Investigation of Spray Detonation Characteristics Using a Controlled, Homogeneously Seeded Two-Phase Mixture

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A two-phase detonation parameter study, in which the effects on detonation behavior of equivalence ratio, droplet size, oxidizer oxygen percentage, and fuel fraction initially present as decane and propane, has been completed. Preliminary data analysis is presented below. Propane detonations and two-phase detonations were found to be heavily influenced by the presence of nitrogen in the sample mixture, leading to unexpected results. The effect of mean droplet diameter on detonation velocity is found to be relatively minor in the range tested. As oxidizer oxygen content increases, the influence of droplet diameter becomes negligible. These and other results are discussed below.

1. Introduction

There is currently an interest in the study of spray detonation with an eye toward possible application in the field of propulsion. If used in a Pulse Detonation Engine (PDE) spray detonation would provide a means to couple the high energy density of liquids and the potentially high thermal efficiency of the PDE cycle. This makes it a compelling research topic. Spray detonation has received attention in the past, but these investigations have provided only a limited understanding of the phenomenon. Our approach is to base our experiments on a well-characterized initial state while at the same time utilizing a practical spray mechanism suitable for real world applications. We wish to characterize and control the size of the droplets, the fuel-to-oxidizer ratio, and the fraction of fuel present in the gas and liquid phases, and we wish to do so in a manner such that each of these variables in homogeneously distributed throughout the volume to be investigated.

We have discovered that no fueling method in wide use for experimental studies fully satisfies these requirements. As a result, we have developed our own seeding technique, dubbed the "Opposed Injection Configuration." This fueling configuration enables us to achieve all of the aforementioned two-phase mixture goals, as demonstrated below, using commercially available injectors. With this seeding method in place, we feel we are in excellent position to study the phenomenon of spray detonation.

2. Experimental Setup

2.1. Detonation Facility

Our detonation facility is a stainless steel, 5.8 m long, 10.16 cm inside diameter tube, closed at both ends. Gaseous reactants are fed to the tube via a gas manifold with 13 distribution points, each separated by 40.6 cm. The large number of distribution points is used to minimize mixing time, as reactants are mixed in-tube (as opposed to pre-mixing.) Between convective mixing and diffusion, it has been found that 30 minutes is sufficient to ensure a well-mixed system. A diagram of the facility appears in Figure 1.

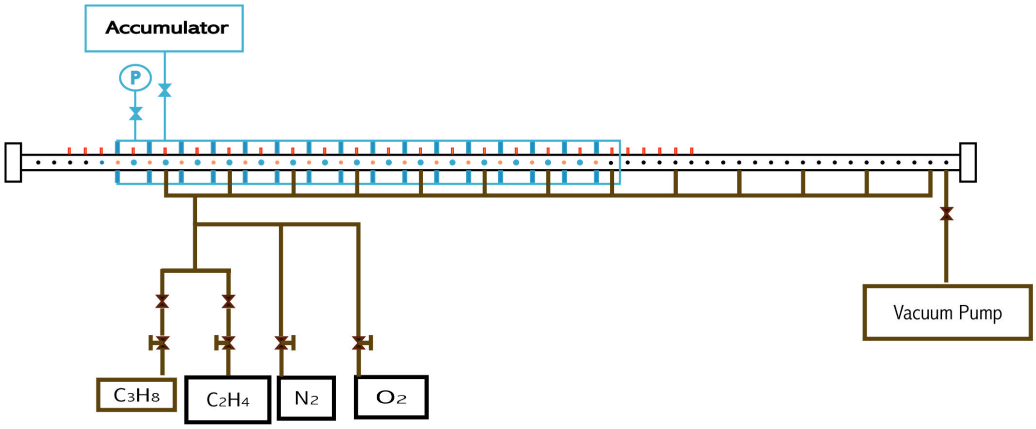

Fig. 1 Detonation Tube Schematic

Champion N2C J-gap spark plugs are used for ionization detectors. The body of the spark plug and the J-prong are connected to ground through contact with the detonation tube. The center wire carries a voltage of 5 volts. This voltage is suitable for detecting the concentrated flame front behind a detonation wave, but is inadequate for weaker flames. Because of this, we are capable of sensing when a detonation's flame front is faltering by observing degradation in the ionization signal. It should be noted that the use of J-gap spark plugs does present a source of physical perturbation to the detonation wave and the flow field behind it. However, tests run with J-gap and surface gap plugs show that identical velocity measurements for a given reactant mixture are obtained despite the perturbation, indicating that it is not a significant effect.

