Detonation Structure, Initiation, and Engine Component Performance

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Research at Caltech is being carried out into the reaction zone structure of propagating detonations, initiation of detonation using detonation focusing, direct measurement of impulse examining the effects of thrust wall porosity and nozzles, and modeling of engine performance based on gasdynamics and control volume approaches to simplified engine geometries.

Introduction

The Explosion Dynamics Laboratory at Caltech is carrying out investigations on the following aspects of pulse detonation engines (PDEs): detonation propagation, initiation, thrust generation by detonation tubes, and engine performance modeling. A brief review of activities over the past year is presented here.

Simultaneous PLIF and Soot Foil Visualization

The cell size is an important parameter characterizing the detonation properties of gaseous mixtures. In a common experimental technique for the determination of cell size, regularity, and shock wave configuration, soot foils are placed on the side and end walls of the detonation tube. The physical principle behind the soot foil technique is not yet completely understood. Soot gets redistributed or removed by the passing detonation. This raises the question of the spatial correlation of the triple point and the soot foil tracks.

We used Planar Laser Induced Fluorescence (PLIF) of the OH radical to visualize the reaction front close to the wall and deduced the approximate position of shear layer, triple point, and leading shocks of the detonation front structure. Simultaneously obtained soot foils allow for an overlay of the obtained soot foil and PLIF image. The distance between the laser light sheet of thickness 0.3 mm and the soot foil is approximately 1 mm. This minimizes the error between the deduced and effective location of the shock front at the wall due to three-dimensional effects of the detonation front. A simplified similarity calculation of the boundary layer indicates that the PLIF images are taken outside of the boundary layer. Fully developed detonations in a stoichiometric H_2-O_2 mixture diluted with 85% Ar at initial conditions of 0.2 bar and 294 K were investigated.

The experiments were carried out in a 7.3 m long, 280-mm diameter detonation tube. The propagating detonation is "square-cut" at the end of the tube by four plates with sharp edges, which form a 152-mm square cross-section, and thereby transitions into the 1.8-m long, 152-mm square test section of the facility.

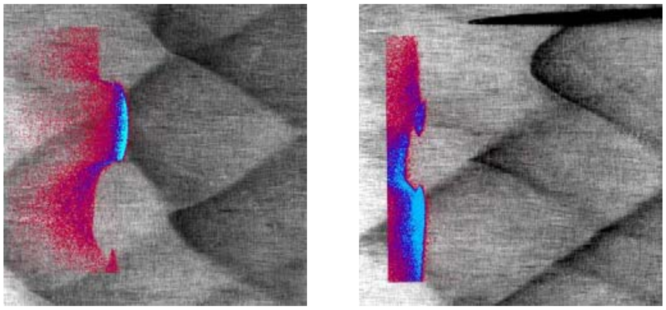
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Figure 1: Overlay of PLIF and soot foil images.

The distinct OH concentration front seen on the PLIF images corresponds to the sharp rise in OH concentration at the end of the induction zone. The previously reported keystones[1,2] of lower fluorescence correlate well with the closing half of cell patterns on the soot foil, and keystones of higher fluorescence with the opening parts of the cell patterns. Using an idealized description of the triple point configuration (see Figure 2) and the normalized shock velocity profile through a cell calculated[3] from a similar mixture, the triple point location can be derived in two ways: The induction zone length behind the incident wave $\Delta_{\sigma IW}$ and the Mach stem $\Delta_{\sigma MS}$ can be used to estimate the distance d from the keystone corner to the triple point.

The triple point location derived from these results seems to be consistently located on the incident shock side of the soot foil track and does not, as commonly assumed, coincide with the soot foil track. Further experiments are planned in a high aspect ratio channel to eliminate three-dimensional effects.

Initiation By Detonation Focusing

Previous work on the development of a wave focusing initiator led to Caltech's first generation of planar and toroidal initiators. The planar initiator is capable of generating a large aspect ratio planar

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detonation wave. The toroidal initiator creates an imploding annular detonation wave.

