Experimental Investigation of Reacting Fuel Droplets Interactions with Detonation Waves

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Introduction

Detonation waves (DW) are supersonic waves similar to shocks that result from combustible chemical reactions. Contrary to common belief, not every explosion is considered a detonation. Common explosions form into deflagrations, a subsonic combustion reaction. However, it has been shown that deflagration waves traveling down a tube will eventually become turbulent, accelerating the wave until an "explosion in the explosion" results in a sustained detonation wave [1]. With high exothermic pressures forming behind a shock front, detonations can reach supersonic speeds. With the Chapman-Jouguet (CJ) conditions, a distinction can be made between the two and how a deflagration can transition to a detonation [2]. Different gases have different sensitivities and cell sizes for detonation requirements. Gavrikov et al. proposed a generalized model for calculating the cell detonation size λ [3]. Different gases have different minimum diameter tubes at which there can be a successful detonation, like for methane mixtures as explored by Zipf et al. [4]. These different parameters are key to designing systems where using said mixtures can succeed.

The key determinant of continuous, steady propagating detonations is the heat release rate from the multi-phase fuel-air mixture, which must be rapid enough to sustain the propagating detonation wave. The overall combustion timescale $\tau_{\text{combustion}}$ of the droplets depends in a complicated way on the timescale of droplet vaporization (τ_{vap}), air/fuel mixing (τ_{mix}), and reaction/ignition/heat release (τ_{react}). In simulating shock wave to detonation wave transition and propagation of detonation waves, various approaches have been taken to model this crucial time scale $\tau_{combustion}$. Some researchers [5-7] have taken a chemical-diffusive approach, where the entire process of droplet combustion is simplified to a tractable single Arrhenius rate law; approaches such as genetic algorithms are used to fit the rate parameters and properties of the fuel-air mixtures in concert, to replicate macroscopic observables (such as detonation wave CJ velocity, temperature rise, etc.). This approach is semi-phenomenological in that the final "fit" parameters are ***not*** the physicochemical properties of the material. Another approach [8-11] is to subsume the chemistry into an expression for an ignition delay time, which is obtained empirically. In a third approach [12-14], the vaporization of the droplet is assumed to be the rate-limiting step, and heat is released at the same rate as the vaporization rate $\dot{m}_v$. All of these current approaches implicitly rely on untested assumptions/approximations and physico-chemical models that are semi-empirical, extrapolated, and likely

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incorrect at conditions relevant to DW. There are significant knowledge gaps at the scale of individual droplets or small clusters of droplets interacting with DW, which currently impede the construction of realistic and accurate models of multi-phase detonations. In addition, models of droplet-DW interactions are not available, even for single droplets. This places severe limitations on understanding DW-droplet interactions and on developing physically correct models for drag, deformation, breakup, vaporization, and combustion.

Many previous experimental studies on detonations involved the use of imaging techniques to visualize interactions between droplets and shock waves or detonation waves [15-20]. For example, Nicholls and Ranger [16] conducted fundamental studies on the interaction of shock waves moving past water droplets using photographic techniques. In their study, they were able to characterize the deformation, displacement, and disintegration of water droplets as the convective flow following the shock wave acted upon the droplets. They also derived a boundary-layer stripping model for the droplet disintegration phenomenon. They assumed that any disintegration of the liquid from the droplet's surface was purely due to the supersonic convective flow over the droplet. Ragland et al. [18] performed schlieren visualization on the propagation of detonation waves through an oxidizing atmosphere containing liquid fuel (diethylcyclohexane, or DECH) droplets. Their detonation tube was oriented vertically to allow the fuel droplets to fall through the length of the tube, and windows positioned along the tube provided optical access to capture detonation wave propagation as well as the disintegration and combustion of individual drops by the detonation wave. Later, they were able to show the detonation wave propagating through sprays of fuel droplets had a velocity that was lower than the ideal CJ velocity for detonations in gaseous mixtures. Furthermore, the larger the size of each droplet in the spray, the slower the detonation wave propagated through the spray [15]. These studies have been instrumental in providing fundamental data and information regarding the interaction between a (fuel) droplet and a shock wave or detonation wave.

