Detonation Initiation and Propagation

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Research at Caltech is being carried out into the reaction zone structure of propagating detonations, initiation of detonation using hot jets and detonation focusing, direct measurement of impulse examining the effects of partial-fill and exit geometry, detonation cell width measurements for JP10 with addition of hydrocarbons that typically result from JP10 decomposition, and the structural response of detonation tubes, including fracture and failure.

Introduction

The Explosion Dynamics Laboratory at Caltech is carrying out investigations on many aspects of detonation propagation and initiation which are relevant to pulse detonation engines (PDEs). A brief review of activities over the past year is presented here.

Detonation Structure

OH Planar Laser Induced Fluoresence (PLIF) was used for direct experimental observations of detonation reaction zone structure. Characteristic "keystone" structures in the OH intensity have been revealed and correlated with detonation wave instability structures computed on the basis of reduced chemistry and also inferred from gas dynamic considerations[1]. The keystone shape is due to the variation of reaction zone length with shock strength and is bounded by the shear layer that is associated with the triple points in the detonation front. Keystone structures were observed to be more irregular in nitrogen-diluted mixtures than in argon-diluted mixtures, which is consistent with the known characterization of the cellular structures as irregular and regular, respectively. This study was extended to include more irregular mixtures. Several new features were observed including shear layer instabilities in highly nitrogen-diluted mixtures and fine scale density and OH front disturbances in mixtures with cellular substructure (Figure 1). Islands of reacted and unreacted gas are observed. The study suggests that besides the classical theory of detonation propagation, other, more complex, combustion processes play a role for more irregular mixtures.

In the current experimental setup, three-dimensional effects complicate both schlieren and PLIF images. An investigation was made of the possibility of simplifying the flow field by damping out-of-plane transverse waves using a porous wall. The technique was found to be successful, but only for a limited range of mixtures. The experiments also studied detonation propagation through narrow channels of different widths. Diagnostics included soot foils to record cell structure and pressure gauges to measure velocity deficits.

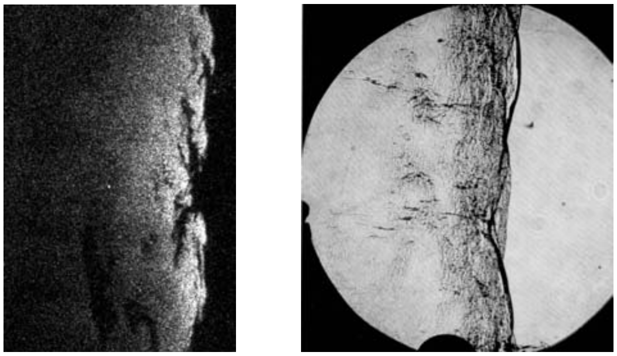

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Figure 1: OH PLIF (left) and schlieren (right) image in a mixture with highly irregular cellular structure (H_2-N_2O-$3N_2$, initial pressure 20kPa).

A narrow channel facility has been designed and is being constructed. The purpose of this facility is to effectively reduce the detonation to two dimensions so that schlieren images can be more readily analyzed. The narrow dimension of the channel, while sufficient to weaken the out-of-plane waves, is intended to be large enough for viscous effects not to dominate the flow. Both these features will make comparison with numerical simulations more valid, allowing us to experimentally investigate the presence of features to date studied only numerically.

JP10 Cell Width Measurements

Liquid fuels of high energy density are important for practical PDEs. Cell width data, obtained from sooted foils (Figure 2), are a useful measure of the detonability of such fuels. We extended our database of cell width measurements in vaporized JP10 in the heated Caltech 280mm diameter detonation tube. Cell width measurements were made in JP10 mixtures with the addition of fuels which typically result from JP10 decomposition[3]. C_2H_2, C_2H_4, and CH_4 were added to JP10, and results are shown in Figure 3. Such data will

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also be useful for validation of reaction mechanisms for JP10.

Figure 2: Soot foil of JP10-20%C_2H_2-Air. Detonation propagated from left to right.