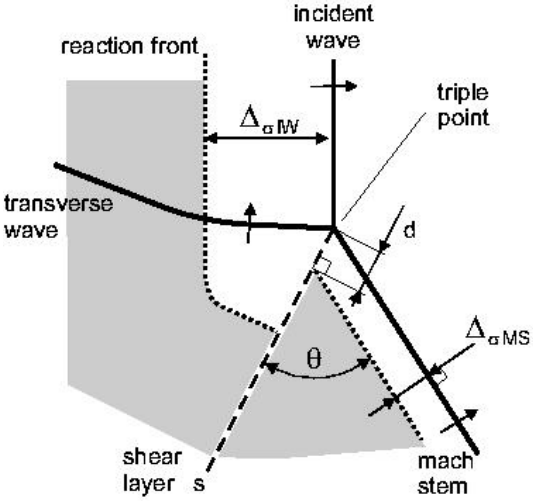

Figure 2: Idealized description of the triple point configuration used for analyzing combined soot foil-PLIF images.

The goal of the toroidal initiator 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. The initiators use a single spark and an array of small diameter channels to generate and merge many detonation waves to create a single detonation wave with the desired shape.

During operation, the initiator would be filled with a driver gas, which would then be ignited to create an imploding wave in the main tube. This imploding wave is expected to transmit the detonation into the hydrocarbon-air mixture in the detonation tube.

The first generation channel design was not capable of dynamic injection of a driver gas into the small channels as each path had a different flow resistance. This variation of flow resistance with path is evidenced in a series of water channel experiments. The first generation planar initiator was filled with water, and blue dye was injected into the main channel. Observation of the dye (Figure 3) showed that it traveled down the main and secondary channels differing distances regardless of the injection rate. Injection of an acetylene-oxygen driver gas yielded the same effect, resulting in a non-optimal operation of the initiators. Thus, it was necessary to modify the channel geometry to allow for dynamic injection of a driver gas.

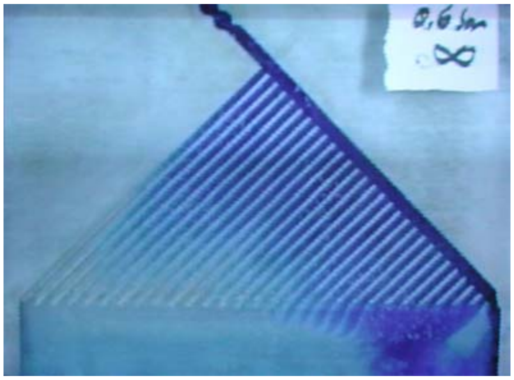

Figure 3: Dye injection into the planar initiator showing the effect of non-uniform flow resistance.

A new channel design was developed such that (1) each channel in the device has equal path length from the spark point to the exit plane and (2) each channel has identical flow resistance. Second generation planar and toroidal devices were built using this channel design and are shown in Figures 4 and 5 respectively. The second generation planar initiator has been successfully tested. The second generation toroidal initiator is currently undergoing testing.

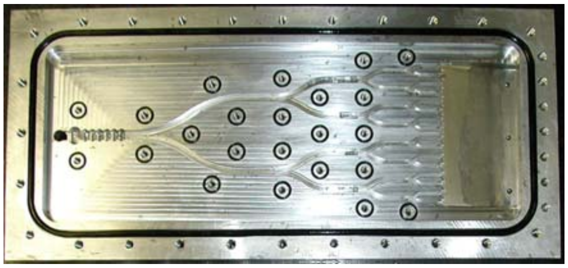

Figure 4: The second generation planar initiator.

Figure 5: The second generation toroidal initiator. The outer sleeve has not yet been placed over the inner sleeve in this view.

During testing, the planar device is filled with the test mixture using the method of partial pressures. The mixture is recirculated using a bellows pump to ensure that the test gas is sufficiently mixed. Shortly before ignition, equimolar acetylene-oxygen driver gas is injected into the main channel near the spark point. Driver injection continues until the driver gas fills the initiator channels. Once the channels are filled with the driver gas, the spark plug is fired, initiating a flame and subsequent detonation in the main channel which branches off into all other channels as with previous designs. The detonation wavelets emerge from the initiator channels into the test section at the same instant and combine to form a planar front.

