Experimental Thermal and Fluid Science 91 (2018) 345–353

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

# Detonation characteristics of stoichiometric $H_2$–$O_2$ diluted with Ar/$N_2$ in smooth and porous tubes

Luqing Wang[a], Honghao Ma[a,b,*], Zhaowu Shen[a], Zhiqiang Fan[c]

[a] CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei 230026, Anhui, PR China
[b] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[c] College of Science, North University of China, Taiyuan 030051, Shanxi, PR China

ARTICLE INFO

*Keywords:*
Hydrogen
Limiting pressure
Detonation velocity
Cell size

ABSTRACT

Detonation propagations in stoichiometric $H_2$–$O_2$ mixtures diluted with Ar and $N_2$ were experimentally investigated in both smooth and porous tubes. The porous wall was made of stainless steel mesh with a 28.6% porosity. Optical sensors were mounted on the tube wall to capture the time of arrival of the detonation wave. Smoked foils were employed to record the cell structure. The limiting pressure for a detonation was determined from the experimental detonation trajectories. The results show that above the limiting pressure, a detonation can be self-sustained with a steady velocity. Past the limiting pressure, a detonation fails and only a deflagration can be observed. In the porous tube, a detonation decays to a deflagration with the velocity of 0.4 $V_{CJ}$ 0.5 $V_{CJ}$, in which $V_{CJ}$ is the theoretical CJ detonation velocity. Smoked foil patterns indicate that at a fixed initial pressure and diluent concentration, the cell size is larger and the limiting pressure is higher in $N_2$ diluted mixtures than that of Ar diluted mixtures. This causes higher limiting pressure of $N_2$ diluted mixtures both in smooth and porous tubes. The detonable range in the porous tube is found to be narrower than for the smooth tube. This manifests that the attenuation of transverse waves impedes the propagation of the detonation. The failure conditions for $H_2$–$O_2$–Ar/$N_2$ mixtures are not uniform in the present study, i.e., $D/\lambda \approx 6$–$9\lambda$, where $D$ and $\lambda$ are the inner diameter of the tube and the cell size.

## 1. Introduction

Hydrogen ($H_2$) is a promising fuel which can be an excellent alternative energy source to replace fossil fuels due to its remarkable properties, e.g., high thermal efficiency, low energy ignition [1,2], no greenhouse gas emissions, etc.. However, because of its wide flammability limit, the existence of potential explosions or even detonations always threatens personal and property security [3–9]. Hence, prior to the wide use of $H_2$ in industry, the related safety issues must be taken into account and assessed.

For the characterization of detonation properties and sensitivities, measurement of the dynamic parameters of detonation waves, i.e., detonation limits [1,10–15], critical tube diameter [16,17], critical ignition energy [18–21] and detonation cell size [1,5,10,14,15,22–24], is of great significance, which can provide substantial information to reveal detonation essences. Detonation limits, referring to the conditions outside of which a self-sustained detonation wave is unable to propagate, is a natural consequence of boundary conditions on the propagation mechanisms of the detonation [1,11,14]. Zhang et al. [14,15] and Gao et al. [1] found that in round and annular tubes, the detonation velocity decreases rapidly with the decreasing of the initial pressure, and the detonation cannot sustain a steady velocity if the initial pressure is lower than a critical value (known as the detonation limit), i.e., the detonation fails. Well within the detonation limit, the detonation propagates with a velocity closed to the Chapman-Jouguet (CJ) value with a small deficit. The velocity deficit can be ascribed to the viscous boundary layer on the tube wall and its effect upon the flow in the reaction zone of the detonation front [25]. Based on the loss due to the uniform flow divergence caused by the effect of the boundary displacement layer, a theory was derived from the conservation equations of a quasi-one-dimensional flow, which can be used to compute the velocity deficits [1,14,25].

For hazard assessment, measurement of the detonation cell size provides fundamental information associated with the detonation sensitivities [14,22]. The detonation cell structure, which represents the trajectory of the triple points, can be experimentally recorded using the

* Corresponding author at: CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei 230026, Anhui, PR China.
*E-mail address:* hhma@ustc.edu.cn (H. Ma).

http://dx.doi.org/10.1016/j.expthermflusci.2017.08.021
Received 17 March 2017; Received in revised form 11 July 2017; Accepted 19 August 2017
Available online 24 August 2017
0894-1777/ 

**Nomenclature**

*Latin*

| | |
|---|---|
| $a_1 \sim a_7$ | constant coefficient |
| $C_p$ | specific heat (J/mol/K) |
| $D$ | tube diameter (mm) |
| $L$ | length of test section (mm) |
| $N$ | test times |
| $R$ | universal gas constant (J/mol/K) |
| $p_0$ | initial pressure (kPa) |
| $p_c$ | limiting pressure (kPa) |
| $S_N$ | standard deviation of measured detonation velocities (m/s) |
| $V$ | measured detonation velocity (m/s) |
| $\overline{V}$ | average detonation velocity (m/s) |
| $V_{CJ}$ | theoretical CJ detonation velocity |

*Greek*

| | |
|---|---|
| $\delta$ | wire diameter (mm) |
| $\varsigma$ | mesh aperture (mm) |
| $\theta$ | wall porosity |
| $\lambda$ | detonation cell size (mm) |

smoked foil technique. Substantially, as the induction zone thickness could be correlated with the detonation cell size [26], observations of cellular structures or measurements of cell sizes could evaluate the critical energy, the critical tube diameter, the detonation velocity deficit and ultimately, the stability of the detonation [5,22,27–30].

