Journal of Loss Prevention in the Process Industries xxx (2014) 1–7

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

DDT and detonation propagation limits in an obstacle filled tube

Mitchell Cross*, Gaby Ciccarelli

Mechanical and Materials Engineering, Queen's University, McLaughlin Hall, 130 Stuart Street, Kingston, K7L3N6, Canada

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form
26 November 2014
Accepted 26 November 2014
Available online xxx

Keywords:
Quasi-detonation
DDT
Choked-flame
Explosions

ABSTRACT

Experiments with hydrogen–air and ethylene–air mixtures at atmospheric pressure were carried out in a 6.1 m long, 0.1 m diameter tube with different obstacle configurations and ignition types. Classical DDT experiments were performed with the first part of the tube filled with equally spaced 75 mm (44% area blockage ratio) orifice-plates. The DDT limits, defining the so-called quasi-detonation regime, where the wave propagates at a velocity above the speed of sound in the products, were found to be well correlated with $d/\lambda = 1$, where d is orifice-plate diameter and λ is the detonation cell size. The only exception was the rich ethylene limit where $d/\lambda = 1.9$ was found. In a second experiment detonation propagation limits were measured by transmitting a CJ detonation wave into an obstacle filled (same equally spaced 44% orifice plates) section of the tube. An oxy-acetylene driver promptly initiated a detonation wave at one end. In this experiment the quasi-detonation propagation limits were found to agree very well with the $d/\lambda = 1$ correlation. This indicates that the $d/\lambda = 1$ represents a propagation limit. In general, one can conclude that the classical DDT limits measured in an orifice-plate filled tube are governed by the wave propagation mechanism, independent of detonation initiation (DDT process) that can occur locally in the obstacles outside these limits. For rich mixtures, transmission of the quasi-detonation into the smooth tube resulted in CJ detonation wave. However, in a narrow range of mixtures on the lean side, the detonation failed to transmit in the smooth tube. This highlights the critical role that shock reflection plays in the propagation of quasi-detonation waves.

1. Introduction

Flame acceleration in a smooth tube can culminate in deflagration-to-detonation transition (DDT), corresponding to a transition from diffusion to shock-ignition controlled combustion. This transition corresponds to a large change in propagation velocity from the speed of sound in the products to the Chapman–Jouguet (CJ) detonation velocity. Enhanced flame acceleration in an obstacle laden channel can result in the steady propagation of a supersonic combustion wave. The nature of the combustion wave depends on the reactivity of the combustible mixture and the obstacle configuration. For very reactive mixtures, where the detonation cell size is one order-of-magnitude smaller than the minimum transverse dimension, transition to detonation occurs and the wave propagates at the CJ velocity. For less reactive mixtures the combustion wave can propagate as a fast-flame (also known as a choked flame) at an average velocity just below the isobaric speed of sound in the products (roughly half the CJ detonation velocity) (Lee and Moen, 1980). In the choked flame regime, small oscillations in the lead shock velocity are due to the interaction of the trailing turbulent flame and reflected shock waves produced off the obstacle and channel surfaces (Ciccarelli et al., 2010). For mixtures with intermediate reactivity the average wave propagation velocity lies between the CJ detonation velocity and the speed of sound in the products, this is often referred to as the quasi-detonation regime (Lee and Moen, 1980).

Experiments performed at McGill University in the 1980s, in tubes filled with orifice plates, show step changes in the average wave velocity (on the fuel lean and rich sides) when plotted versus composition (Knystautas et al., 1986; Peraldi et al., 1986). This step change in average velocity that occurs at the speed of sound in the products, demarks the limits of the quasi-detonation regime, often referred to as the DDT limits. Peraldi et al. (1986) proposed that for an orifice plate filled tube, the quasi-detonation regime limits are correlated with $d/\lambda = 1$, where d is the orifice plate opening, and λ is the detonation cell size. This correlation is based on basic similarity arguments where the detonation and orifice plate length-scales are equal. Subsequent investigations have shown that this critical

* Corresponding author.
E-mail address: mitchellcross@gmail.com (M. Cross).

http://dx.doi.org/10.1016/j.jlp.2014.11.020
0950-4230/© 2014 Published by Elsevier Ltd.

condition also depends on the obstacle spacing, S (Teodorczyk et al., 1988). Dorofeev proposed a DDT criterion that takes into account the obstacle spacing, i.e., $L/\lambda > 7$ where L is a characteristic macroscopic length-scale (Dorofeev et al., 2000). For a tube with inner-diameter, D, filled with orifice plates, the length-scale is defined by $L = (S + D)/2/(1 - d/D)$. Note, the first part of this expression represents the average size of the chamber enclosed by the tube wall and the orifice plate, and the denominator takes into account the fact that experiments have shown that detonation initiation occurs more easily for smaller blockages (larger $(1 - d/D)$ yields smaller L).

