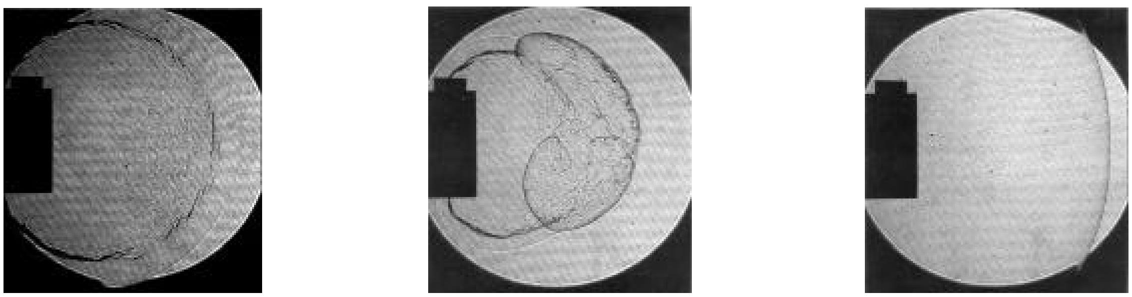
Detonation Initiation, Diffraction, and Impulse

J. E. Shepherd, J. Austin, T. Chao, E. Schultz, E. Wintenberger, S. Jackson, M. Cooper
Graduate Aeronautical Laboratories, California Institute of Technology
Pasadena, CA 91125 USA

Research at Caltech is being carried out on the diffraction of detonations, initiation of detonation using deflagration-to-detonation transition, direct measurement of impulse in single detonation and DDT events, the measurement of detonation cell width and impulse for storable fuels, and the structural response of detonation tubes, including fracture and failure.

Introduction

The Explosion Dynamics Laboratory research group at Caltech is carrying out investigations on many aspects of detonation initiation and propagation which are relevant to pulse detonation engines. A brief review of these activities is presented here.



(a) (b) (c)

Figure 1: Detonation diffraction cases a) subcritical, b) critical c) supercritical.

Detonation Diffraction

The problem of a self-sustaining detonation wave diffracting from a tube into an unconfined space through an abrupt area change is characterized by the geometric scale imposed by the tube and the reaction scale of the detonation. Previous investigations have shown that this expansion associated with a detonation transitioning from planar to spherical geometry can result in two possible outcomes (see Fig. 1) depending upon the combustible mixture composition, initial thermodynamic state, and confining geometry. Competition between the energy release rate and expansion rate behind the diffracting wave is crucial. The subcritical case is characterized by the rate of expansion exceeding the energy release rate. As the chemical reactions are quenched, the shock wave decouples from the reaction zone and rapidly decays. The energy release rate dominates the expansion rate in the supercritical case, maintaining the coupling between the shock and reaction zone which permits successful transition across the area change.

A survey[1] of the literature on detonation diffraction reveals an extensive degree of empirical work but no means by which the critical conditions can be calculated from first principles. Empirical correlations between the critical diameter, cell width, and reaction length have been collected and analyzed. In the present investigation,[1,2] an analytical expression has been derived from a model of detonation diffraction through an abrupt area expansion which permits the calculation of critical conditions which separate the sub-critical and

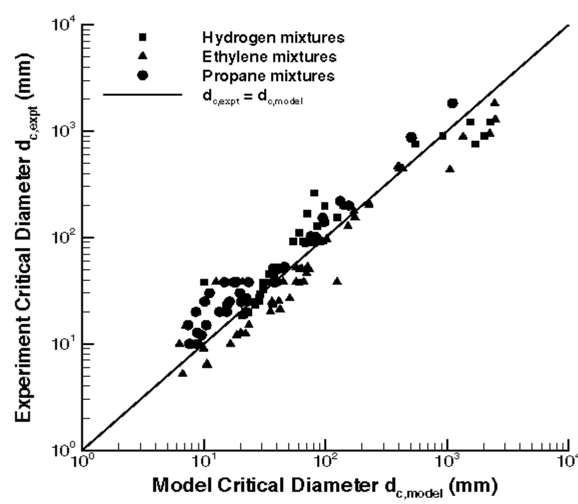


Figure 2: Evaluation of the critical diameter model based on the critical decay rate concept.

