DDT in Fuel-air Mixtures at Elevated Temperatures and Pressures

J. Card, D. Rival and G.Ciccarelli¹

Queen's University, Mechanical Engineering, Kingston, Ontario, Canada K7L 3N6

S. Murray and F. Zhang

Defence Research and Development Canada - Suffield, Ralston, Alberta, Canada

Key words: DDT, Pulse Detonation Engine, JP-10

The phenomenon of flame acceleration leading to detonation initiation in obstacle-laden tubes, commonly referred to as deflagration-to-detonation transition (DDT), has been studied experimentally. The investigation was carried out in connection with industrial explosion safety and Pulse Detonation Engine (PDE) development. For both applications the detonation run-up distance, defined as the distance traveled by the flame from the point of ignition to the point of detonation onset, is a key parameter. For industrial safety the detonation run-up distance has been used to characterize the detonability of reactive mixtures. In PDEs the detonation run-up distance provides a rough estimate of the shortest possible combustor length for a PDE operating with the DDT mode of initiation. There is an abundance of data in the literature on DDT in fuel-air mixtures at ambient temperature and pressure (Lee et al. 1984, Kuznetsov et al, 2000). For both applications cited above, under normal operating conditions the combustible mixture is often at an elevated temperature. In this investigation emphasis has been placed on determining the affect of initial temperature on both the detonation run-up distance and DDT limits. A comprehensive study of DDT in high-temperature hydrogen-air-steam mixtures was reported by Ciccarelli et al. (1996) in connection with nuclear reactor safety. In the context of PDEs, DDT results from experiments with propane-air at elevated temperature were reported by Ciccarelli et al. (2002). In the present investigation DDT experiments were performed in fuel-air mixtures, including hydrogen, acetylene, ethylene. Experiments were also performed with JP-10 at prototypic PDE combustor pressures and temperatures.

Experimental Apparatus

The experiments were performed in a 3.1-m long, 10-cm diameter heated detonation tube. The tube was completely filled with 0.43 blockage ratio orifice plates equally spaced at one tube diameter. The test mixture is prepared by method of partial pressures in a separate chamber and then downloaded into the heated detonation tube. The constituents are mixed using a pneumatic-motor driven propeller inside the mixing chamber. The mixing chamber is at room temperature except for the JP-10 tests where it is heated to 410K to vaporize the fuel. The mixture is heated to the test temperature in transport through heat-traced tubing connecting the mixing chamber to the detonation tube. Since the gas is prepared at a low temperature there is no concern for pre-oxidation of the mixture prior to ignition. Typically the mixture is present in the detonation tube at the test temperature for no more than 15 seconds before ignition. Combustion is initiated at one end of the tube via a standard automobile engine spark plug system. The average flame velocity is derived from time-of-arrival data obtained from ionization probes located along the complete length of the tube, typically spaced at 30.5-cm. Details about the experimental facility can be found in Ciccarelli et al. (2002).

¹ Corresponding author, e-mail: ciccarel@me.queensu.ca

Detonation Run-up Distance

The flame velocity along the length of the tube was recorded in four fuel-air mixtures. The fuels investigated include hydrogen, acetylene, ethylene and JP-10. For each fuel-air mixture the flame acceleration history and detonation run-up distance was measured at temperatures between 300K and 500K. Flame velocity versus distance data obtained for acetylene-air at 473K for four different compositions is shown in Figure 1.



Figure 1: Flame acceleration data for acetylene-air mixtures at 473K and 1 atm

In all four mixtures flame acceleration resulted in transition to detonation. As expected the highest acceleration is observed for the stoichiometric mixture, i.e., 7.75% acetylene. Theoretically transition to detonation occurs at the point where the flame velocity abruptly jumps from a value equal to the isobaric speed of sound in the combustion products to the Chapman-Jouget detonation velocity. For stoichiometric acetylene-air the CJ detonation velocity and the isobaric speed of sound in the products at 473 K and 1 atm are 1848 m/s and 927 m/s, respectively. Experimentally this jump in velocity is not always well defined due to deviations from these two theoretical velocities caused by obstacle-induced momentum and heat losses, most notable in Figure 1 is the results for the least reactive mixture containing 4.75% acetylene. The location of detonation transition can only be measured to within the spatial resolution of the average flame velocity measurements, which for this apparatus is 30.5 cm. For the purpose of this study the detonation run-up distance is determined based on the tube location where the average flame velocity measurement points. Veser et al. (2002) used the following non-dimensional parameter grouping to normalize the distance L required for a flame to accelerate to the choking velocity, i.e., the isobaric speed of sound in the products,