In order to visualize the operation of the device, transparent polycarbonate was used as a cover plate for the device. A 1-mm thick Teflon gasket was used to seal between the cover plate and the aluminum substrate containing the channels. Use of an intensified CCD camera allowed visualization of the chemiluminescence of the front. As is shown in Figure 6, the detonation wave branches through each channel of the device, moving at an equal speed in all channels. Pressure transducers located in the test section of the initiator indicated that the resulting 18 cm wide wave is planar to within 6 mm under dynamic injection conditions.

Preliminary tests have been conducted with the second generation toroidal initiator. During these tests, no driver gas was injected. Instead, the device was filled with homogenous stoichiometric hydrocarbon-oxygen mixtures ignited under static conditions to verify that the channel geometry of the device produced regular toroidal waves. Initial tests show that the device produces a repeatable imploding toroidal wave for ethylene-oxygen mixtures at 1 bar initial pressure (Figure 7). Pressures at the implosion center are approximately 8 times the Chapman-Jouguet pressure of the mixture.

For propane-oxygen mixtures at 1 bar initial pressure, the device produces non-repeatable results (Figure 8). The detonation is delayed or fails in some initiator channels resulting in a skewed implosion. Pressures at the implosion center are still in excess of five times the Chapman-Jouguet pressure of the mixture, however.

Ongoing testing will determine the performance of the second generation toroidal initiator with dynamic driver gas injection. The failure of detonation in the initiator channels with propane-oxygen mixtures will also be investigated.

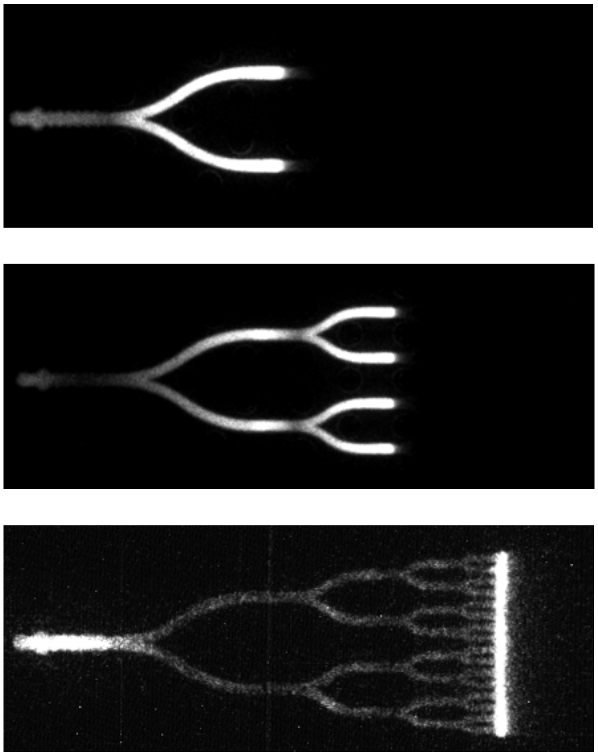

Figure 6: Chemiluminescence images of the second generation planar initiator operating under dynamic driver injection.

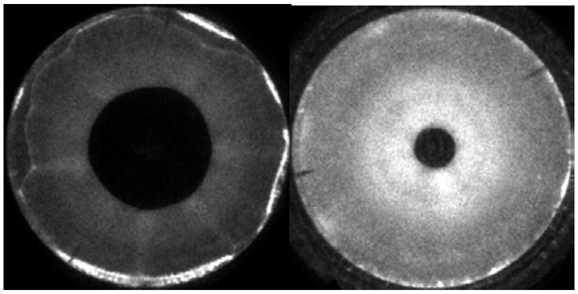

Figure 7: Chemiluminescence imaging results of the collapsing wave for the toroidal initiator with ethylene-oxygen mixtures.