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super-critical regimes. This model is based on the critical decay rate concept[3] developed at Caltech to enable the prediction of critical energies in blast initiation. This model is based on a competition between the sustaining effect of energy release and the quenching effect of unsteadiness.

Assumptions regarding the unsteady expansion propagation into the undisturbed planar detonation, reaction zone quenching behind the diffracted shock, and the axial shock decay after the critical time have been supported by computations and experiments with single- and multi-sequence shadowgraphy and digital chemiluminescence imaging. The parameters necessary for evaluation of the analytical expression were obtained with thermochemical equilibrium calculations, steady, one-dimensional detonation simulations, and constant-volume explosion simulations with a validated[4] detailed reaction mechanism.

The critical diffraction conditions were calculated for fuel-oxygen and fuel-air mixtures with varying stoichiometry, initial pressure, and diluent type (argon, carbon dioxide, helium, nitrogen) and concentration for hydrogen, ethylene, and propane fuels. Results from the critical diffraction model were compared (Fig. 2) against experimentally-determined critical conditions for diffraction from a circular cross section and found to be in complete qualitative agreement, and in quantitative agreement to within the uncertainty associated with the calculation of model parameters and the experimental measurements.

DDT and Impulse Measurements

Previous work[5] on deflagration-to-detonation transition (DDT) has demonstrated that for fuel-air mixtures, the transition distance or time can be extremely long for plain tubes (Fig. 3). Obstructions (internal obstacles) are required in order to obtain a detonation within a short tube. The effect of these obstacles and the DDT process on the impulse obtained from a single tube have not been previously measured.

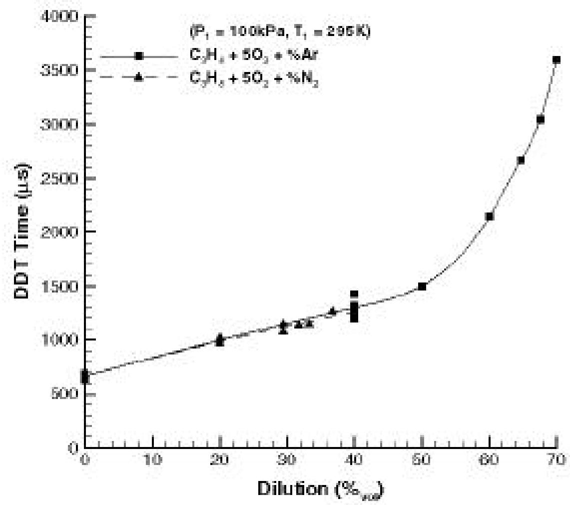

Figure 3: Excessive transit time during DDT in C_3H_8+5O_2+xN_2 mixtures in 38 mm diameter tube.

Direct measurements were made[6,7] of the impulse delivered by a DDT-initiated detonation or a fast flame. The impulse was determined by measuring the displacement of a ballistic pendulum in which a tube was suspended from the ceiling by steel wires (Fig 4). The combustible mixture, initially contained in the tube by a thin diaphragm, was ignited by a spark at the thrust wall. Combustion products were free to expand out from the tube into an unconfined volume. Pressure histories (Fig. 5) were recorded, including the pressure at the thrust wall which was then integrated for comparison with the ballistically-determined impulse.

