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The influence of wall roughness on detonation limits in hydrogen–oxygen mixture

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ABSTRACT

In this study, wall roughness is generated by inserting a Shchelkin spiral with different wire diameter (δ) and pitch (L_s). Roughness is defined as the ratio δ/L_s. The effect of tube wall roughness on the detonation limits in stoichiometric hydrogen–oxygen mixture is systematically examined. The detonation velocity is determined from optical fibers and shock pins spaced at 10 cm intervals along the tube. Smoked foils are employed to record the cellular detonation structure near the limits. The experimental results indicate that detonation in both smooth and rough sections can be self-sustaining and can propagate with a steady velocity as the conditions are well within the detonation limits. However, the detonation velocity decreases as it transmits into the rough-walled tube. The velocity deficit is more significant in tubes with larger roughness due to the interaction of the detonation reaction zone and the boundary layer formed behind the shock. Single-headed spinning structure is observed as the detonation approaches the limits in the rough-walled tube. Below the minimum initial pressure at which single-headed spinning phenomena occur, detonation fails and decays to deflagration, and the minimum velocity is approximately $0.4V_{CJ}$. It is found that wall roughness can either promote or prohibit the detonation propagation limits. When the roughness is smaller than 0.231, it is believed the turbulence generated from the roughness facilitates detonation and extends the detonation limits. However, when the roughness is larger than 0.333, low-velocity behavior plays a dominant role in prohibiting the detonation, which indicates that roughness above a certain level has a negative effect on detonation limits.

1. Introduction

Detonation limits refer to the conditions outside of which a self-sustained detonation wave can no longer propagate, which is one of the fundamental dynamic parameters of detonation physics, as well as a practical problem in industrial safety [1,2]. The detonation limits can be achieved through various methods, for example, changing the thermodynamic properties (initial pressure, composition, amount of inert diluent, etc.) of the mixture and the boundary conditions (inner diameter, annular gap, roughness, etc.) of the tube. When detonation propagates well within the limits, the velocity is steady and near the theoretical Chapman–Jouguet (CJ) value. Near the limits, the propagation phenomenon is unsteady and more complex. Four propagation modes near the detonation limits were proposed by Haloua et al. [3]. These are stable detonation, stuttering mode, galloping mode, and fast flame.

Most of the previous investigations on the detonation limits were performed in smooth circular tubes, annular channels and narrow gaps. For example, Gordon et al. [4] studied detonation limits in hydrogen-air, hydrogen–oxygen and hydrogen–oxygen-diluent mixtures using a 12 m long 20 mm diameter tube. They observed single head spinning detonations over a wide range of conditions near the limits. Lee et al. [5] studied near-limit propagation of detonations in various explosive mixtures using a long circular tube. They used a Doppler interferometer to continuously measure detonation velocity near the limits. They also observed large velocity fluctuations as the limits were approached. Recently, Kitano et al. [6] studied the propagation of detonation in a hydrogen–oxygen mixture in various small diameter tubes. They investigated the cellular structure and velocity behavior. A modified Zel'dovich-von Neumann–Döring (ZND) model that takes into account heat and momentum losses to determine the detonation limits was developed and validated. Camargo et al. [7] studied the near-limit propagation of detonations of different mixtures in small diameter round tubes. Stable (with regular transverse wave pattern) and unstable (with irregular transverse wave pattern) mixtures were examined to investigate the role that instability plays in the

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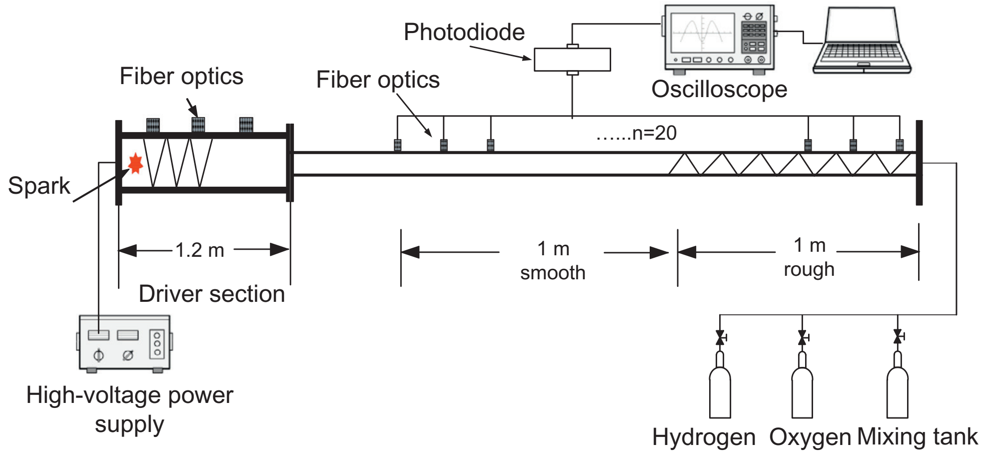

