Aerospace Science and Technology 69 (2017) 193–200

Contents lists available at ScienceDirect

Aerospace Science and Technology

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An experimental study on the detonability of gaseous hydrocarbon fuel–oxygen mixtures in narrow channels

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ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 12 June 2017
Accepted 27 June 2017
Available online 1 July 2017

Keywords:
Detonability
Hydrocarbon fuels
Velocity deficit
Cellular structure

ABSTRACT

This study was performed to address the detonability related to gaseous hydrocarbon fuel–oxygen mixtures (i.e., CH_4–$2O_2$, C_2H_6–$3.5O_2$ and C_3H_8–$5O_2$) in different ducts (36-mm circular tube and annular channel heights with 2-mm, 4.5-mm and 7-mm gaps). The results show that detonation can achieve self-sustained propagation with a steady velocity because the conditions are within the detonability in C_1–C_3 alkanes/oxygen mixtures; the velocity decreases as the detonation transmits into the annular channel due to increased heat and momentum losses from the wall. A modified theoretical model is proposed to predict the detonation velocity deficit for different size channels. Through a comparison with the experimental results, this model was determined to be suitable for predicting the velocity deficit in C_1–C_3 alkane fuel with oxygen mixtures within reasonable accuracy. Both experimental and theoretical predicted data indicate that velocity deficit is more significant in the smaller channel gap, which verifies that losses are more prominent in the narrower channel. Furthermore, the detonation cellular structure from the smoked foil was measured to analyze the propagation mechanism. The results show detonation has a single-headed spinning structure when detonability is approached. The onset of single-headed spinning detonation of CH_4–$2O_2$, C_2H_6–$3.5O_2$ and C_3H_8–$5O_2$ in a 36-mm circular tube occurs from $p_0 = 3$–7 kPa, 4.2–5 kPa and 3.5–3.6 kPa, respectively. This suggests the pressure range of the single-headed spinning phenomenon is narrower for hydrocarbon fuels with more carbon atoms.

1. Introduction

Methane (CH_4), ethane (C_2H_6) and propane (C_3H_8) are the three simplest gaseous hydrocarbon alkane fuels but are important and have many industrial and civil applications for heating and cooking. For example, methane and ethane are the main components of natural gas and are normally stored as gases under pressure; therefore, they are easier to transport as liquids, which requires both compression and cooling of the gas. Furthermore, C_1–C_3 alkanes are widely used as fuels in internal combustion engines and recently were considered as fuels in the research of Pulse Detonation Engines (PDE) due to their excellent combustion performance [1–7].

In the detonation ability condition, self-sustained propagation causes decay up to failure, referring to the detonability or detonation propagation limits [8–14]. For a given explosive mixture, the detonability is approached by adding inert diluent, changing the composition of fuel/oxidizer, decreasing the initial pressure, or reducing the tube diameter. Knowledge of the detonability of C_1–C_3 alkanes is important to ensure safety in industries that produce or use these alkanes, especially when these fuels are used in aerospace propulsion. Numerous investigations have been performed to understand the phenomenon and mechanism of detonability in hydrocarbon fuel–oxygen mixtures.

Near the detonability condition, a spectrum of unstable near-limit phenomena (e.g., spinning, galloping, pulsating and stuttering modes) can occur; e.g., Lee et al. [15] investigated near-limit propagation of detonations in various explosive mixtures using a Doppler interferometer to measure the detonation velocity. Chao et al. [10] studied the detonation limits of hydrogen–oxygen and acetylene–oxygen mixtures with more than 50% vol. of argon dilution in annular channels. Kitano et al. [16] observed single-head spinning detonations for a wide range of initial pressures near the limit. Fischer et al. [17] studied detonation limits of stoichiometric ethane–oxygen mixtures in capillary tubes. A velocity deficit of up to 50% V_{CJ} was measured near the limit. Camargo et al. [9] found that, as the limit was approached, the detonation velocity decreased and was observed to fluctuate near the limit. In

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http://dx.doi.org/10.1016/j.ast.2017.06.032
1270-9638/

stoichiometric acetylene–oxygen, a velocity deficit of 15% V_{CJ} was measured near the limit. Researchers also attempted to develop models or theories to predict the detonability and propagation limits. Zeldovich [18] was possibly the first to develop a detonation limit theory in which the effects of heat and momentum losses on the tube wall were considered. Fay [19] argued that the boundary layer causes the streamlines to diverge in the reaction zone and reduce the detonation velocity. Lee [8] indicated that the Fay model agreed with the experimental data in high-argon diluted stable mixtures, but this model did not agree with the results in unstable mixtures. This indicates that detonations in unstable mixtures with argon dilution were less affected by the boundary layer because the propagation mechanism is dominated by instability in the detonation structure.

The aforementioned literature review indicates that, due to the complex phenomenon near detonation propagation limits, a limit criterion is necessary and the quantitative theory for predicting the limit needs to be improved. In this study, the three gaseous hydrocarbon fuels chosen were methane, ethane, and propane because of their broad applications in industry. Additionally, they belong to the same alkane group, so a comparison is significant. In addition, for the fuel–oxygen mixtures characterized as unstable mixtures applied in engines for aerospace propulsion, the newly collected experimental data could be used to update the existing prediction model, especially for those unstable mixtures. In this work, velocity deficits are measured in different channels for those mixtures, and the results are compared with a modified theoretical prediction model. Smoked foils are used to record the cellular structure of detonation. The detonation structure near detonability is also analyzed to study the propagation mechanism.