2.2 Velocity Detection

As mentioned above, Champion N2C J-gap spark plugs, operating with a 5V bias, were used as ionization detectors in these experiments. 40 detectors were used, spaced at 10.16 cm intervals. These detectors, in turn, were connected to a digital circuit (described below) used to determine the flame front's time of flight between each spark plug. In this manner, 39 velocity measurements, associated with regular positions in the tube, were collected and used to generate the velocity profiles that are presented in the results section.

The principle on which the velocity circuit operates is simple. The voltage on each of the detectors is simultaneously monitored. When the detonation wave passes the first of these detectors, the ionization of the flame front allows current to pass from the detector's center wire to ground forming a voltage bridge with a pull-up resistor in the circuit. Since the pull-up resistor is large (100k O), the voltage at the center of the bridge is close to ground. When the detector sees this low voltage, a logic flag is raised and latched, and a counter running at a known frequency is started. When the detonation wave passes the next ionization detector, the next logic flag is raised. This simultaneously stops the first counter, and starts the second counter. This process is repeated down the line until 39 counts have been obtained. Each of these counts represents the detonation's time of flight between 2 detectors, and can readily be converted to an average velocity associated with the section of the tube, or "cell," bounded by that counter's detectors. Taken together, these velocities define a velocity profile from which one can ascertain a detonation's behavior and its approach to steady state.

2.3. Opposed Injection Configuration

The key to our seeding technique is the Opposed Injection Configuration. The features of this configuration are illustrated in Figure 2, below.

Two Siemens Direct Injection gasoline fuel injectors are positioned directly opposite one another in a tube with a nominal 10 cm diameter. These two injectors are operated under identical conditions, i.e. same fuel, same fuel pressure, same injection hold time. During an injection event, the liquid fuel flows entrain ambient gas jets, which in turn induce the development of torroidal vortices. Large droplets are relatively unaffected by local gas velocity and tend to adopt ballistic trajectories and strike the opposite walls, where they are sequestered as a cold liquid film. Small droplets, on the other hand, are entrained by the gas flow, and tend to follow the local gas velocity.

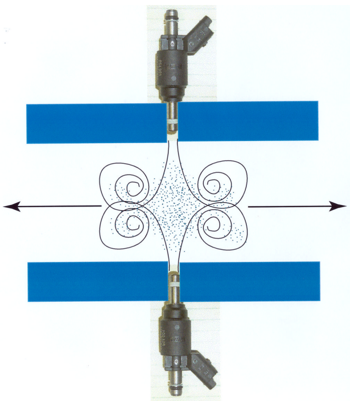

Fig. 2 Opposed Injection Configuration

After injection, the gas jets, vortices and entrained droplets expand and move toward the center of the tube. Eventually the flows induced by the two opposed injectors meet one another. At this point, the linear momentum of the gas jets cancels, creating a stagnation plane along the center of the tube. This keeps the small droplets from being thrown against the far walls, and greatly reduces wall wetting. At the same time, the two torroidal vortices begin to influence one another, pushing each other down the axis of the tube. The entrained droplets are carried along with this flow, and thus are distributed to the left and the right of the initial line of injection.

3. Results and Discussion

3.1. Two-Phase Mixture Homogeneity

Prior to performing detonation experiments, the homogeneity achieved with the Opposed Injection Configuration was tested. This was done by analyzing ensemble-averaged images produced by Mie scattering of an ND:YAG laser sheet. Uniformity in these images is evidence of homogeneity, where a homogeneous two-phase mixture is defined here as a mixture with a spatially uniform *intensity function* for every size class of droplet. The *intensity function* is defined as the probability of a droplet passing through an infinitesimal volume of space in an infinitesimal period of time. It should be noted that the intensity of Mie scattered light is dependent on the surface area of droplets illuminated. Because of this, uniform intensity in the ensemble images taken is not necessarily indicative of a homogeneous two-phase mixture as defined above. Rather it is a necessary but not sufficient test of homogeneity.

