DETONATION INITIATION IN PULSE DETONATION ENGINES: EXPERIMENTS AND SIMULATIONS

V. E. Tangirala, P. F. Pinard, K. Hinckley, A. Rasheed, and A. J. Dean
General Electric Global Research Center,
Niskayuna, One Research Cycle, NY 12309

Introduction

Pulse Detonation Engines (PDEs) are exciting new propulsion devices which have potential application across the flight envelope spanning subsonic, supersonic and hypersonic flight [1]. The pressure rise associated with a detonation makes this an efficient combustion process when compared to a constant pressure deflagration typical of gas turbine combustors. The present investigation addresses the key challenge of obtaining a reliable and repeating detonation initiation, during the periodic operation of a PDE. One practical method of initiating a detonation is via spark ignition of a fuel-air mixture in a confined chamber resulting in flame acceleration and transition to detonation. This process is termed Deflagration to Detonation Transition (DDT). Many implementations of PDEs rely on DDT to avoid the high energy required for direct initiation. Typically, internal obstacles are used to significantly reduce run-up distance in fuel-air mixtures [2-4]. For propulsion systems, DDT optimization is a trade-off between minimizing run-up distance via more obstacles or higher blockage ratio per obstacle, and minimizing performance losses via less obstacles. In the present study, the effect of key parameters namely fuel fill, operating pressure, spark energy, number of sparks and their arrangement on detonation initiation in a tube-PDE is investigated.

Previously, simulations and test measurements of DDT were obtained for a laboratory-scale PDE test rig ('benchmark tube') at ambient temperature and pressure [5-6]. Experimental and numerical visualizations of flame initiation, acceleration, transition to detonation and detonation propagation for H_2-air [5] and C_2H_4-air mixtures [6] were presented. The method of weak spark initiation of combustion in a small region was investigated using 2D axisymmetric simulations. The predicted flame acceleration behaviour showed flame wrinkling, typical of shock-flame interactions caused by Taylor-Markstein interface instability. Hot spots were predicted to occur in (i) the stagnation regions near obstacles and (ii) vortex rollup regions in the wake of the obstacles. Computations showed that the irregular/Mach reflections of the pressure waves generated at the edges of the hot spot play an important role in the onset of detonation. The predicted run-up time agreed reasonably well with test measurements. However, run-up distance was underpredicted, and a need to improve the run-up distance predictions was identified. A 3D unsteady CFD model is used in the present study to simulate the detonation initiation and the propagation processes in a tube-PDE.

Key Experimental Results

Previously [6.] it was reported that, for a successful DDT initiation in a C2H4-air mixture in a 2" diameter, a minimum length of 20 diameters of the tube was required. In the present study, a series of experiments and simulations was performed to reduce the length of the tube to under 15 diameters in which robust detonations can be obtained by optimizing various parameters that influence the DDT process. The occurrence/failure of the detonation initiation was determined using ion probe measurements of the detonation wave velocities. A systematic variation of key parameters was performed and these parameters are valve response time, fuel fill time, fuel-line pressure, axial variation of the mixture composition in the tube, the initial pressure of the fuel-air mixture and spark energy were the parameters which had a significant impact on the DDT process. Firstly, it was found that previously used slow-response time valves (~ 10 ms opening time) resulted in a lean fuel-air mixture towards the tail end of the tube at the time of spark initiation and the DDT initiation process did not yield detonations in the lean mixture region. By using faster response time valves (~ 2 ms opening time) and slightly overfilling the tube, a near-stoichiometric mixture was obtained throughout the tube and the DDT initiation in this mixture yielded quasi-steady detonations, which was verified using the time of flight measurements obtained using ion probes. In addition to the parameters mentioned above, increasing spark energy, use of multiple sparks, axial distribution of the sparks, and the high initial pressure of the fuel-air mixture were found enhance the success rate of the DDT and running the PDE tube at 2 atm also enhanced the DDT. As a result of these studies, extended duration runs (5 minutes) with repeating and reproducible detonations are made possible in a 30" PDE tube. In the reminder of the section, a brief description of the abovementioned parametric studies are presented.