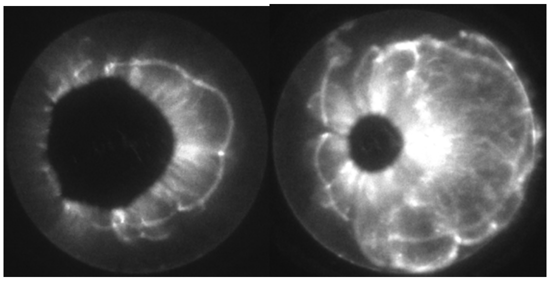

Figure 8: Chemiluminescence imaging results for the toroidal initiator with propane-oxygen mixtures**.**

Effect of Thrust Surface Porosity on Impulse

As pulse detonation engine development matures, it becomes increasingly important to consider how practical details such as the implementation of valves and nozzles will affect the performance. Inlet valve timing and inlet designs without valves may result in flow of products back upstream and, consequently, reduction in impulse over the ideal case. In an effort to understand this effect, a series of single-cycle tests have been carried out to measure the impulse in a detonation tube with a porous thrust surface. The impulse was measured for porous thrust surfaces with blockage ratios ranging from completely solid (100% blockage ratio) to complete open (0% blockage ratio) at initial pressures from 20 to 100 kPa in stoichiometric ethylene-oxygen mixtures ignited with a weak spark. The detonation tube used had an internal diameter of 76 mm and a length of 1.058 m. It was hung from the ceiling in a ballistic pendulum arrangement and the impulse was calculated based on the maximum deflection of the tube. The time required for the initial deflagration to transition to a detonation (DDT time) was measured by ionization probes mounted along the tube length.

The DDT time is plotted in Figure 9 as a function of the initial pressure in the tube. For all thrust surfaces tested, the time to transition increases as the initial pressure decreases. This effect was also observed in the previous work of Cooper et al.[4]

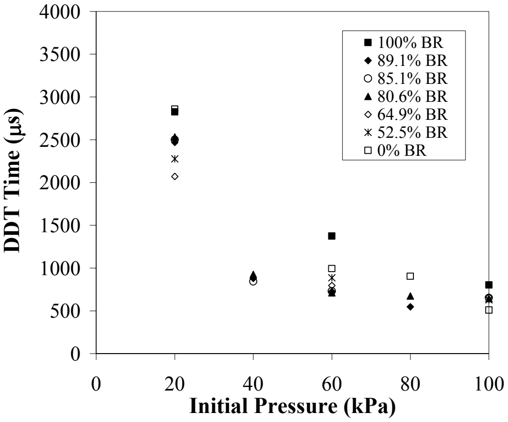

Figure 9: DDT time as a function of the initial detonation tube pressure. Data presented from tubes with different thrust surface blockage ratios.

The DDT time is plotted in Figure 10 as a function of the thrust surface blockage ratio. At each initial pressure as the blockage ratio changes, the DDT time is relatively constant. Thus, the DDT time is more sensitive to changes in the initial pressure and relatively insensitive to changes in the thrust surface blockage ratio.

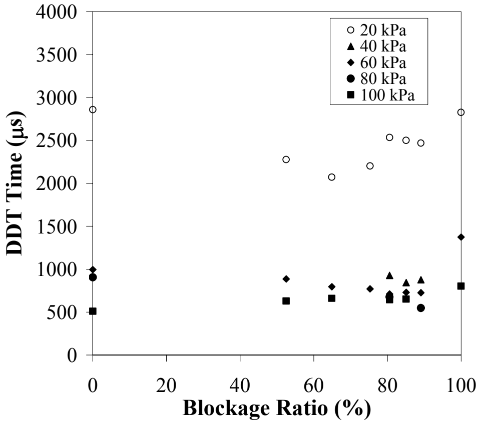

Figure 10: DDT time as a function of the thrust surface blockage ratio. Data presented from tubes with different initial pressures.