Figure 3 shows a typical ensemble image taken of the tube's cross-section along the injectors' centerline. Figure 4 is an image taken perpendicular to the cross-section, and describes the droplet distribution along the tube's axis in a given cell. The color scale in each of these images has been compressed about the mean intensity to bring out any inhomogeneities.

The low standard deviation of intensity in these figures (5%) is indicative of uniform intensity throughout the area imaged. Standard deviation varied from 5% to 20% over the range of injection variables used in the parameter study.

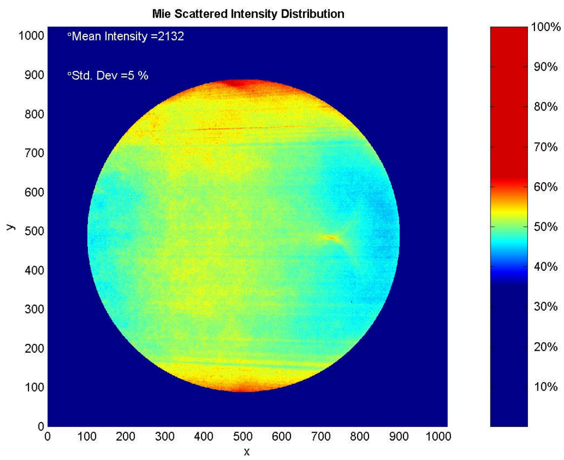

Fig. 3 Ensemble Average Image, 1425 psig Fuel Pressure, 14.4 ms Hold Time

3.2. Propane Detonations

In detonations fueled purely by propane, it was found that as nitrogen concentration is increased and equivalence ratio is decreased, the resulting detonation wave may exhibit a non-monotonic approach to CJ velocity. This approach is characterized by an initial velocity undershoot, followed by a rapid transition to a velocity and pressure overshoot. See Figures 5 and 6

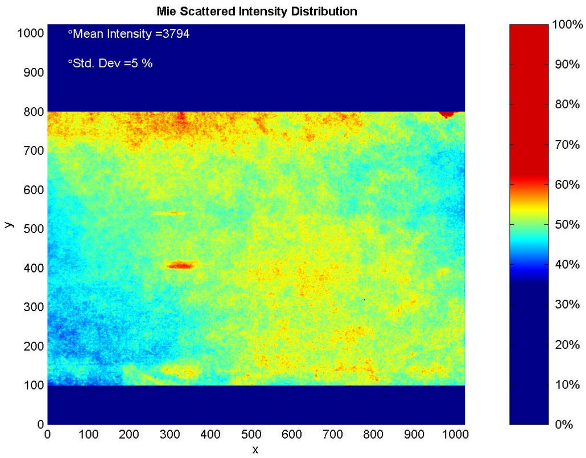

Fig. 4 Axial Distribution, 575 psig Fuel Pressure, 22.9 ms Hold Time

These velocity profiles indicate unusual chemical energy release in propane detonations in the presence of nitrogen and for lower equivalence ratios. Because of this, one must exercise caution when comparing two-phase detonations to gas-phase detonations. Velocity profiles should be compared directly to identify differences in the pattern of energy release for mixtures in which only the fraction of fuel in the liquid phase differs.

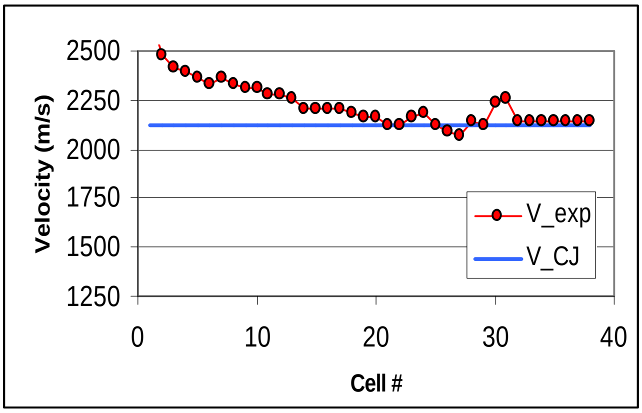

Fig. 5 Smooth Approach to CJ Velocity (100% O_2, F=0.6)

3.3. Spray Detonation Velocity Profiles

A velocity profile similar to those seen in Figs. 5 and 6 was captured for each condition tested in the parameter study. Two such profiles appear in Figs. 7 and 8. When reviewing these figures, it is important to note that the region between injection cell #1 and injection cell #33 is seeded with two-phase mixture. For detonations with a high percentage of fuel in the liquid phase, the wave typically fails in the vicinity if cell #32 or #33.