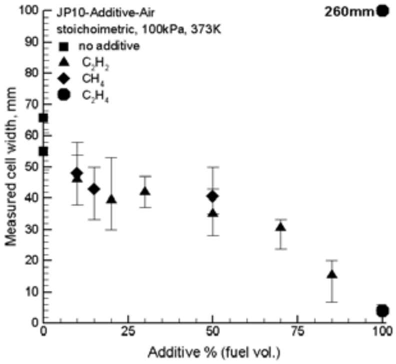

Figure 3: Detonation cell width measurements in JP10-hydrocarbon-air at 100kPa initial pressure, 353K initial temperature. All data points for hydrocarbon-air are from Tieszen et al. 1991[4]. CH_4-air cell width is actually 260mm.

A more extensive study of the effectiveness of adding low-molecular weight fuels as sensitizers to heavy hydrocarbon fuels was previously carried out in hexane mixtures[5].

Effect of Exit Conditions on Impulse

The effect of detonation tube exit conditions on performance was examined. A semi-empirical model was developed to relate the fraction of the detonation tube filled with the combustible mixture to the impulse. For cases where the combustible mixture filled more than 15% of the tube, experimental[6, 7, 8,9] and numerical[11] data show a linear relationship between the impulse and fill fraction. For cases where less than 15% of the tube was filled with the combustible mixture, we used data from numerical simulations that indicate a very nearly constant value of specific impulse for these conditions.

We have used a simple model for metal acceleration to examine the amount of chemical energy that is converted to impulsive motion of the tube. The Gurney model[8] uses an energy parameter indicative of the chemical energy of the high explosive that is converted into the kinetic energy of the body. These energy values are well known for most high explosives only. For gaseous combustible mixtures, we have utilized the Jacobs thermodynamic cycle that connects the equilibrium states to determine the maximum available work obtainable from the detonation of these gaseous fuels. The energy used to impart impulse to the body is only a fraction of the total energy available due to the detonation. A large amount of thermal energy is lost when hot products are ejected from the tube. We found energy going into impulse to be approximately 45-65% of the total available energy available for ethylene- and propane-oxygen-nitrogen mixtures at 100 kPa. These energies are approximately 10-30% of the heat of combustion of the fuel.

Based on experimental and numerical data and also simple physical ideas, we have developed a semi-empirical model relating the percent of the detonation tube filled with the combustible mixture to the resulting impulse. The experimental impulse has been normalized by the impulse predicted from our analytical model[13] for the fully-filled tube. Our partial-fill model appears in Figure 4 along with experimental data for detonation tubes of a constant cylindrical cross-section. The data has been corrected for the additional explosive tamping effect of the diaphragm.

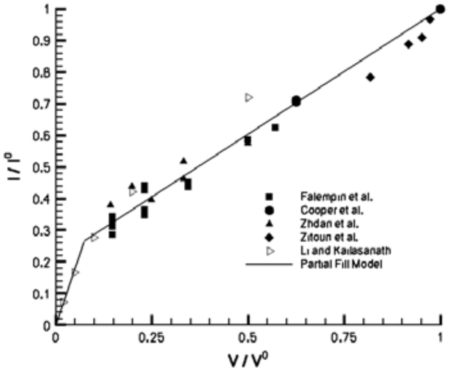

Figure 4: Normalized impulse versus percent fill for tubes of constant cylindrical cross-section. Data has been corrected for diaphragm effects.

In cases of detonation tubes with varying cross-sectional area such as tubes with diverging nozzles, the impulse depends primarily on the volume ratio of the combustible mixture to the air mixture (or the percent of the tube filled with the combustible mixture). Figure 5 shows the experimental data for tubes of varying cross-sectional area as a function of the fill fraction.

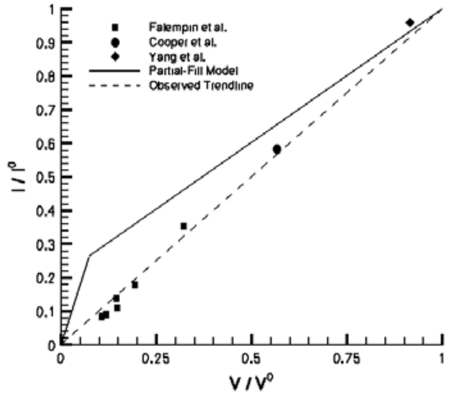

Figure 5: Normalized impulse versus percent fill for tubes of varying cross-section. Data has been corrected for diaphragm effects.

