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Effect of fully blocked non-rigid boundary conditions on detonation wave

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ABSTRACT

For the past half century, the research on boundary conditions on the detonation wave resulting in a velocity deficit or detonation failure mainly focused on the rough-walled or acoustically absorbing condition in one/two-dimensional models. In this paper, experiments on gaseous detonation propagation are conducted in the tube fully blocked by the non-rigid obstacles, under 20 kPa with the explosive gas of $C_2H_2 + 2.5O_2 + nAr$. The polypropylene membrane (PET) is selected as the non-rigid obstacle in this paper. The detonation wave behavior is to decelerate, accelerate, and overdrive prior to reaching a stable state once passing through the PET obstacles. When the initial pressure decreases or the layers of PET obstacle increases, the detonation wave will transit from a velocity deficit mode to a failure mode after deceleration occurs. With the PET layers increasing, the velocity minimum decreases continuously from $0.61\, v_{CJ}$ ($m = 1$) to $0.23\, v_{CJ}$ ($m = 8$). The propagation mode is associated with the average diameter of the hole after passing through the PET obstacles. The detonation wave will diffract when the average diameter decreases. In addition, the Mach reflection degenerates to the expansion wave and self-ignition ceases. As the shock is reflected from the tube wall, the initial regular reflection changes to a Mach reflection and auto-ignition forms again. For the multi-PET obstacles, the velocity after obstacles fluctuates more violently. The instability is regarded as the critical factor in the deceleration and acceleration.

1. Introduction

It is generally known that combustion wave propagating in a premixed gas can be classified as either deflagration wave or detonation wave. Compared with deflagration, detonation is more significant in leading to human injuries, death and destruction of equipment in industrial processes. Boundary conditions are regarded as the key measurement to predict and appraise the probability of detonation. Fay (1959) described accurately the influence of the boundary layer on detonation propagation, then Lee (2008) achieved great advances in gas explosions experimental researches since the 1960s. At present, more and more researchers focus on the flame acceleration (Ugarte et al., 2016), DDT (deflagration to detonation transition), detonation limit and the failure mechanism (Zhang, 2016) in rough conditions.

How obstacles have effect on the DDT has widely been studied (Ciccarelli et al., 2005; Johansen and Ciccarelli, 2009) via using fuel–air mixtures to establish the critical conditions to assess the industrial hazard risk. However, it has been argued that an obstacle influenced flame acceleration by causing positive coupling between the flame and a turbulence (Moen et al., 1980). An early investigation by Urtiew and Oppenheim (1966) showed multi-frame schlieren photographs observing the DDT process, in which the detonation wave was established instantaneously as the consequence of the localized explosion between the leading shock wave and turbulent flame front. In addition, the mechanism of DDT above repeated obstacles was studied by Obara et al. (2012), and the pitch and height of the repeated obstacles were varied to obtain the optimum conditions that caused DDT a short distance from the ignition source. Peraldi et al. (1988) proposed that for an orifice plate filled tube, the quasi-detonation regime limits were correlated with $d/\lambda = 1$, where d was the orifice plate opening, and λ was the detonation cell size. Similarly, Cross and Ciccarelli (2014) also performed the detonation in tubes filled with orifice plates and showed that the wave propagated at a velocity above the speed of sound in the products was well correlated with $d/\lambda = 1$. In Maeda et al.'s study (2016), the DDT process in a square cross-sectional channel equipped with repeated obstacles was investigated for a highly reactive mixture. The results showed that the DDT distance was reduced compared with the case without obstacles, and a detonation transition did not always require global flame acceleration

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beyond the speed of sound for highly reactive combustible mixtures.

For decades, the research on detonation has been changing from mechanism and experiment to all of the modern approaches, the application focused more from hazard assessment to high efficiency combustion. However, the boundary condition has always been as the key point for the detonation phenomenon (Zhang et al., 2015). An early experiment on detonation and shock wave absorption was reported by Evans et al. (1955), who studied the transition to detonation in a tube lined with an acoustic damping material and found that the transition was delayed or even prevented. Later it was recognized that transverse waves were essential to the propagation of detonation waves (Strehlow, 1969). Besides, Radulescu and Lee (2002) conducted experiments in porous-walled tubes to clarify the important role of the transverse wave structure in real detonations. The effect of porous coatings on the walls was increased in tubes that were of a critical diameter of the stationary detonation propagation (Teodorczyk and Lee, 1995). Subsequently, various devices to suppress the detonation were compared by Guo et al. (2002), and it was found that the metal wool was much more effective at suppressing a detonation wave than the perforated plates. Furthermore, Makris et al. (1995) suggested that the failure mechanism was governed by the detonation instability of the given explosive mixtures. In addition, experiments were carried out to investigate the failure mechanisms in the critical tube diameter phenomenon for stable and unstable mixtures (Mehrjoo et al., 2014). Bivol et al. (2016) studied the deceleration and attenuation of a detonation wave in a cylindrical channel with a hydrogen–air mixture, and the results showed that increasing the thickness of the porous material on the walls led to further attenuation of the detonation wave. It was also found that the recovery of the detonation wave was possible if the shock wave velocity did not drop below the Chapman–Jouguet acoustic velocity.