A model of the impulse expected from a detonation tube with a porous thrust surface was developed. We present the model with the experimental impulse values for initial pressures between 40 and 100 kPa. The model assumptions can not be applied to the experimental data at 20 kPa because of the late DDT event and long DDT times shown in Figure 10. The model is based on a modification to the existing impulse model developed by Wintenberger et al.[5] In the model for a solid thrust surface, the normalized impulse depends on the detonation wave speed U_{CJ} and plateau pressure P_3. Because of the non-zero flow exiting the tube through a porous thrust surface, we predict a new plateau pressure P_3' by assuming the flow exiting through the thrust surface is choked.

The predicted plateau pressure P_3' is compared to the experimental values as a function of the thrust surface blockage ratio (Figure 11).

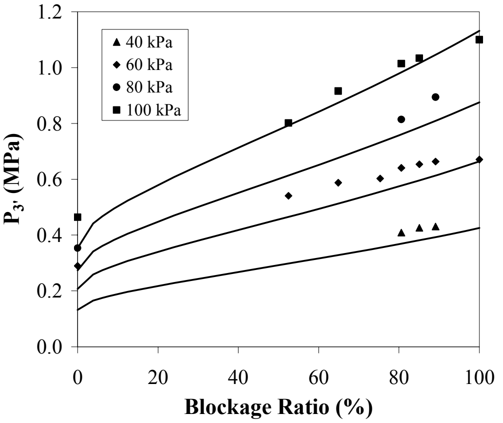

Figure 11: Plateau pressure P_3' versus thrust surface blockage ratio. The lines represent the model predictions for different initial pressures.

There is good agreement between the predicted and experimental values. By substituting this new plateau pressure into the existing impulse model[5] and adding a factor to account for the fraction of thrust surface area that is open, the impulse can be predicted for detonation tubes with porous thrust surfaces. The predicted and experimental impulse values are plotted in Figure 12 as a function of the thrust surface blockage ratio. A loss in impulse of approximately 75% was observed with a thrust surface blockage ratio of 50% at an initial pressure of 100 kPa.

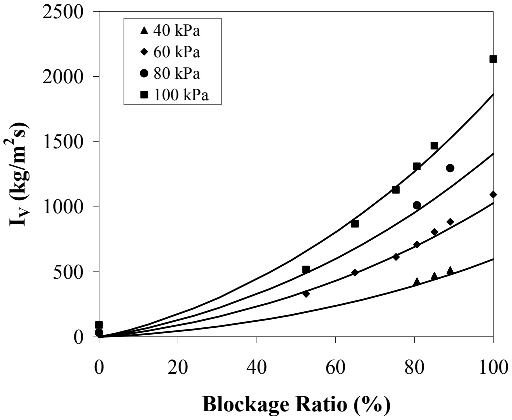

Figure 12: Normalized impulse versus thrust surface blockage ratio. Data are presented for initial pressures between 40 and 100 kPa.

All data presented above were generated by thrust surfaces containing an arrangement of 7 holes. A second thrust surface with an arrangement of only 4 holes was also tested. Although only tested at one blockage ratio, the results were similar to the 7-hole arrangement at the same blockage ratio. Thus, the blockage ratio seems to be an effective means with which to effectively model different thrust surfaces, and the spatial arrangement of the open area is less important to the measured impulse.

Flow Path and Performance Modeling

Although many efforts have focused on understanding the flow in detonation tubes measuring and predicting PDE static performance, there is much to learn about the flow field inside an air-breathing PDE due to the unsteady nature of the flow. We are developing control-volume models of both steady detonation engines[6] and an unsteady air-breathing single-tube PDE, whose configuration is shown in Figure 13.

Our single-tube PDE model has a large acoustic cavity (or plenum), which acts as a damped reservoir for filling the detonation tube during each cycle. Assuming choked flow through the inlet diffuser (i.e., supersonic flight), the plenum is a system characterized by a steady inlet and an unsteady outlet (the valve opening and closing). The flow between the plenum and the detonation tube is coupled, and we perform a cycle-averaged control volume analysis in order to determine the average conditions in the plenum. We model the mass flow rate, velocity, pressure, and total enthalpy at the valve plane as piecewise constant functions of time, based on the results of numerical simulations of the filling process, which show that the flow out of the plenum is generated by a steady expansion after a short transient that we neglect in our modeling.