Effect of Fuel Fill: A non-intrusive laser absorption-based fuel sensor has been developed to measure fuel-air stoichiometry in pulse detonation engines (PDEs) at kHz rates. Figure 1 shows a schematic of the sensor applied to the tail end of the PDE tube at which location the path-averaged ethylene concentration is measured. Figure 2 shows a sample data trace of the time-resolved stoichiometry which shows the arrival time of the fuel at the tail-end of the tube and it also captures the plateau value of stoichiometry, demonstrating that the engine was operating with a rich (ϕ=1.3) ethylene-air mixture. The fuel sensor has been used to modulate the supply pressure to the fuel valve to ensure a stoichiometric (ϕ=1) fill to aid in the initiation of a detonation wave. The time of arrival information has also been used to optimize the timing diagram of the fuel valve and spark ignition source. A series of experiments was run to vary the duration of the fuel fill time, and investigate its effect on deflagration-to-detonation transition (DDT). The default condition was to spark-ignite the mixture when the fuel had first arrived at the tail end. However, due to the finite (and slow) opening time of the fuel supply valve, an axial gradient in fuel concentration is established toward the tail end of the PDE tube, as shown schematically in Fig. 3. Thus the tail end of the tube is fuel-lean. Direct visualizations of the chemiluminescent emission from combustion wave using a hi-speed digital camera and a clear, polycarbonate tube show the failure of the detonation wave as it propagates into this fuel-lean region.. The present tests also show that in order to obtain robust quasi-steady detonations at the tube exit, it is necessary to slightly overfill the tube.

Effect of Initial Pressure: A test rig (see Fig. 4) was designed and built to study the detonation phenomenon and operability of a PDE at elevated pressures. The rig is composed of a 2-in diameter, 48-in long PDE tube firing into a large 16-in diameter dump tank. The PDE tube is contained within a larger 6-in pressure vessel. Primary air flows continuously through the PDE, into the dump tank and exits the dump tank through a backpressure valve. Secondary air flows continuously into the dump tank through a circumferential manifold and exits through a backpressure valve. This secondary airflow and the backpressure valve position can be adjusted in order to obtain the desired backpressure on the PDE up to 10-atm. The inlet details, internal geometry and ignition system of the PDE are identical to those described in the other sections.

Initial tests were conducted at 1-atm and 2-atm backpressure. Pressure transducers located near the end of the PDE were used to monitor the combustion wave and determine whether or not transition to detonation had occurred. In order to determine the effect of pressure on the detonability of C2H4-Air mixtures a number of tests were conducted over a range of equivalence ratios at each pressure. The results presented (Figures 5(i) and 5(ii)) indicate that a wider range of mixtures successfully detonated at the 2-atm backpressure condition. A smaller cell size results in a shorter run-up distance and therefore wider limits for DDT in a fixed-length PDE.

Effect of Spark Energy: The influence of spark energy and location on deflagration to detonation transition (DDT) was studied during cyclic operation of a PDE. Experiments were conducted in a 50 mm diameter PDE operating with stoichiometric mixtures of ethylene and air. Total spark energy was varied from 100 mJ to 4J and distributed between one and four spark locations. Measurements of run-up time and run-up distance were obtained using high speed chemi-luminescence imaging. It was found that increasing the total spark energy reduced the run-up time by up to 20% compared to a baseline case (see Fig. 6). Distributing the total energy between multiple sparks and synchronizing the timing resulted in a similar reduction in run-up time. Comparisons of test measurements and 3D CFD simulations are summarized for selected cases in which the number of ignition sources, the location of the ignition sources and the amount of spark energy were varied.