As claimed by Lee [31], the boundary conditions can be divided into three kinds, i.e., smooth wall, rough wall (obstacle) and acoustically absorbing wall. However, most of the previous studies related with the detonation limits were conducted in smooth tubes, such as circular tube and annular tube. Recently, Zhang [32] investigated the detonation limits in stoichiometric $H_2$–$O_2$ mixture in rough walled tubes by inserting Shchelkin spirals with different roughness. The results showed that rough tubes have both positive and negative effects on the propagation of detonations, and the limits are wider than those in smooth tubes. In addition, the velocity deficit is more prominent, with the maximum value of about 60%.

The detonation structure is considered to be a closely coupled shock-deflagration complex [33–35] and comprises interacting normal and transverse waves [36]. To form transverse waves, the rigid wall plays a vital part. When a rigid wall is replaced by acoustically absorbing materials, the transverse waves are attenuated or even die out. As the transverse waves and their interactions act a crucial role in the surviving of the detonation, attenuation of the transverse waves by porous materials results in the failure of the detonation, which can be seen in previous studies [36–43]. Radulescu and Lee [43] also found that in tubes lined with steel mesh, transverse wave interactions are of essence in the failure mechanism of gaseous detonations.

In this study, we attempt to explore the detonation behaviors $2H_2$–$O_2$–Ar/$N_2$ mixtures in both smooth and porous tubes. The porous wall is produced by inserting tightly rolled stainless steel mesh. Optical sensors were employed to record the time of the arrival (TOA) of the detonation. The detonation cell was obtained using smoked foils and the cell size was measured carefully. The effects of dilutions as well as porous wall on the detonation characteristics were investigated.

## 2. Experimental details

### 2.1. Experimental setup

Experiments were performed in a 5000 mm circular tube with the inner diameter of 32 mm, as is shown in Fig. 1. The tube consisted of two modules with the equal length, i.e., a smooth driver module and a test module (smooth or porous). Herein, a stainless steel mesh (see Fig. 2) was tightly rolled to insert into a 2500 mm long tube (46 mm inner diameter) to generate the porous test module. The wire aperture ($\varsigma$) and the wire diameter ($\delta$) are 0.15 mm and 0.35 mm, respectively.

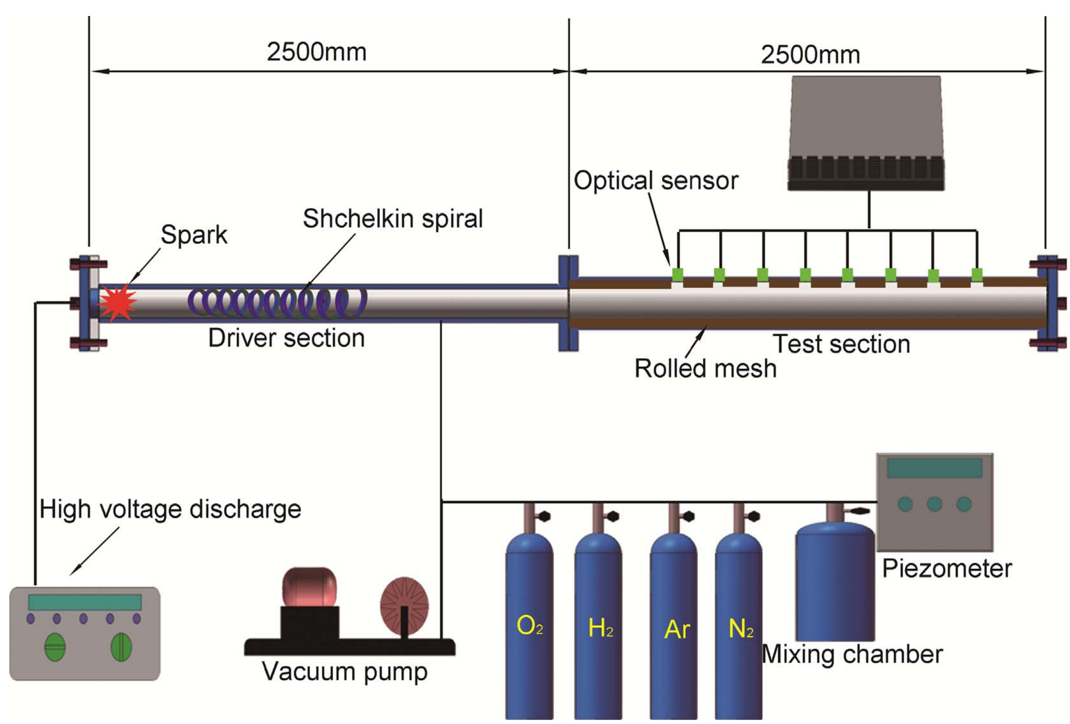


**Fig. 1.** Sketch of the experimental apparatus.