The model was also validated against additional experimental data from multi-cycle experiments by Schauer et al.[12] as shown in Figure 6.

A separate quasi-steady model has been developed to treat the restricting effects of converging nozzles. Preliminary results indicate heat transfer may play an important role in determining the performance of detonation tubes with converging-diverging nozzles at the exit.

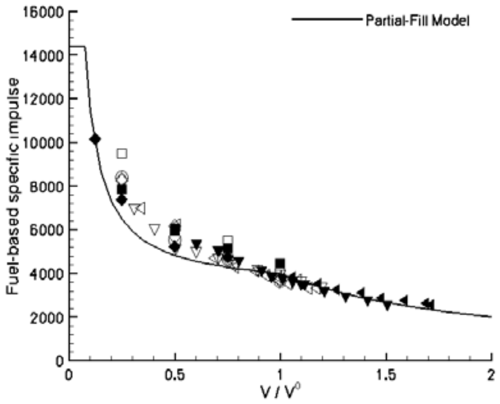

Figure 6: Comparison of partial-fill curve with experimental data from Schauer et al.[12] Symbols represent different operating frequencies and detonation tubes.

Hot Jet Initiation

The effectiveness of using a hot turbulent jet to initiate a detonation in a short distance was investigated experimentally. A turbulent jet of combustion products, passing from a driver section through an orifice into a test section, was used to initiate a turbulent flame in the test gas. The turbulent flame may transition to detonation. Such low energy methods of detonation initiation are of particular interest to PDEs.

The experiments were performed in the ballistic pendulum facility with a tube that consists of two vessels: a 100 cm^3 volume driver section and a 1 m long by 76.2 mm diameter test section. The vessels are connected by an orifice, the diameter of which can be varied. The test section is equipped with three pressure transducers and ten ionization probes to measure the pressure history and wave velocity. The driver section has a pressure transducer on the ignition end wall. The driver is filled with stoichiometric propane-oxygen and the test section is filled with stoichiometric propane-oxygen mixture with varying nitrogen dilution. A Mylar diaphragm initially separates the driver and test gases. The aim of the current study is to examine the effect of the orifice diameter and the initial pressure of the driver section on the maximum nitrogen dilution for which a detonation can be initiated in the test section.

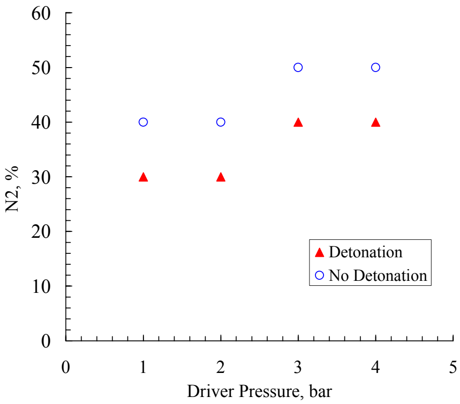

Figure 7: N_2 dilution of the test gas vs initial pressure in the driver section.

Driver pressure is found to have a mild effect on the critical N_2 dilution. Figure 7 is a plot of test section N_2 dilution versus initial driver pressures of 1 to 4 bar. The orifice diameter is 3.125 mm. Increasing the driver pressure by a factor of four resulted in a 10% increase in the critical N_2 dilution.

Figure 8 shows the orifice diameter versus N_2 dilution with the initial driver pressure at 1 bar. Specific impulse measurements are also shown. The black line corresponds to the analytical model[12]. Increasing the orifice diameter from 3 mm to 19 mm increases the critical dilution level from 30% to 40% N_2.

Experiments were also carried out with an array of orifices to examine the role of jet mixing. For a given open area, the multiple hole geometry resulted in a 5% increase in the critical dilution level over the equivalent single hole geometry

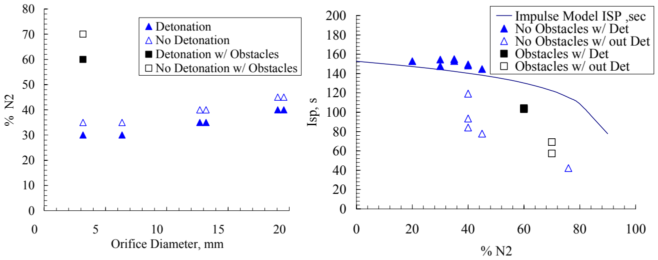

Figure 8: Left: N_2 dilution of the test gas vs orifice diameter. Right: Corresponding I_{SP} measurements.

