) on the detonation propagation behavior in a hydrogen–air mixture; different propagation regimes of turbulent flames and detonations in small rectangular channels with obstacles were described. Mehrjoo et al. [24,25] introduced a technique for promoting detonation transmission from a confined tube into a larger area; they investigated the effect of small perturbations with varying blockage ratios (*BR* = 8% and 10%) on the critical tube diameter in unstable and stable mixtures. Ogawa et al. [26] numerically studied the detonation passes around array obstacles; they found the collisions between detonation–detonation, detonation–shock, and shock–shock produce strong transverse shocks that promote the detonation. By inserting Shchelkin spiral obstacles with different degrees of roughness, the positive and negative effects of the roughness on the detonation propagation limits were examined by Zhang [27].

Based on extensive experimental and numerical work, it has been established that obstacle-induced perturbation increases the flame surface area and the transport of local mass and energy, thereby increasing the flame burning rate. However, the perturbation may also result in flame stretching and rapid mixing of the burned gas, adversely affecting further flame evolution and even causing the flame to be completely quenched [28]. Hence, the scale of the perturbation is of significant importance to the initiation and propagation of detonation. However, the quantitative analysis of the perturbation scale on initiation and propagation of detonation still requires further exploration.

Furthermore, although a number of investigations have been performed to study the effect of obstacles on the detonation propagation, most of them studied obstacles with a small blockage ratio. Little attention has been paid to large blockage ratio (greater than 0.9) obstacles on detonation propagation, despite it being a more practical and important problem in industry safety. As suggested by Radulescu et al. [29–31], detonation in methane–oxygen is unstable, and the detonation structure pattern that is recorded from soot-foil is highly irregular because of its high values of activation energy (hence, highly temperature-sensitivity). Thus, a small perturbation may result in a large fluctuation in the reaction rate. As a result, more effort is required to explore the large scale perturbation induced by high *BR* obstacles on the propagation of detonation. To date, it is still not clear whether the detonation can survive after suffering a large-scale perturbation and to what extent the perturbation facilitates or prohibits the detonation propagation. In addition, the cellular structure of methane–oxygen is extremely irregular at high initial pressure, and the detonation cell size is on the order of several millimeters at the atmospheric pressure; the critical length scale between the cell size and the blockage ratio when the detonation fails or succeeds as it passes through the obstacles is important for the chemical industry safety and the detonation pulse engine design and, therefore, must be addressed. This work aims to investigate the mechanism of the perturbation scale on the propagation of detonation and the relationship between the blockage ratios of the obstacles and the length scale of detonation cellular structure.

2. Experimental details

A brief description of the experimental setup is given below (see our previous literature reports [32–34] for detailed information). The experiments were performed in a shock tube with a total length of 3.7 m; the tube was divided into two parts, the driver section and the test section. The driver section is 1.2 m long and has an inner diameter of 68 mm, and the test section is 2.5 m in length and has an inner diameter of 36 mm. An obstacle was located between the driver and the test section (the position is given in Fig. 1), and the blockage ratio of the obstacle was calculated by $BR = 1-(d/D)^2$ in which d is the hole diameter of obstacle and D is the inner diameter of test section, i.e., D = 36 mm. *BR* was varied by changing the hole diameter. In this study, orifice plates with four dimensions (i.e., d = 20, 15, 10 and 7 mm) served as obstacles, which yielded *BR* = 0.691, 0.826, 0.923 and 0.962, respectively. The criterion we used to select the hole diameter of the orifice was to ensure we have different *BR* obstacles to allow for a comparison. Blockage ratios higher than 0.9 were selected, because most of the previous studies had focused on the relatively low blockage ratio obstacles, e.g., [14,17,23,25,35,36], whereas few focused on the effect of significantly high blockage ratio obstacles on the detonation propagation. *BR* = 0.923 and 0.962 were chosen because of the machine work of drilling the hole.

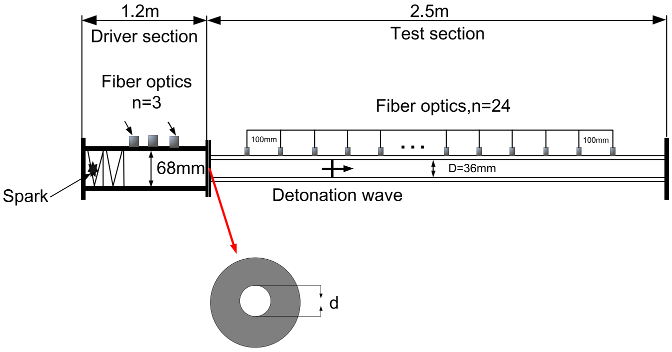

Fig. 1. Experimental apparatus.

Stoichiometric methane–oxygen (CH_4–$2O_2$) mixtures were considered as the test mixtures, and the initial temperature for all the mixtures used in this study was 300 K. The test mixture was mixed in a 40-L bottle by diffusion for more than 24 h to ensure homogeneity prior to being used. The detonation tube was evacuated to lower than 100 Pa (absolute pressure) before each experiment. It was then filled with the combustible mixtures to the desired initial pressure. The initial pressure was monitored by an accurate digital manometer, model OMEGA HHP242-030 A (0–30 psi), with an accuracy of ± 0.10% (i.e., ± 0.2 kPa) full scale.

In the experiment, optical fibers connected to a photodiode (IF-950C) were employed to record the time-of-arrival (TOA) of the detonation wave. Three optical fibers with an interval distance of 20 cm were located in the driver section to verify a Chapman–Jouguet (CJ) detonation was created before it transmits to the test section. In the test section, 24 optical fibers with an interval distance of 10 cm were used to measure the TOA; the distance between the obstacle and the first optical fiber in the test section was 10 cm. The local velocity of the wave was determined by calculating the distance over two neighboring signals. Figure 2 shows a typical TOA signal for a single shot in CH_4–$2O_2$ mixture at the initial pressure $p_0 = 10$ kPa for an obstacle with *BR* = 0.691.

3. Results and discussions

3.1. Velocity behavior

(a) No obstacle, *BR* = 0

Figure 3 shows the detonation velocity of CH_4–$2O_2$ in the tube without obstacle at the super-critical condition (a, b), critical (c)