Quasi-detonations are highly unsteady, with large swings in instantaneous velocity as the wave propagates past individual obstacles. Using high-speed schlieren photography Teodorczyk et al. (1988) showed that in the quasi-detonation regime the large CJ detonation velocity deficit (difference between the measured the average wave velocity and the theoretical CJ detonation wave velocity) can be attributed to intermittent detonation initiation and failure during diffraction around obstacles. In recent experiments performed with sub-atmospheric hydrogen–oxygen in an optically accessible channel equipped with top and bottom surface mounted fence-type obstacles Kellenberger and Ciccarelli (2014) showed that the quasi-detonation regime can be subdivided into several propagation modes, that do not all involve detonation wave propagation. A common feature for quasi-steady combustion wave propagation at an average velocity above the speed of sound in the products (roughly 1200 m/s for stoichiometric hydrogen–oxygen) is the presence of precursor shock wave that is not coupled with a reaction zone. Reflection of the precursor shock wave off the obstacle results in "ignition" of the thin layer of unburned mixture next to the upstream side of the obstacle. The blast waves that form, as a result of the explosions at the corners of the top and bottom obstacle, interact at the centerline of the channel to form a Mach stem inside the reaction zone (thick turbulent flame). When the Mach stem encounters the compressed unburned gas (between the precursor shock wave and the turbulent flame) there are three possible outcomes, depending on the mixture reactivity. 1) For the least reactive mixtures (reactivity based on magnitude of the initial pressure), the Mach stem overtakes the precursor shock wave resulting in a lead shock velocity excursion of about 300 m/s above the speed of sound of the products. 2) For slightly more reactive mixtures, the Mach stem triggers a local explosion in the compressed gas region that generates a strong blast wave (failed detonation initiation) that quickly overtakes the precursor shock wave producing a lead shock wave excursion of about 800 m/s above the speed of sound of the products. 3) For even more reactive mixtures, the transmission of the Mach stem into the compressed gas results in the formation of a detonation wave. The diffraction of the detonation wave around the next obstacles can result in failure (complete decoupling) followed by re-initiation at subsequent obstacles, or attenuation (decoupling with prompt re-initiation).

The objective of this study is to look more closely at the DDT limits in an obstacle filled tube. Specifically, to determine if the measured DDT limits are dictated by the DDT event, or by the quasi-detonation wave propagation requirements. This will be done using the classical flame acceleration and DDT experiment and a new approach, where a CJ detonation wave is transmitted into an obstacle filled tube. For both set-ups, the limit for successful transmission from the obstacle-section into the smooth tube is also obtained in order to gain insight into the propagation mechanism of the quasi-detonation wave in the obstacle section. For example, if a quasi-detonation propagates through the orifice plates but fails to transmit into a detonation in the smooth tube, the propagation of the quasi-detonation relies on shock reflection for detonation initiation. Therefore, it is possible that the detonation transmission limits could be narrower than the detonation limits.

2. Experiments

Experiments were carried out in an apparatus consisting of a 6.1 m long, 0.10 m inner-diameter tube. The tube contained 0.076 m diameter orifice plates (44% area blockage) equally spaced at the tube diameter ($L = 0.417$ m) arranged in different configurations, as shown in Fig. 1. In the first series of experiments a length of obstacles was positioned at the right-end of the tube and the left-end of the tube empty, as shown in Fig. 1a. Tests were first carried out with 4.11 m of obstacles (with 1.07 m of obstacles to the left of midspan of the tube), followed up with a few tests with an extended 5.18 m of obstacles. Ignition was via a weak automotive capacitive discharge spark positioned centrally at the right-endplate, such that flame acceleration occurred in the left direction. In a second series of tests, a CJ detonation wave, initiated promptly using an oxygen-acetylene gas driver on the left-end of the tube, propagates into the obstacle section. These tests are done in two configurations (see Fig. 1b). In configuration 1, the orifice plates filled the entire right-half of the tube. In configuration 2, the orifice plates were located in the first half of the second-half of the tube, i.e., 1.52 m long section of the tube starting at 3.04 m from the ignition endplate. The average wave velocity was obtained from flame time-of-arrival measurements deduced from ionization probe (IP) signals. The IPs were distributed evenly, 0.61 m apart (spanning roughly eight orifice plates), down the length of the tube. The test mixture was prepared by the method of partial pressures in a separate mixing chamber equipped with an air driven stirrer. The mixture constituents were added to the chamber and mixed for 20 min. Gases were supplied by standard compressed gas cylinders.

3. Results and discussion

3.1. DDT experiments

Experiments were performed with hydrogen-air and ethylene-air mixtures at an initial pressure of 101 kPa and room temperature. Experiments were carried out using the traditional flame acceleration setup shown in Fig. 1a with 4.11 m of obstacles. The orifice plate configuration and blockage ratio used in this experiment is very similar to that used by Knystautas et al. (1986) where they performed experiments in 0.05 m and 0.15 m diameter tubes. The measured flame velocity down the tube is shown in Fig. 2a for three lean mixtures and stoichiometric hydrogen-air mixtures. The velocity data points in the obstacle section (open symbols) are based on the flame time-of-arrival for two ionization probes 0.61 m apart, whereas the flame velocity in the smooth part of the tube (closed symbols) is averaged over 1.22 m after the last obstacle. The lines represent a fourth order polynomial fit of the velocity data in the obstacle section. The speed of sound in the combustion products for a 19% hydrogen in air mixture (dotted line) calculated using the equilibrium code STANJAN is included for reference in Fig. 2a. The test performed with 30% hydrogen resulted in relatively quick flame acceleration leading to DDT and quasi-detonation propagation in the obstacles. A detonation wave was successfully transmitted into the smooth part of the tube that propagated at close to the CJ value. For the other three fuel-lean mixtures the flame accelerates reaching a maximum velocity above the products speed of sound at 2.5 m. For the 19% mixture the flame velocity remains above the products speed of sound but for the 17% and 18% mixture the flame velocity dips below in the last part of the obstacles. For all three of these mixtures the flame decelerates in the smooth part of the tube to a velocity below the products speed of sound typical of a

Please cite this article in press as: Cross, M., Ciccarelli, G., DDT and detonation propagation limits in an obstacle filled tube, Journal of Loss Prevention in the Process Industries (2014), http://dx.doi.org/10.1016/j.jlp.2014.11.020