Initiation By Detonation Focusing

A device capable of creating a collapsing toroidal detonation wave front has been designed and constructed. The goal is to generate pressures and temperatures at the focal point of the collapsing detonation wave that will be sufficient to initiate detonations in insensitive fuel-air mixtures inside a detonation tube without blocking the flow path and causing associated losses in propulsive efficiency. This toroidal initiator uses a single spark and an array of small diameter channels to generate and merge many detonation waves to create a single detonation wave with a toroidal front.

A planar detonation wave initiator was first built and tested to demonstrate the principles of merging a series of wave fronts into a single front. This device served as a stepping-stone in the development of the toroidal wave generator discussed below. The planar initiator is capable of producing a large aspect ratio, planar detonation from a weak spark. The planar version, shown in Figure 9, consists of a main channel with secondary channels branching off the main channel. All secondary channels terminate on a line and exhaust into a common test section area. The channel geometry is such that all path lengths from the spark point to the secondary channel termination line are equal.

To create a toroidal wave, the planar initiator design was modified such that the exit of each channel lies on a circle with the channels exhausting inwards. This involved mapping the planar design onto a cylinder, creating an annular imploding wave instead of a planar wave as shown in Figure 10. The mapping transforms the metal substrate containing the channels into an inner sleeve while the cover plate becomes the outer sleeve. Creation of a pressure seal between the inner and outer sleeves was accomplished by a shrink fit All initiator channel dimensions are similar to that of the previously described planar initiator. The small channels exhaust into a test section that is 76.2 mm in diameter. This design allows the initiator to be incorporated into the walls of a PDE. Since no part of the initiator is inside the flow path, there are very few losses in propulsive efficiency associated with the device.

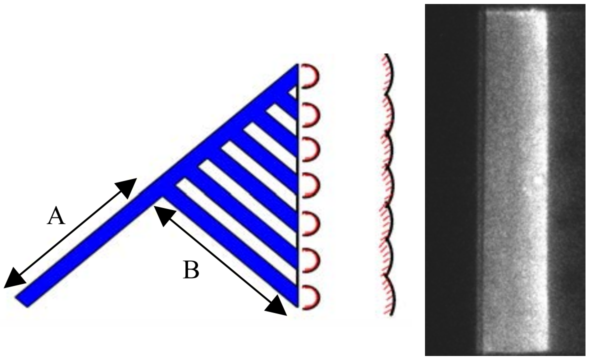

Figure 9: Left:schematic of planar initiator. (A+B = constant for all paths.) Right:chemiluminesence image of merged planar detonation front. Flow is left to right.

Testing was performed with stoichiometric propane-oxygen mixtures at 1 bar to determine the pressure increase achieved by toroidal focusing. The device was filled using the method of partial pressures. The mixture was circulated to ensure homogeneity using a bellows pump which limited initial mixture to pressures of 1 bar or greater. Pressure histories were obtained at locations near the focus of the collapsing torus by four pressure transducers, one of which was placed as close to the implosion axis as possible. The distance separating the pressure transducer axis from the implosion center was 19.05 mm. The transducers were equally spaced 10.7 mm apart on a radial line with the central transducer located on the central axis of the initiator tube. A typical set of pressure traces is shown in Figure 11.

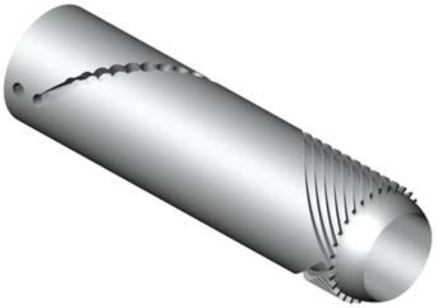

Figure 10: Schematic of annular detonation wave initiator. (Covering shell omitted for clarity.)

The outermost three pressure transducers show a gradually decreasing pressure wave as the radius of the imploding torus decreases. The central pressure transducer (P4), however, recorded a value above its maximum reliable operating range. This value was four times larger than the Chapman-Jouguet pressure for the mixture.

