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Measurement and relationship between critical tube diameter and critical energy for direct blast initiation of gaseous detonations

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ABSTRACT

For the explosion safety assessment in industrial setting, detonation dynamic parameters provide important information on the sensitivity and conditions whereby detonations can be favorably occurred. In this study, new measurement of the critical tube diameter and the critical energy for direct initiation of a detonation is reported for a number of hydrocarbon–oxygen mixtures. The simultaneous experimental measurement carried out in this work allows the investigation of the direct scaling between these two dynamic parameter quantities of gaseous detonations. Using the new set of data, this paper also assesses the validity of an existing semi-empirical initiation model, namely, the surface energy model by Lee, and a simplified work done model. Both phenomenological models provide a general relationship between the two dynamic detonation parameters and comparison shows a good agreement between the theoretical results and the experimental measurement. The scaling of critical tube diameter with detonation cell size in this study also confirms the results in the previous literature.
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1. Introduction

Accidental explosions are key concern for all combustible fuels related to process safety. Accidental explosions and detonations occur often in industry and result in casualty and severe loss of property at industrial facilities (e.g., Gao & Hirano, 2006; Hirano, 2001; Johnson, 2010; Wen, Heidari, Ferraris, & Tam, 2011). For preventive measures of these accidents and the design of effective mitigation scheme, it requires a realistic assessment of explosion hazards of combustible fuels. Accumulation of detonation dynamic parameter data such as cell size, initiation energy, critical tube diameter or detonability limit for various combustible systems and the ability to predict these quantities not only are of great fundamental significance to further the understanding of the detonation wave structure and its propagation, but also provide useful information for safety assessment and evaluation of potential hazards of explosive mixtures (Lee, 1984; Matsui & Lee, 1978; Ng & Lee, 2008). In this study, two particular detonation dynamic parameters, namely the critical tube diameter and critical energy of direct initiation are studied in detail. The critical tube diameter, d_c, is the minimum tube diameter from which an emergent planer detonation wave can transmit into free space without failure. Critical initiation energy, E_c, refers to the minimum energy required for the direct blast initiation of a spherical detonation in a given explosive mixture.

From the dimensional analysis consideration, it is possible to realize that once a characteristic length scale is determined, the various dynamic parameters can be readily correlated with that particular length scale. Indeed, there are numerous studies attempted to link the characteristic detonation cell size λ – the average width of the cellular or fish-like pattern measured from smoked foils – as the fundamental chemical length scale, to the critical tube diameter, initiation energy as well as detonation limits (Lee, Knystautas, & Guirao, 1982). However, a quantitative theory for predicting the cell size is still lacking and experimental determination of a unique characteristic cell size from smoked foils can be difficult and often very subjective due to the inherent instability of the detonation front and cellular irregularity in common explosive mixtures (Lee, 2008).

Beside the characteristic cell size λ, critical tube diameter d_c can be considered as an alternative length scale for various correlations. It can be argued that direct experimental measurement of critical tube diameter is perhaps more trustworthy than the determination of cell size. In fact, many initiation models such as the work done

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concept and the surface energy model are developed based on the relationship linking the cell size to the critical energy via the critical tube diameter (Benedick, Guirao, Knystautas, & Lee, 1986; Lee, 1984, 1997). Therefore, one should verify the direct link between the initiation energy and the critical tube diameter without evaluation of the cell size. The critical tube diameter phenomenon may also provide a better problem from the modeling point of view compared to a quantitative theory of cell size prediction.

In this paper, new measurement of critical tube diameter and critical energy for direct initiation of spherical detonation are reported. Unlike cell size data which are abundant in the literature but yet possess a significant degree of uncertainty, data on critical tube diameters for a wide range of hydrocarbon gaseous mixtures are relatively scarce. Therefore, these new measurements provide addition to the detonation database and give further useful information for the explosion safety assessment in industrial setting. In this study, the critical tube diameters experiments with five different tube diameters scales, *D*, were performed for a number of different explosive mixtures at various initial conditions. In addition, the purpose of this work is the simultaneous determination of critical tube diameter and initiation energy for direct blast initiation of detonations in these different mixtures. The results then allow one to verify directly the scaling relationship between these two dynamic parameters. In fact, comparison and validation of detonation initiation models are often made between the measured values of the critical initiation parameters with those predicted with cell sizes as input parameters following the classical empirical relationships ($d_c = 13\lambda$ and $E_c \sim \rho_o V_{CJ}^2 \lambda^2$); and large discrepancies often obtained due to the uncertainty in cell size measurement and in some special mixtures such as highly argon diluted mixtures, the breakdown of the classical empirical correlation (Desbordes, Guerraud, Hamada, & Presles, 1993). Here, the direct scaling between the critical tube diameter and initiation energy is reported and verified through the use of two semi-empirical initiation models without the recourse to the cell size measurement.