Computational Simulations

The unsteady Reynolds Averaged Navier Stokes (RANS) equations are solved using a coupled, unstructured solver [7], which is second-order accurate in space with total-variation-diminishing (TVD) interpolation and a nonlinear Reimann solver, namely HLLC (Harten, Lax and van Lear with Contact discontinuity). Variable thermal and transport properties were used for all species. A realizable k-ε model was used for modeling turbulence processes. For all the simulations reported here, viscous terms are included because they are considered to be important for the PDE cycle processes. A 2-step reduced chemical mechanism, which considers a total of 8 species, was used for simulating C_2H_4-air chemical reactions [8].

The geometry used in this simulation of the tube-PDE is the same as the geometry used in 2D axisymmetric simulations reported earlier [7]. Figure 7 shows an unstructured mesh of size 2.5 million cells (tetrahydral and prismatic cells). 3D CFD Predictions of run-up distance (Fig. 8(i)) is are in better agreement with test measurements than the predictions of 2D axisymmetric simulations. Figure 8(i) shows that the flame acceleration is slightly underpredicted in 3D simulations when compared to 2D axisymmetric predictions. Figure 8(ii) shows the run-up time is slightly underpredicted in 3D simulations compared to the test measurements.

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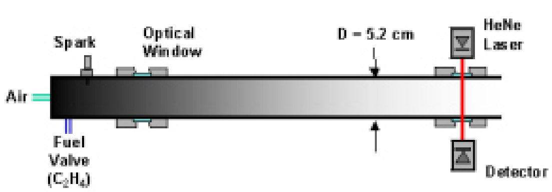

Figure 1. Schematic of the laser sensor applied to the PDE tube.

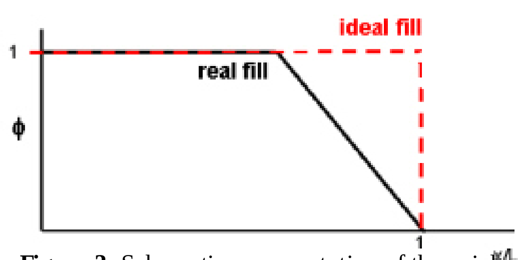

Figure 3. Schematic representation of the axial variation of the mixture stoichiometry.

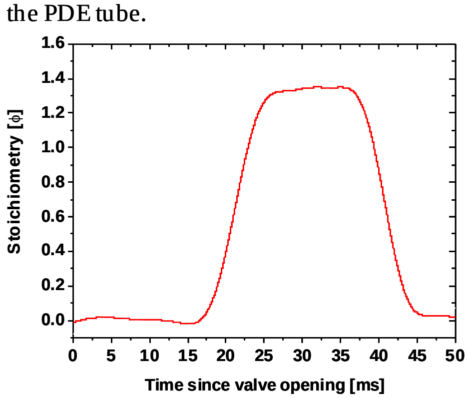

Figure 2. Time variation of PDE tail-end mixture stoichiometry.

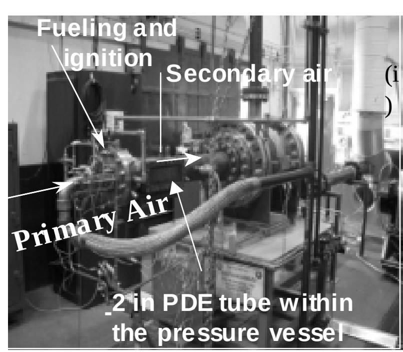

Figure 4. High pressure test rig used in DDT initiation studies.

