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On the dynamic detonation parameters in acetylene–oxygen mixtures with varying amount of argon dilution

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ABSTRACT

In this investigation, the dynamic detonation parameters for stoichiometric acetylene–oxygen mixtures diluted with varying amount of argon are measured and analyzed. The experimental results show that the critical tube diameter and the critical energy for direct initiation of spherical detonations increase with the increase of argon dilution. The scaling behavior between the critical tube diameter d_c and the detonation cell size λ as well as the critical direct initiation energy E_c is systematically studied with the effect of argon dilution. The present results again validate that the relation $d_c = 13\lambda$ holds for 0–30% argon diluted mixtures and breaks down when argon dilution increases up to 40%. It is found that the explosion length scaling of $R_o \sim 26\lambda$ becomes also invalid when the mixture contains approximately this same amount of argon dilution or more. This critical argon dilution is indeed close to that found from experiments in porous-walled tubes by Radulescu and Lee (2002) which exhibit a distinct transition in the failure mechanism. Cell size analysis in literature also indicates that the cellular detonation front starts to become more regular (or stable) when the argon dilution reaches more than 40–50%. Regardless of the degree of argon dilution or mixture sensitivity, the phenomenological model developed from the surface energy concept by Lee, which provides a relation that links the critical tube diameter and the critical energy remains valid. The present experimental results also follow qualitatively the observation from chemical kinetic and detonation instability analyses.

1. Introduction

Gaseous detonations in most hydrocarbon mixtures are generally unstable with an ensemble of transverse waves interacting at the shock front that forms the characteristic irregular cellular structure [1]. In critical situations where the detonation propagation is close to failure, or with initial and mixture conditions at which the detonation characteristic cell size becomes comparable with the physical boundary size and dependent on these conditions, the instability at the cellular front can play an important major role on the dynamics of the detonation wave. Lee [1] argued that for an unstable detonation particularly at the above scenarios, the inability to maintain or develop instability at the detonation front is the mechanism that leads to failure in several situations. For example, detonation waves are observed to fail when the instabilities are suppressed as transverse waves are damped by acoustic absorbing walls or porous media [2–4]. Studies also suggested that detonation limits in tubes [5] and the critical tube diameter problem [6] are due to a local failure mechanism where instabilities fail to be maintained at the wave front. For a self-sustained diverging detonation, new cells must also be continuously generated via instability as the wave expands, otherwise the unstable diverging cellular detonation may fail to propagate outward in the radial direction [1]. Hence, both favorable initial conditions and detonation instability are essential and bring together mechanisms to promote sufficiently high combustion rates that can maintain the propagation of a self-sustained detonation.

Using the detonation cell size λ to characterize the unstable cellular structure, dynamic parameters in these common mixtures usually follow well with classical empirical correlations. For example, the critical tube diameter scales with the detonation cell size according to the $d_c = 13\lambda$ correlation [7,8]. The critical energy for direct initiation of spherical detonations [9,10] can also be scaled adequately from the explosion length $R_o \sim 26\lambda$ where $R_o = (E_c/p_o)^{1/3}$. Exceptions to these universal correlations were mixtures with high argon dilution [11–13] that emerged from smoked foil measurements, the corresponding detonation structure is usually

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found to be highly regular or piece-wise laminar closely described by the classical Zel'dovich–von Neumann–Döring (ZND) model [11–14].

Highly argon diluted mixtures were often considered as special mixtures to investigate the dynamics of detonation initiation and propagation, failure in detonation limits and the critical tube diameter problem (e.g., [4,12–17]). In highly argon diluted mixtures, the propagation relies mainly on the shock ignition mechanism and the ZND induction length scale represents an appropriate chemical length to correlate with different dynamic detonation parameters [10,15]. Detonation limits in tubes and the transmission of a detonation wave from a confined tube into a sudden open area are also thought to be governed by a global failure mechanism. This mechanism appears to be driven from excessive front curvature, above a critical value of which a steady ZND detonation can no longer be obtained [5,18,19]. Evidences also pointed out that the local instability seems not to play a prominent role in the critical tube diameter problem [6].

To clarify between the two possible modes of propagation and failure mechanism, i.e., one caused by suppression of instability and the other by excessive curvature, previous studies often considered the two extreme cases, i.e., detonations in undiluted C_2H_2–O_2 mixtures and diluted C_2H_2–O_2 mixtures with heavy amount of argon addition more than 70%. Only few studies systematically investigate the quantitative effect of increasing amount of argon dilution on the behavior of the detonation wave and its dynamic parameters. It is of interest not only to look at the transition of the two proposed distinct modes of propagation and failure mechanism, but also to study different scaling relationships and to determine what quantity of argon diluent in the explosive mixture such that cellular instabilities start to become less significant in the detonation dynamics.