2. Experimental details

The direct measurement of the critical tube diameter and the critical energy has been carried out in a number of common combustible mixtures (i.e. C_2H_2–O_2, C_2H_2–$2.5O_2$, C_2H_2–$4O_2$, C_2H_4–$3O_2$, C_3H_8–$5O_2$, C_2H_2–$2.5O_2$–50%Ar, C_2H_2–$2.5O_2$–70%Ar). The schematic of the critical tube diameter experiment is shown Fig. 1. The detonation is first initiated by a high-voltage spark ignition source at the top of the vertical circular steel tube and exits into a large spherical bomb chamber at the other end. A photo probe and a shock pin are mounted at the top and bottom of the spherical bomb, which are used to determine the time-of-arrival signal of the wave.

Typical traces for a surviving diverging detonation wave, i.e., for $d > d_c$ and a detonation failure case in a stoichiometric C_2H_2–$2.5O_2$ 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 velocity of the wave is 2073.4 m/s and 2136.7 m/s in the vertical tube and spherical chamber, which is of 91.1% and 94.4% of 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 detonation. While for an unsuccessful transmission when $d < d_c$, Fig. 3 shows that when the initial pressure decreases to 11 kPa, although a detonation wave propagates in the vertical tube at a velocity around 90% CJ detonation velocity, the detonation fails after exiting into the free space

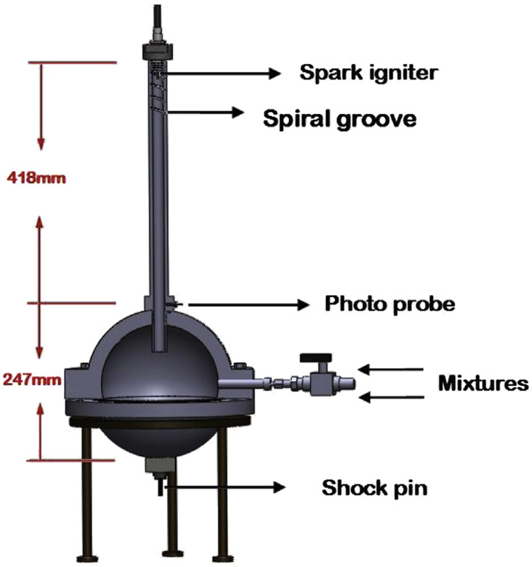

Fig. 1. Schematic of the experimental setup for the critical tube diameter measurement.

and the velocity of the expanding wave is only 23.6% of the CJ velocity value. For each successful and unsuccessful initiation of spherical detonation at least 3 shots are repeated to confirm the critical pressure that can form a spherical detonation at each tube diameter. In some experiments, the tube inner diameters are also varied via inserting smaller diameter tubes.

Using the same spherical bomb setup and by removing the vertical circular tube as shown in Fig. 1, experiments are also carried out to determine the critical initiation energy using the same mixtures and under the same initial conditions considered for the critical tube diameter problem. The procedure to distinguish detonation initiation and details to estimate the actual spark discharge energy from the ignition system can be found in authors' previous studies (Kamenskihs, Ng, & Lee, 2010; Zhang, Kamenskihs, Ng, & Lee, 2011; Zhang, Ng, Mével, & Lee, 2011; Zhang, Ng, & Lee, 2012a,b).

3. Results and discussion

The critical tube diameter for various mixtures as a function of initial pressure obtained by experiment is shown in Fig. 4. Other correlations for undiluted mixtures, which are based on the

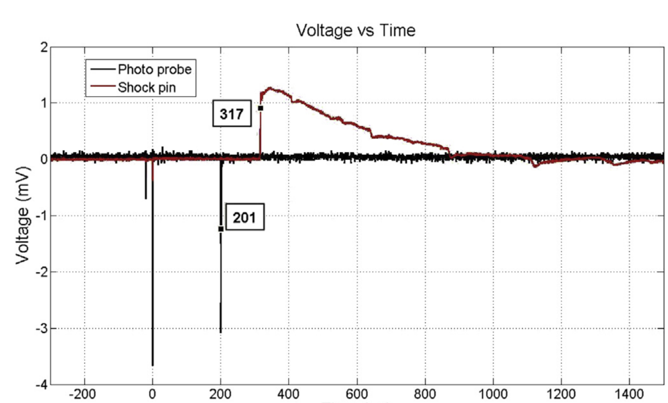

Fig. 2. Arrival time trace of a planar detonation emerging into an unconfined space: successful initiation of a spherical detonation for C_2H_2–$2.5O_2$ mixture at an initial pressure of 12 kPa.

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