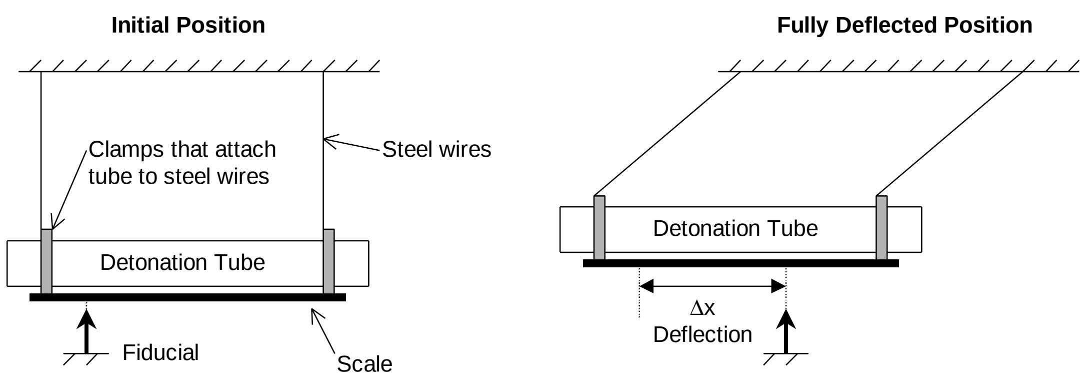

Figure 4: Ballistic pendulum method of measuring impulse of open-ended detonation tube.

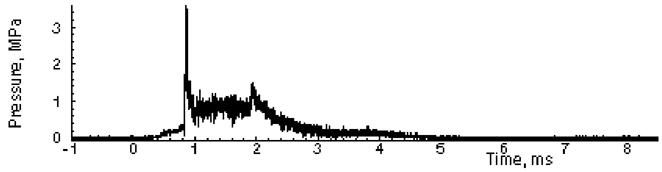

Figure 5: Sample pressure trace at thrust wall.

Ionization gauges were used to determine the time-of-arrival of the wave. A calibration experiment was performed in which a detonation was directly initiated in stoichiometric acetylene-oxygen with no obstacles present in the tube. The ballistically-measured impulse was within 3.5% of the value obtained by integrating the thrust-wall pressure trace.

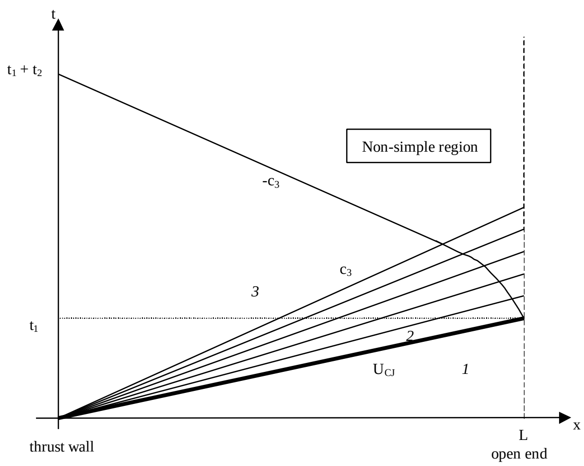

Figure 6: X-T diagram inside detonation tube

Experimental impulse measurements for detonations were compared with analytical predictions and with numerical simulations. The analytical model approximates the pressure history by two regions: an approximately constant pressure region which begins with the passage of the Taylor wave and ends with the arrival of the first characteristic of the reflected wave (usually an expansion) at the thrust wall, and a second region which models the pressure decrease through the remaining reflected wave (Figs. 5 and 6). The similarity solution for the Taylor wave and dimensional analyses have been used to predict the measured impulse if the thermochemical properties of the mixture are known. This model requires some nondimensional constants which are obtained by integrating the appropriate region of experimental and numerical pressure traces. Both experimental and numerical results indicate that the flow may be overexpanded by the reflected rarefaction. If this occurs, the impulse decreases from the peak value and care must be taken in determining the impulse from the integrated pressure trace.

The impulse was directly measured for three tube configurations with length to internal diameter (L/d) ratios of 40, 13, and 8. Various obstacle configurations were investigated, including blockage plates, orifice plates and spirals of varying pitch. Different regimes of detonation, DDT and fast flames were observed.