As it is clear, very few papers in the literature discuss the interaction between droplets and DWs [11, 12] mostly due to the challenges in performing such experiments; therefore, new experimental investigations are clearly needed to understand these interactions. The ability to characterize this interaction further would have immediate applications to the development of pulse-detonation engines (PDEs) and rotating detonation engines (RDEs) [20], where the fuel would likely need to be stored and later ignited while in the liquid state. This paper discusses preliminary results from a new experimental method that has been developed to obtain high-speed visualizations of the interaction between liquid droplets (in this case, isopropanol) and a DW.

Experimental Method

Figure 1 shows a general representation of the detonation tube and imaging setup. The UCF detonation tube employed for this study consists of a stainless-steel test section and dump section, which are two tubes initially separated by a polycarbonate Lexan diaphragm. The dump section is maintained at vacuum until the detonation wave bursts through the diaphragm. The dump section is primarily used to reduce any adverse effects of reflected detonation waves in the tube on equipment and to prevent overpressure of the system. The test section tube consists of a pre-detonator containing a series of obstructions placed in a relatively small cross-sectional area, as well as a spark plug ignition source, similar to the one described by New et al. [21]. The pre-detonator expands through a transition section into a region where the inner diameter of the test section is approximately 7 cm. This pre-detonator is similar in concept to the pre-detonator presented by Saretto et al. [22]. In the expanded volume, four ports are spaced 3.81 cm evenly amongst each other, with the most downstream port located 12.07 cm from the diaphragm. Three ion gauges and one piezoelectric pressure sensor are used to capture velocity and pressure data as the wave passes, respectively. The pressure sensor is located at the most downstream port. A pair of 0.5-inch (1.27 cm) diameter sapphire windows are located at the same axial location as the pressure sensor.

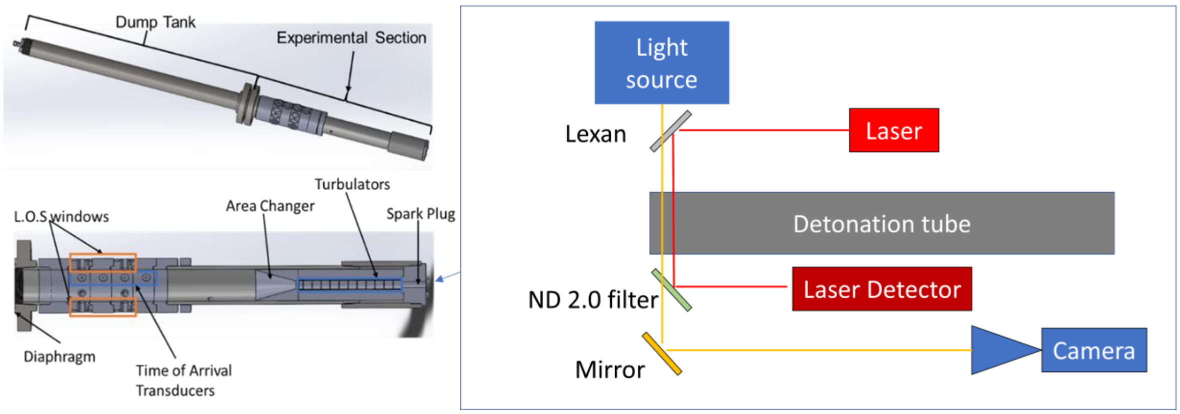

Figure 1: Schematic Diagram of *UCF's* detonation tube (left) and optical setup (right).

Two gaseous mixtures were created: a stoichiometric mixture of methane (CH_4) and oxygen (O_2), and another mixture of methane and oxygen at an equivalence ratio of 0.9. Using the Dalton's Partial Pressure Law, the mixture was made in a 17-liter tank using a manifold and a Setra 280-E Transducer with a range of 0-12,900 Torr. This mixture provides a dependable detonation at an initial pressure of 760 Torr and a temperature of 293 K upon ignition in the detonation tube.

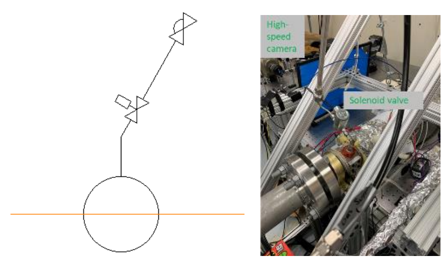

Figure 2: (left) Cross-Sectional View of Liquid Droplet Introduction. (right) Test section picture

For the liquid droplet injection (Figure *2*), a solenoid valve was added to an additional port located at the same location as the windows and pressure sensor. The solenoid valve's small orifice diameter (0.635 mm) enables the introduction of gravity-fed droplets from an isolated reservoir, similar to those produced by a syringe. When the droplet passed through the continuous laser signal, a drop in signal strength occurred. This allowed for precise timing to trigger the spark ignition inside the detonation tube and produce a detonation wave that would impact the droplet once it was in the line of sight of the windows.