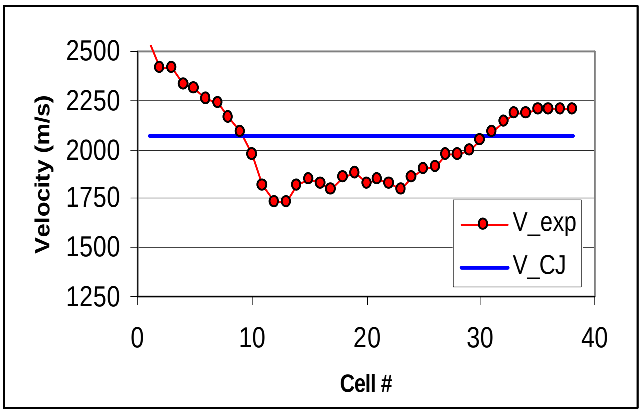

Fig. 6 Undershoot then Overshoot (60% O_2, F=0.8)

Two-phase mixtures proved to be readily detonable in most cases, though there were some problems when large droplets were combined with high nitrogen concentration. Mixtures in which all of the fuel was present in the liquid phase prior to detonation also proved to be detonable, though they were less energetic than their split-fueled counterparts. This indicates that liquid fuel mechanisms (e.g. evaporation, droplet stripping and break-up) play a significant role in spray detonation but at some point become slower than gas-phase mechanisms Figure 9 shows the velocity profile of a detonation fueled entirely by liquid.

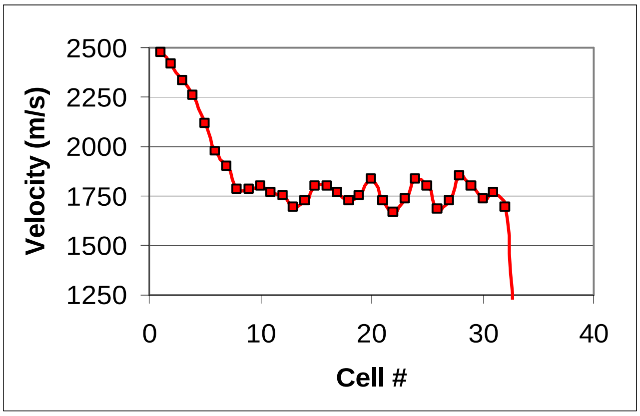

Fig. 7 Two-Phase Split-Fueled Detonation Profile (60% O_2, 69% liquid fuel, D_{32}=18.2 μm, F=1.09)

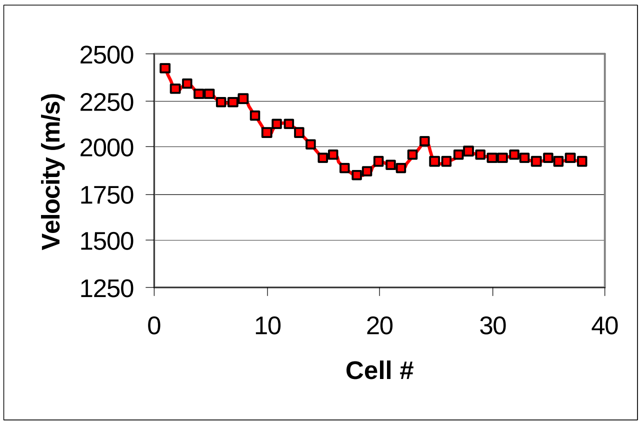

Fig. 8 Two-Phase Split-Fueled Detonation Profile (100% O_2, 35% liquid fuel, D_{32}=26.4 µm, F=0.87)