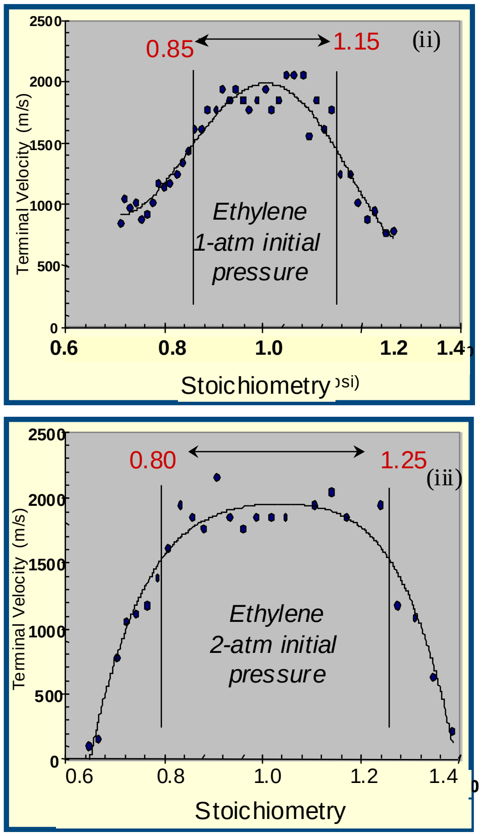

Figure 5. Effect of mixture stoichiometry on detonation velocity for an initial pressure of (i) 1 atm, and (ii) 2 atm.

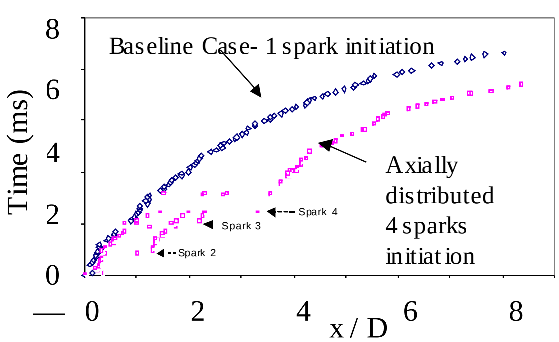

Figure 6: X-t diagram comparing baseline (1-spark) to a case with 4 distributed axial sparks

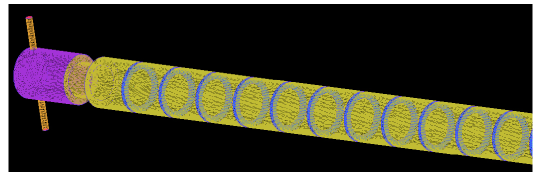

Fig. 7: A 3D unstructured grid of size 2.5 M cells used in 3D simulations.

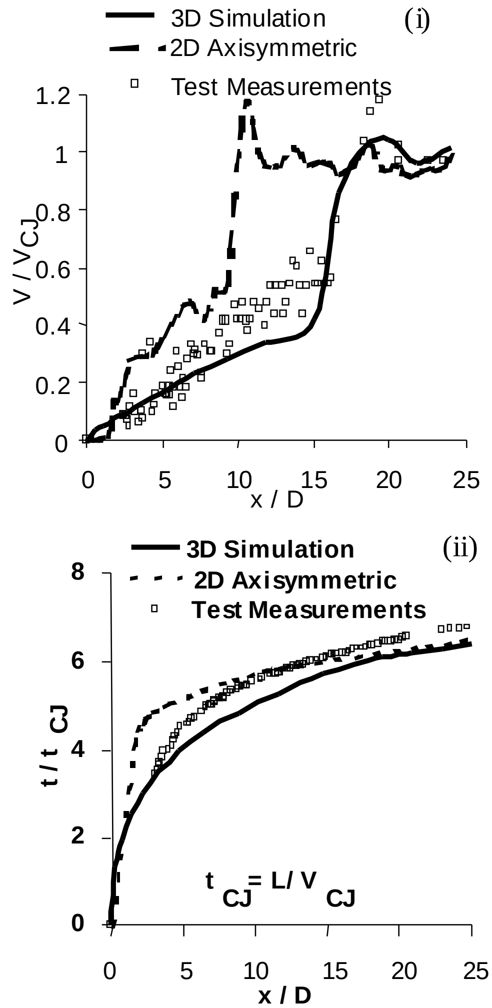

Fig. 8: Comparisons of test measurements with 2D axisymmetric and 3D simulations of detonation initiation in a tube-PDE.

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