The tube with L/d ratio of 13 has a 3-in internal diameter. Measurements were carried out in stoichiometric ethylene-oxygen mixtures with nitrogen dilution with the tube free of obstacles and with three different obstacle configurations. Each obstacle configuration has a blockage ratio of 0.43. The inclusion of obstacles dramatically reduced the DDT times and distances (Fig. 7). At 30 kPa initial pressure, the obstacles reduced the DDT time and distance by 88.5%. The obstacles allowed DDT to occur in mixtures

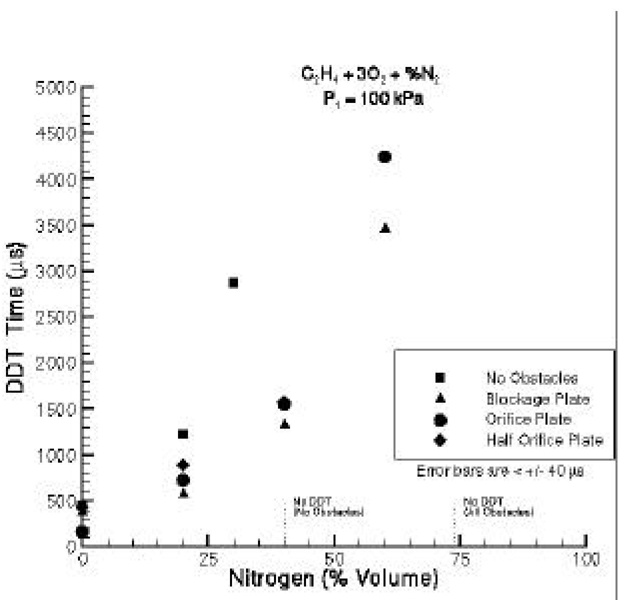

Figure 7: DDT time for varying diluent and obstacle configurations.

composed of up to 60% nitrogen. With no obstacles present, DDT was not achieved in mixtures with more than 30% nitrogen. Only a fast flame could be initiated in ethylene-air.

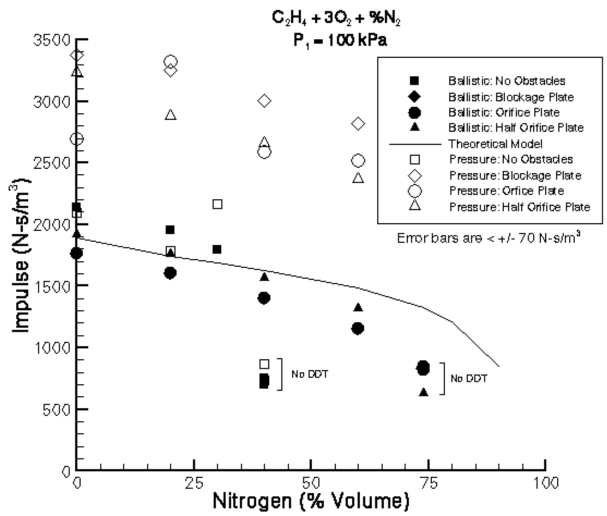

Figure 8: Normalized impulse for varying diluent and obstacle configurations.

Approximately 100% more impulse was produced when a highly diluted mixture could be made to transition to detonation by the presence of obstacles than in the case of a fast flame (Fig. 8). In mixtures in which DDT occurred in the absence of obstacles, the inclusion of obstacles reduced the impulse measured by about 25%. It is important to note that in these cases, the impulse derived from the thrust-wall pressure trace overpredicts the impulse measured by the ballistic pendulum by a factor of two since the pressure integration neglects the momentum lost to drag over the obstacles.

The tube with L/d ratio of 8 also has an internal diameter tube of 3-in. Results for two spiral geometries are shown in Fig. 9. Both spirals had a blockage ratio of 0.43. Mixtures used were ethylene or propane in oxygen with increasing nitrogen dilution up to air. Initial pressures ranged from 50-100 kPa.