Fig. 1. Experimental setup.

detonation limits, and an operational criterion for the propagation limits was developed. Teng et al. [8–11] argued that the cellular instability is essential for the self-sustained propagation of detonations. Some investigations have been carried out to look at the detonation limits in thin annular channels and narrow gaps. Chao et al. [12] studied the detonation limits of hydrogen–oxygen and acetylene–oxygen mixtures with argon dilution in annular channels. Because detonation in those mixtures has a ZND structure, the failure mechanism was found to be due to flow divergence caused by the negative displacement thickness of the boundary layer behind the precursor shock of the detonation wave. The near detonation limits behavior of methane–oxygen, hydrogen–oxygen–argon and binary fuel blends of methane/hydrogen mixtures were studied by Zhang et al. [13–16]. The composition of the binary fuel causes the different degrees of instability in the mixture. The effect of instability on near-limit behavior was systematically studied. Ishii et al. [17,18] investigated the propagation of detonations in narrow rectangular channels. The limits were approached by reducing the channel height for various hydrogen–oxygen mixtures with argon or nitrogen dilution. They found that the combination of the calculated velocity deficit and the number of cells in the channel is essential for detonation limits. Wu et al. [19,20] investigated the flame acceleration and detonation propagation limits in micro-gaps (i.e., 260 μm and 120 μm). Their visualizations clearly showed the shape of the outward propagation reaction wave. The cellular pattern also indicated that the deflagration transition to detonation occurs earlier and within a shorter induction distance in the smaller gap.

A rough-walled tube was used to facilitate the DDT (deflagration-to-detonation transition). These studies were undertaken because of their importance for the industrial safety of nuclear power stations and propulsion devices [21], e.g., PDE (pulse detonation engines) and RDE (rotating detonation engines). Recent experimental and numerical simulation work [22–25] on the DDT in rough tubes has provided insights into understanding its mechanism. Wall roughness is created by inserting obstacles. Studies have been performed to look at the flame acceleration and DDT under different scales of orifice [26–31]. The roughness can be produced by adding porous-walled tubes. A previous investigation was carried out by Radulescu et al. [32,33] to research the failure mechanism of gaseous detonation in porous-walled tubes. More recently, results were reported by Starr et al. [34]. They concerned the velocity deficit and detonation structure near the limits in tubes with porous walls using stable and unstable mixtures. They found that the detonation limits in rough tubes are wider than those in smooth tubes.

In smooth-walled tubes, the maximum velocity deficit of a steady self-sustained detonation is seldom larger than 20% V_{CJ}. However, the maximum velocity deficit was observed to be more than 60% V_{CJ} in a very rough tube. Starr et al. [34] claimed that the turbulence generated by the wall roughness facilitates the propagation of the detonation and hence extends the limits. In fact, the influence of roughness on the detonation limits has both positive and negative effects. One “positive effect” is that the turbulence does facilitate the onset of detonation as argued in Starr et al. [34], which provides a key mechanism for the self-sustained propagation of low-velocity detonations. However, detonation velocity in the rough tube is much lower than that in the smooth section. The low-velocity propagation behavior renders the detonation more prone to failure because the detonation suffers more losses from the wall. However, quantitative analysis of these two aspects of roughness on the detonation limits is still lacking. In this study, the wall roughness is generated by inserting a Shchelkin spiral with different wire diameter (δ) and pitch (L_s). Roughness is defined by the ratio δ/L_s. A wider range of roughness (from 0.133 to 0.75) is used to systematically investigate the effect of a rough-walled tube on detonation near-limit behavior. The results are compared with the smooth tube under the same initial condition to explore the behavior of detonation limits in rough tubes.

2. Experimental details

2.1. Experimental setup

Experiments were performed in a 1.2 m long, 68 mm inner diameter steel driver section, followed by a test section of tube 2.5 m in length with an inner diameter of 36 mm. The mixture was initiated by a high-voltage spark, which was used in our previous studies [35–40]. These are shown in Fig. 1. In the test section, the length of the Shchelkin spiral (rough section) is 1 m. This is located at the end of test section. The smooth tube is also 1 m in length, and it is seated before the rough section. This is used for comparison with the data in the rough section.

Fiber optics 2.2 mm in diameter connected to a photodiode (IF-950C) were employed to record the time-of-arrival (TOA) of the detonation wave in both the smooth and rough sections. Twenty optical fibers with an interval distance of 10 cm are used to measure the TOA of the combustion wave. Three optical fibers with an interval distance of 20 cm were located in the driver section to verify that a CJ detonation was created before it transmits to the test section. Near the detonation limits, self-luminescence peaks were not observed in some cases because of the low luminescent