In this study, the critical tube diameter and critical energy of direct initiation of spherical detonations in stoichiometric acetylene–oxygen mixtures diluted with varying amount of argon from 0% to 70% at different initial pressures are measured experimentally. New experimental data of critical tube diameter and critical initiation energy are first reported, and the relation between these detonation dynamic parameters along with increasing amount of argon dilution in stoichiometric acetylene–oxygen mixtures is then discussed.

2. Experimental details

Mixtures of stoichiometric C_2H_2–O_2 with different argon dilutions were investigated; the sensitivity of the mixtures was controlled by the initial pressure p_o and the range is given in Table 1. The mixture were prepared beforehand in a separate vessel by the method of partial pressure and the gases were allowed to mix for at least 24 h to ensure homogeneity for each tested mixture. Schematics of the experimental apparatus for the measurements of the critical tube diameter and critical energy are shown in Fig. 1. Both experimental setups were previously used for the same type of measurement for other hydrocarbon systems (e.g., [10,15,20,21]) and therefore, detailed description is omitted here.

Table 1
Initial conditions used in the critical tube diameter experiment.

Ar (%)	p_o (kPa)
0	11–21
22	13–27
30	16–33
40	25–51
50	43–81
65	55–99
70	75–141

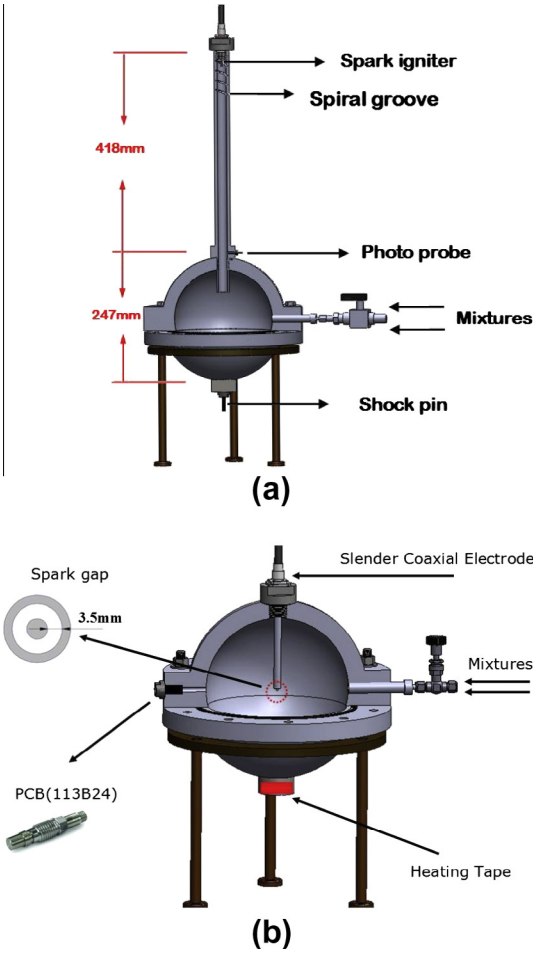

Fig. 1. Schematics of the experimental setup for (a) the critical tube diameter; and (b) direct initiation experiments.

For the critical tube diameter measurement, the apparatus is shown in Fig. 1a. The setup connected a vertical circular steel tube to a large high-pressure spherical chamber. Different diameters of the tube d were considered, i.e., d = 19.1, 15.5, 12.7 and 9.1 mm. The tube diameter d was varied via inserting smaller diameter tubes. The detonation was initiated at the top of the vertical circular steel tube and subsequently transmitted into the relatively larger spherical chamber. A photo probe and a piezoelectric shock pin (CA-1136, Dynasen Inc.) were mounted at the top and bottom of the spherical bomb, which were used to record the time-of-arrival (TOA) signals of the wave. From the TOA between initiation and photo probe – which locates at the top of the spherical bomb (i.e., near the end of the vertical tube) – it can be known whether a successful detonation is first initiated in the vertical tube. Using the TOA measurement from the piezoelectric shock pin located at the bottom of the spherical chamber, it is then possible to distinguish between successful detonation transmission or failure. For example, successful transmission and failure cases in a stoichiometric C_2H_2–O_2 mixture with the tube diameter of 19.05 mm and initial pressures of p_o = 12 kPa and 11 kPa are shown in Figs. 2 and 3, respectively. It can be seen from Fig. 2 that at an initial pressure of 12 kPa, the arrival time of the expanding wave is 201 μs when it reaches the photo probe and 317 μs at the shock pin. The computed velocities of the wave are 2073.4 m/s and 2136.7 m/s in the vertical tube and spherical chamber, which are 91.1% and 94.4% of the CJ detonation velocity, respectively. It shows that at an initial pressure of 12 kPa, the tube diameter is above the critical value, thus the planar detonation can successfully transit into a spherical