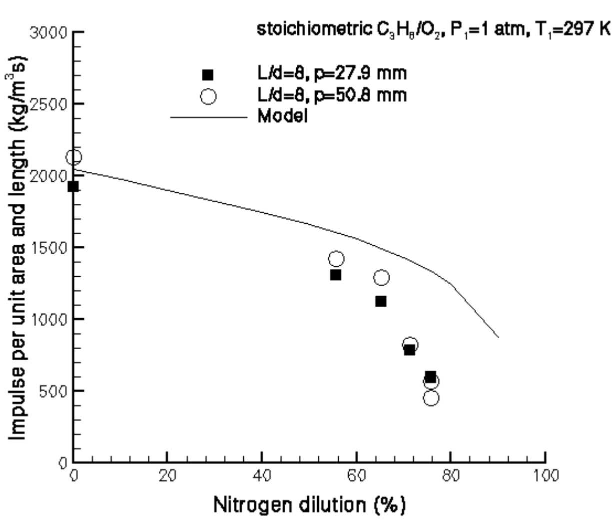

Figure 9: Normalized impulse for propane-oxygen-nitrogen detonations with Schelkin spiral.

The volume of this tube is about one-half that of the longer tube discussed above and with a spiral of the same blockage ratio as the blockage plates, the measured impulse is approximately one-half that measured for the longer tube for the same mixture. Similar trends are observed as in the longer tube: in the presence of obstacles, integrating the thrust-wall pressure history leads to an overprediction of the impulse.

Further tests are planned in vapor phase JP-10-O_2 mixtures with nitrogen dilution up to air. The 3-in tube is currently being modified to include a heating system and a new propane-oxygen initiator system. The effects of tube extensions, baffles, and nozzles are also being examined. Analytical model predictions for normalized impulses in fuel-air systems are shown in Fig. 10.

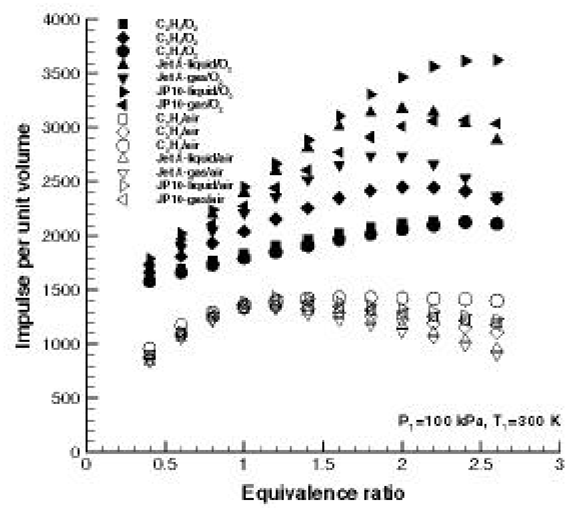

Figure 10: Ideal single-cycle impulse performance of fuel-O_2 and fuel-air PDEs.

Cell Width Measurements

Detonation cell width measurements on hydrocarbon fuels have been extremely useful as a simple characterization of fuel detonability. In a previous study,[8] various blends of hydrocarbon fuels were examined. One conclusion from this work is that smaller hydrocarbons such as C_2H_2 are not very effective sensitizers for heavier fuels such as C_6H_{14} (Fig.11). Large amounts of the smaller hydrocarbon are required before a substantial decrease in cell size will occur. Similar types of measurements for aviation fuels are now in progress at Caltech. Before examining fuel blends, the individual fuels JP-10 and Jet A will be studied as a function of the amount of nitrogen dilution, initial