$$\frac{L}{R} \left(\frac{10S_{lam}}{C_p} \right) (\sigma - 1)$$

where S_{lam} is the laminar burning velocity, σ is the ratio of the unburned and burned gas density ratio, and C_p is the isobaric speed of sound in the combustion products and R is the tube radius. Veser et al. (2002) proposed that ten times the laminar burning velocity is typically the maximum turbulent burning velocity attained during flame

acceleration in an obstacle-lade tube. In most cases the flame accelerates to the choking velocity at which point a detonation is initiated. As a result, the flame acceleration run-up distance is typically the same as the detonation run-up distance. Plotted in Figure 2 is the measured normalized run-up distance versus equivalence ratio for the various fuel-air mixtures and initial temperatures tested.



Figure 2: Non-dimensional run-up distance as a function of mixture composition at various temperatures

Note only a single JP-10 data point corresponding to a stoichiometric mixture with air at 373K and 2 atm is included in the plot due to a lack of published laminar burning velocity data in the literature at this time. This data point is based on a burning velocity of 0.6 m/s obtained by Shepherd (2002) at 373K and 1 atm. As can be seen from the figure the data for acetylene and ethylene correlate very well over a wide range of equivalence ratio and initial temperatures. The hydrogen-air data is well above the scatter of the hydrocarbon data, this is most likely due to the difference in speed of sound and molecular diffusivity relative to the hydrocarbons. This will be further investigated for the final paper.

JP-10 data

Because of the importance of JP-10 in the PDE application a comprehensive study of flame acceleration and DDT in JP-10/air mixtures was performed. Experiments performed at an initial pressure of 1 atm did not result in detonation initiation. In general there was only a moderate enhancement observed in flame acceleration at 573K compared to 373K. This is consistent with the results from the other hydrocarbons tested and opposite to that observed in hydrogen. A similar observation was made in DDT experiments with propane-air and hydrogen-air (Ciccarelli et al., 2002). Detonation initiation was observed at all temperatures for tests performed at 2 atm. Shown in Figure 3 is the measured flame velocity history along the tube in various JP-10/air mixtures at 473K and 2 atm (the legend gives the mixture equivalence ratio and % JP-10 in brackets).

Based on the data shown in Figure 3 the lean DDT limit is 1.1% JP-10 in air. In a similar fashion the lean and rich DDT limits in JP-10/air at 2 atm and 373K, 473 and 538K were measured, the data is summarized in Table 1. The

lean DDT limit is only slightly influenced by initial temperature but a much more pronounced effect is observed for the rich limit. The rich limit decreases significantly with an increase in temperature from 373 to 473K but then remains constant to 538K. Using cell size data from Zhang et al. (2001) and Shepherd (2003) for JP-10/air at 373 K, the lean limit of 1.15% JP-10 correlates well with the classical $d/\lambda=1$ criterion. Additional cell size measurements will be made to generalize this finding for the other composition limits given in Table 1.



Figure 3: Flame acceleration in JP-10/air mixtures at initial temperature and pressure of 473K and 2 atm

Temperature (K)	Lean DDT Limit (% JP-10)	Rich DDT Limit (% JP-10)
373	1.15	2.10
473	1.10	1.75
538	1.25	1.75

Table 1: DDT Limits for JP-10/air Mixtures

References

G. Ciccarelli and P. Dubocage (2002) "Flame Acceleration in Fuel-Air Mixtures at Elevated Initial

Temperatures" AIAA/SAE/ASME Joint Propulsion Meeting, Indianapolis, IN, June 2002.

G. Ciccarelli, et al., (1996) "The influence of Initial Temperature on Flame Acceleration and Deflagrationto-Detonation Transition," Proceedings of the Combustion Institute Vol. 26.

M.S. Kuznetsov, V.I. Alekseev, S.B. Dorofeev (2000) Shock Waves, 10:217-223.

J.H. Lee, R. Knystautas, C.K. Chan, (1984) 20th Symposium on Comb, pp 1663-1672.

Shepherd (2002) Private communications

J. Shepherd (2003), web site http://www.galcit.caltech.edu/EDL/projects/pde/pde.html

A. Veser, W. Breitung, and S. Dorofeev (2002) Run-Up Distance to Supersonic Flames in Obstacle-Laden

Tubes," 4th Intl. Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, France, Oct. 2002.

F. Zhang, S. Murray, K. Gerrard. (2001) JP-10 Vapour Detonation at Elevated Pressures and Temperatures, Presented at 18th ICDERS, Seattle.