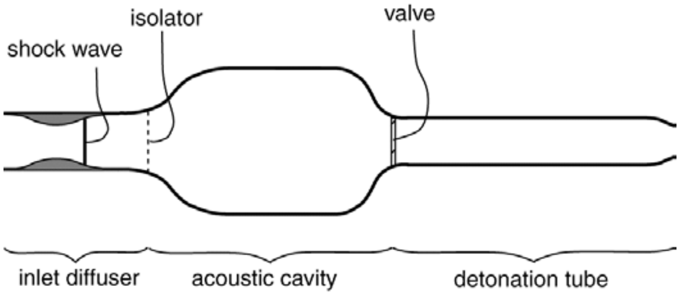

Figure 13: Schematic of air-breathing single-tube PDE.

Two cases occur, depending on whether the flow at the valve plane is choked. The results show that the average stagnation temperature in the plenum is equal to the stagnation temperature downstream of the inlet, but that the stagnation pressure is slightly lower (by up to 10% depending on the area ratios considered). From the average plenum conditions, we then solve the unsteady mass and energy equations and calculate the temporal variation of the properties in the plenum, which is critical in order to evaluate the inlet response.

During supersonic flight, the flow generated by the high pressure in the plenum during the filling process has a significantly high velocity (supersonic in some cases). Assuming the detonation wave is initiated immediately after valve closing, it catches up with the expansion generated by the valve closing and propagates into a moving flow. We consider the problem of a detonation wave propagating into a flow moving in the same direction at a constant velocity. The detonation wave is followed by a stronger Taylor wave, which has to expand the flow back to zero velocity at the thrust wall. We modified our impulse model in order to determine how the performance is affected by the flow velocity in front of the detonation. A modified similarity solution was derived to include the effect of moving flow ahead of the detonation on the pressure plateau time[5], while the blow down process was modeled with the same non-dimensional coefficient[5]. In order to validate the model, the flow was simulated numerically using Amrita[7], starting with an idealized straight jet configuration ahead of the modified Taylor solution for the detonation at the tube exit.

Figure 14 shows the comparison of the thrust wall pressure integral non-dimensionalized with the initial speed of sound and pressure in the tube as a function of the filling Mach number with the predictions of our model. The numerical pressure integration was carried out for a time equal to $20t_{CJ}$, where $t_{CJ} = L/U_{CJ}$. The model predictions agree generally well with the numerical results, within 25% error, with better agreement at lower filling Mach numbers (within 11% for M_{fill}<2 and 4% for M_{fill}<1). As the filling Mach number increases, the flow expansion through the Taylor wave is more severe and the plateau pressure behind the Taylor wave P_3 decreases. Additionally, even though P_3 is lower, the blow down process is accelerated due to the presence of the initial moving flow. Consequently, the overall result is that the detonation tube impulse decreases with increasing fill Mach number. This impulse decrease is quite significant, in particular at supersonic filling velocities, and will affect the overall performance of an air-breathing PDE.

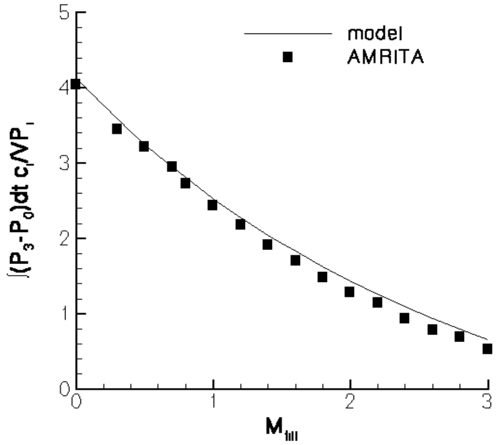

Figure 14: One-dimensional detonation tube impulse as a function of the filling Mach number. Comparison of model predictions with the results of numerical simulations with Amrita.

The different elements of our air-breathing PDE (steady inlet, plenum, valve, detonation tube) are currently being combined into an overall model that we will use to predict performance parameters.

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