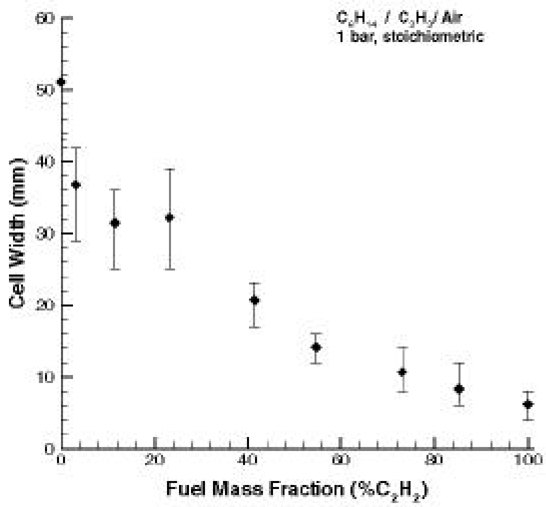

Figure 11: Detonation cell width measurements for a hexane-acetylene fuel blend in air.

pressure, and equivalence ratio. These tests will all be carried out at elevated temperatures (80 to 100C) with pure vapor phase fuel in order to avoid the problems connected with dispersing and characterizing sprays.

To enable detonation cell size measurements in vapor-phase mixtures of fuels such as JP-10 and Jet A in air, we have structurally modified the existing Caltech 280-mm detonation tube. The tube flange connections have been strengthened and the tube was hydrostatically pressure tested to 200 bar, an increase of 42% over the previous test pressure. A 10 kW electrical heater and controller system, capable of evenly heating the tube from 20C to 100C in 4 hours, has also been installed. The tube and heaters will be covered with silicone glass insulation blankets. Various components of the facility have been modified in order to achieve the operating conditions of 100C.

Tube Fracture Experiments

Previous work[9,10] at Caltech on mechanical response of

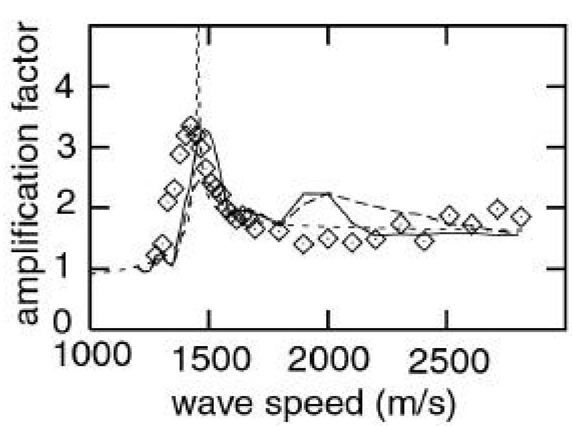

Figure 12: Amplification factor for resonant excitation of flexural waves in shock tube.

detonation tubes has emphasized the importance of flexural waves and the possibility of resonant excitation of flexural waves by detonations or shock waves. Laboratory measurements, analytic solutions of elastic equations, and numerical solutions to finite-element models have all demonstrated that strains up to 4 times higher than the static values can be produced (Fig. 12).

An apparatus (Fig. 13) is currently being set up to investigate the fracture behavior and failure criteria of pre-flawed and thin-walled tubes under single cycle detonation loads. Preliminary studies involve measurements of crack propagation speeds and crack tip stability. These will be followed by high-speed photography that will visualize the displacement field near the crack-tip.

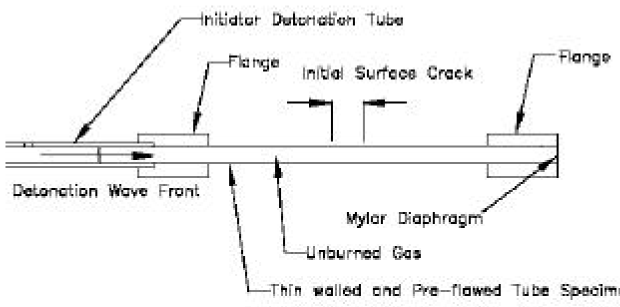

Figure 13: Crack propagation experiment in detonation tube.

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