2. Experimental details

Experiments were performed in a steel detonation tube that was used in our previous study to investigate the detonability in explosive mixtures, and the references are therein [12,20–22]. The detonation tube was divided into a driver and driven section (or test section). The driver section is 1.2 m long with an inner diameter of 68 mm. The driven section is 2.5 m in length with an inner diameter of 36 mm. Three annular channel gaps ($w = 2$ mm, 4.5 mm and 7 mm) were created by inserting smaller diameter tubes (with the same steel material as the detonation tube) into the test section. The annular channel test section was supported by fins at the beginning and end of the detonation tube to form a uniform annular gap size. The leading edge of the smaller tube was chamfered to prevent any wave process from affecting the propagation of the detonation wave. The annular section was 1.1 m long.

Equimolar C_2H_2–O_2 was used as a driver mixture to promote the initiation of a detonation in the driver section of the tube. C_2H_2–O_2 is a readily detonable mixture that is very sensitive and requires less ignition energy than most hydrocarbon fuels to directly form a detonation. Additionally, detonation can be guaranteed to initiate in the driver section. The initial pressure of the driver section was maintained at a constant 10 kPa. A Mylar diaphragm (with a thickness of 0.5 mm) was placed between the driver and test section to separate the driver and test mixtures. In some cases, overdriven detonation was observed in the distance following the diaphragm; therefore, to minimize the influence of the driver section on the propagation in the test section, the first optical fiber was placed in the test section far enough (350 mm) from the driver section.

Three stoichiometric mixtures, i.e., CH_4–$2O_2$, C_2H_6–$3.5O_2$ and C_3H_8–$5O_2$, were the test mixtures in this study, and the initial temperature for all the mixtures used in this study was $T_0 = 300$ K. The test mixtures were mixed in a 40-L bottle by diffusion for at least 24 h in order to ensure homogeneity prior to use.

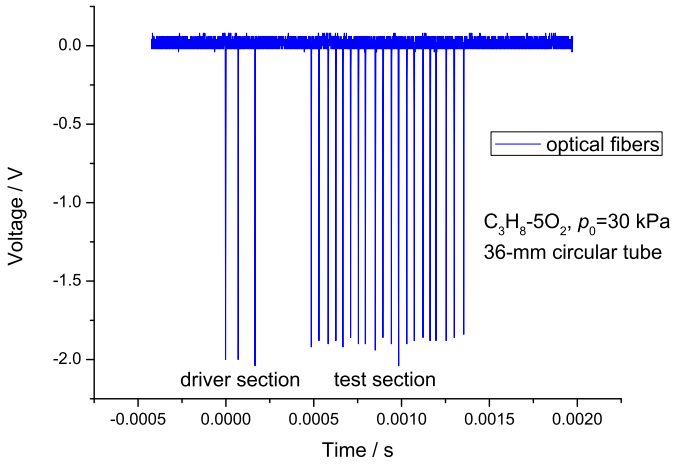

Fig. 1. Sample signals from the optical detectors.

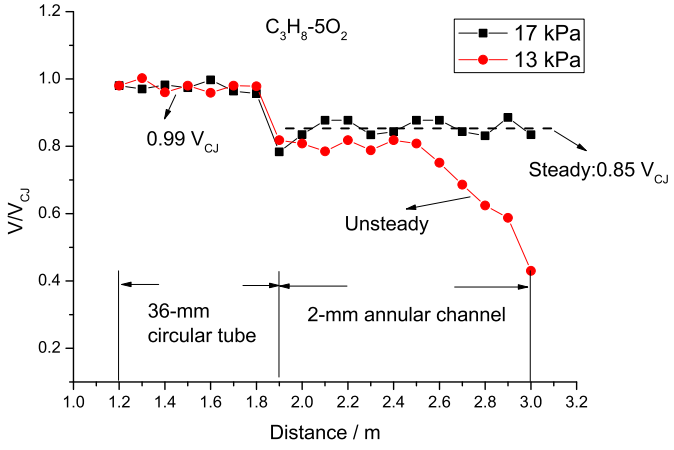

Fig. 2. Local velocity that well within (17 kPa) and far away (13 kPa) from the detonability in C_3H_8–$5O_2$ mixture.

In the experiment, optical fibers connected to a photodiode (IF-95OC) 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 was transmitted to the test section. In the test section, twenty optical fibers with an interval distance of 10 cm were used to measure the TOA. The local velocity of the wave was calculated using the distance over two neighboring signals, and the average velocity (V_{ave}) was obtained using the slope of the trajectory of a distance-time plot. Fig. 1 is the typical TOA signal for a single shot in the C_3H_8–$5O_2$ mixture ($p_0 = 30$ kPa), the time zero was defined as the detonation arriving at the first optical fiber. The signals in the test section are fairly uniform, which indicates the detonation velocity is steady. When the detonation is well within the limits, the maximum difference of the velocity measurement is ~5%. When the detonation approaches its limits, the repeatability of the measurement is poor, and large fluctuations occur.

3. Results and discussions

3.1. Velocity deficit

The detonability is approached by gradually decreasing the initial pressure for a given mixture in a certain circular tube/annular channel. Fig. 2 shows the results of the experimentally measured local velocity in a 36-mm inner diameter circular tube and 2-mm