A quenched detonation wave appeared when a detonation front diffracted over an abruptly expanding geometry, resulting in a so-called decoupled shock–flame complex. According to Matsui and Lee (1979), the detonation cell size had to be large enough in order to trigger quenching. Lee (2008) has proposed that differences in diffraction behavior of mixtures with regular and irregular cellular structure reflects a fundamentally different propagation and failure mechanism in the two cases. Another viewpoint was that the failure mechanism was associated with a decoupling of the shock and reaction zone (Anderson and Dabora, 1992). Bhattacharjee et al. (2013) showed that decoupling would take place when the time scale characterizing the lead shock decay was comparable to a critical shock decay time computed from idealized reaction zone models. The observed relationship between cellular regularity and diffraction behavior may indicate a link between the extent of fluctuation within the reaction zone and diffraction behavior but this was speculative. Mostofi et al. (2017a,b) and Babaei et al. (2015, 2016); Babaei and Mostofi (2017) investigations, a series of experimental tests have been conducted on aluminium alloy and mild steel plates with different thicknesses to examine large ductile transverse deformations of rectangular plates with clamped edge conditions subjected to gas mixture detonation loading. The main aim of the experimental section is to investigate the effects of pre detonation pressures of acetylene (C_2H_2) and oxygen (O_2) gasses and different mixture ratios on the dynamic response of specimens. The numerical simulation and empirical modelling can be useful methods to correctly predict dynamic plastic response.

Research of effects of boundary conditions on DDT, failure mechanism and detonation diffraction with obstacles is beneficial for understanding the detonation wave evolution process. In the above-mentioned researches, most researchers focused on the propagation characteristics as the obstacle BR is less than 1 (Zhang, 2016; Goodwin et al., 2016). Nevertheless, obstacles with BR = 1 possibly exist in the actual industrial processes, such as the air door in the coal mine. If a detonation wave is formed in the coal mine roadway, the detonation wave whose overpressure is far higher than that of deflagration may destroy the air door and propagate continuously. Then, clarifying the propagating characteristics of the detonation wave after its passing through the air door is also significant for the safety protection in the coal mine. Therefore, it is also significant to study the characteristics of detonation wave passing through obstacles with BR = 1. Up to now the research on detonation waves passing through BR = 1 is relatively scarce. In this paper, the obstacle (BR = 1) was set to isolate the media and to resist the impact of the detonation wave. A $D_i = 50$ mm, $L = 4000$ mm detonation tube was built with carbon steel. Photoelectric diodes were installed to measure the detonation velocity and smoked foils were used to record the cellular structure. Polypropylene membranes (PET) as the fully blocking obstacles were installed vertically between two flanges to study the detonation propagation characteristics.

2. Experiments

2.1. Experimental setup

The experimental apparatus is shown in Fig. 1. It is mainly composed of the four components below.

a Detonation tube.
b Charge/discharge system.
c Data acquisition system.
d Ignition device.

The detonation tube was fabricated from a DN50 ($D_i = 50$ mm) steel and quartz tube with fittings dividing it into a 1300 mm driver section and a 2700 mm test section. A 600 mm (axial direction) spiral wire was inserted to increase the flame turbulence for rapid detonation transition in the driver section. When detonation occurred, the detonation velocity was in theory equal to that of the flame front. Therefore, the detonation velocity could be obtained by measuring the flame front velocity. The flame front was captured by a photodiode. When the detonation wave passed through the photodiodes along the tube, the visible light which was radiated by the flame front excited the photodiodes. Then the average flame front velocity can be calculated by dividing the distance between the two adjacent photodiodes by the time interval. At the end of the driver section, two photodiodes (N_1, N_2) were set obtained the flame front velocity to confirm whether the detonation was generated. Another 14 photodiodes were repeated regularly along the axial direction on the test section. The distance interval of N_1–N_6 was 200 mm and that of N_7–N_{16} was 150 mm, as shown in Fig. 1.

Smoked foils made of 0.5 mm mylar plate covered with carbon powder were installed to record the cellular structure of the detonation front. The bent foils expanded to cling onto the wall, giving minimal disturbance to the flow. According to Dalton's law of partial pressure, the gas mixtures $C_2H_2 + 2.5O_2 + n\mathrm{Ar}$ were stored in the premixing tank, and fully mixed for more than 24 h.

Experiments were conducted to study the detonation wave propagation characteristics after passing through the obstacle (BR = 1). For rigid obstacles, the detonation wave cannot pass through the obstacle into the next space because of the high intensity. Taking into account the position of the rupture and the sealing of the obstacle material, polypropylene membranes were selected as the obstacles (BR = 1) in the experiments.