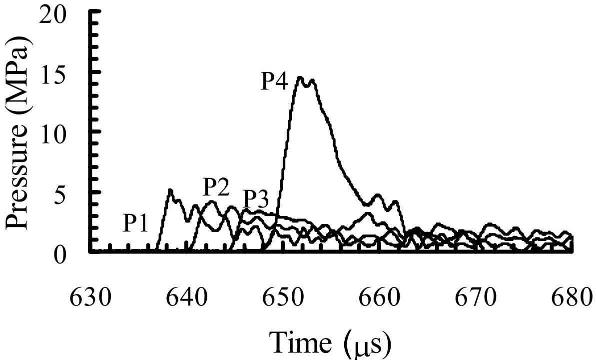

Figure 11: Pressure traces

Images of the detonation front show a nearly circular wave front (Figure 12). Some structure behind the wave is also visible. It is not clear at this time what the structure is; it may be due to the detonation interacting with the window.

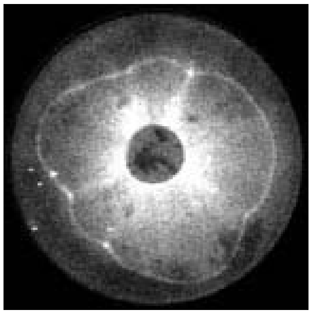

Figure 12: Chemiluminescence image of imploding detonation wave. Irregular secondary wave is thought to be due to interaction with window.

Fracture experiments and correlations

If structural failure may occur, it is desirable and often possible to have benign failure rather than catastrophic failure. The use of a fracture mechanics approach in structural design allows the cracks to be brought to quick arrest and prevent fragmentation. Experiments at Caltech have shown that the fracture modes in axially preflawed aluminum tubes loaded by detonations are a strong function of the initial flaw length. Different fracture modes were observed (sometimes all on the same specimen) including short distance straight propagation, helical propagation, and bifurcation (Figure 13).

Figure 13: Crack propagation and bifurcation under detonation loading. Detonation propagated from left to right. P_{CJ}=6.2 MPa, notch length 50.8 mm.

It is common for flaws such as voids or cracks to develop in aerospace structures during their manufacture or lifetimes. Flaws can be small and insignificant, or they can lurk until they are fatigued to a critical size, at which point the structure fails. A fracture threshold model was developed to predict the single-cycle detonation pressure at which the tubes would burst given the tube's geometry and material properties. The experimental data showed fair agreement with the model (Figure 14). Strain gages were also mounted on the tubes to monitor the large scale yielding during dynamic fracture.

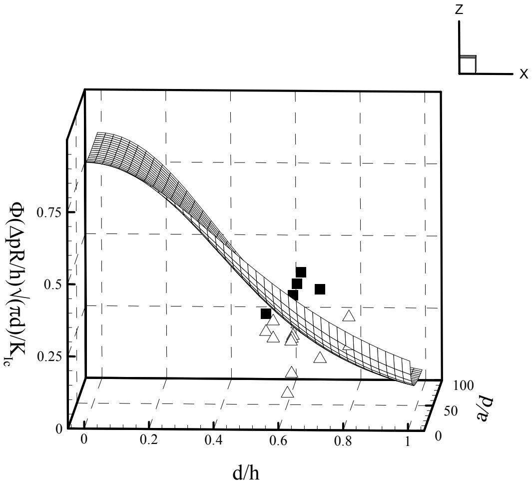

Figure 14: Fracture threshold model and experimental data. Mesh surface: theoretical threshold. Filled squares: rupture. Open triangles: no rupture.

The parameters used in developing the model and the symbols in Figure 14 are given in the Tables below.

Tube material	6061-T6
Wall thickness	0.89- 1.2 mm
Tube O.D.	41.3 mm
Axial flaw length	13 to 76 mm
d/h	0.5 to 0.8
P_{CJ}	2 to 6 MPa

Table 1. Experimental parameters

ΔP	$P_{CJ}- P_{atm}$
R	Tube mean radius
h	Tube wall thickness
d	Surface notch depth
2a	Surface notch length
K_{Ic}	Fracture toughness
Φ	Dynamic amplification factor

Table 2. Model Parameters

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