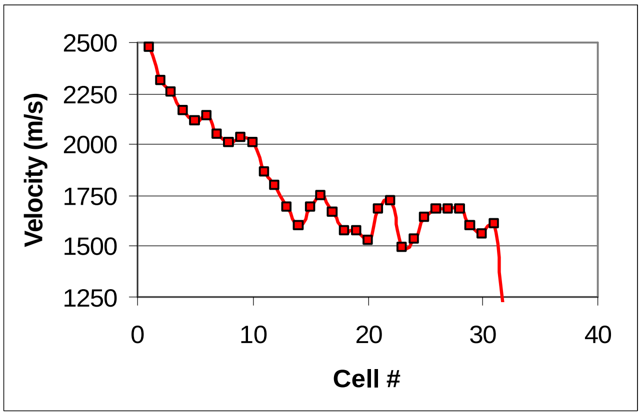

Fig. 9 Two-Phase Liquid-Fueled Detonation Profile (100% O_2, 100% liquid fuel, D_{32}=16.7 µm, F=0.87)

From Figs. 7 and 9 it can be seen that the detonation velocity seems to fluctuate about its mean value. This is likely due to the inherent heterogeneity present in a two-phase mixture, and is similar to what one would see in a poorly mixed gas-phase detonation.

3.4. Summary of Results

A large amount of data was gathered as a result of the recently completed parameter study. Analysis of this data is only in its initial phases. Two trends stand out immediately, however:

Mean droplet diameter in the range between 15 µm and 30 µm is relatively unimportant in the presence of pure oxygen. As nitrogen content increases, the importance of droplet diameter increases. This is likely indicative of a change in rate limiting process as the concentration of nitrogen is increased. The behavior can be seen in Figures 10 and 11.

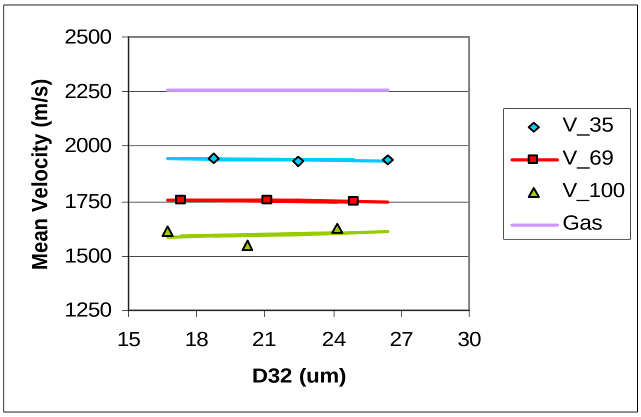

Fig. 10 Velocity vs. Droplet Size (100% O_2, F=0.87)

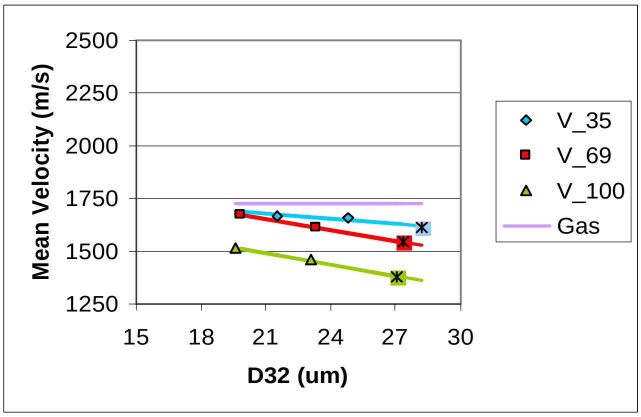

Fig. 11 Velocity vs. Droplet Size (60% O_2, F=0.65)

In these figures, the blue data and linear fit represents experiments in which the fuel was 35% liquid, red represents 69% liquid and green represents 100% liquid. Starred data points indicate marginally stable detonations—detonations that failed then reignited.

In mixtures in which nitrogen is present, the detonation behavior when the fuel is 35% liquid is very similar to the behavior when the fuel is 69% liquid. When the oxidizer is 100% O_2, however, velocity is much higher for systems with only 35% liquid fuel. This effect can also be seen from a comparison of Figs. 10 and 11. The cause of this behavior is likely related to the effect of nitrogen on the kinetics of propane combustion. It has been shown above that propane detonation behavior changes drastically as the concentration of nitrogen in the mixture is increased. Figs. 10 and 11 may indicate that in pure oxygen, the rate of energy release due to propane combustion greatly exceeds that due to liquid combustion, but that as nitrogen concentration is increased, the two rates become comparable, and thus lead to similar detonation velocities.