The high-speed imaging camera and laser system are aligned to view the same pair of windows for droplet imaging. Detonations in the first mixture were captured with the Phantom Miro M310 camera, and for the second mixture, the Photron FASTCAM SA-Z camera was used. The 532 nm laser was used to detect the presence of the droplet at the windows. The light source was used for the camera to illuminate the droplet and its disintegration. A Lexan polycarbonate film was used to allow the light source to pass through the film while also enabling the laser to be reflected through the same windows for droplet detection.

A neutral density filter with an optical density of 2.0 was used to reflect the laser to a detector while also reducing the amount of light reaching the camera.The Phantom Miro M310 camera used a 64x56 resolution at 340,000 fps with a 1 μs exposure time and an exposure index of 64,000. Phantom calibration and settings are done through the Phantom Camera Control (PCC) Application. The Photron SA-Z 2100K functioned at 900,000 fps, 128x56 resolution, and a 0.35 μs exposure time, and these settings were adjusted through Photron FastCam Viewer 4 software. A 1200 lumens light source was used as a backlight for clear imaging through the windows. Data acquisition was made through an NI PCI-6115 unit sampling at 4 MS/s.

Results & Discussion

Several images of detonation wave interaction with isopropanol droplets were observed using each of the high-speed cameras. Weber numbers are also provided in the figures, which are based on the CJ DW velocity. In Figure 3, 8 consecutive frames of two droplets with a diameter of about 1.2 mm and 2.3 mm are shown to be impacted by a detonation wave initiated through DDT. Note that these are two separate droplets generated prior to the arrival of the DW. The initial conditions in the detonation tube consisted of a stoichiometric methane-oxygen mixture at an initial pressure and temperature of 1 atm and 293 K, respectively. Immediately after the wave passes the droplet, no significant change is observed. However, as the high-speed flow continues to act on the droplet, the droplet appears to take on a hemispherical shape, with the rounded edge facing the direction of the incoming flow. Furthermore, streaks of atomized and vaporized liquid begin to form downstream of the droplet, becoming more prominent as the droplet continues to deform. Eventually, the apparent diameter of the droplet grows suddenly as the droplet surface continues to atomize and form a larger wake region. Meanwhile, the droplet is also displaced slightly in the direction the initial detonation wave traveled.

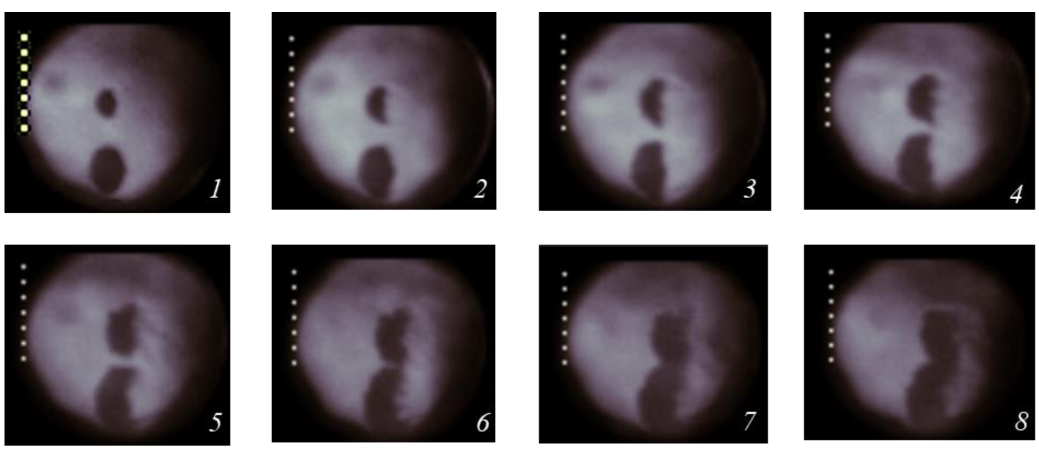

Figure 3: Series of photographs obtained with the Phantom Miro M310 high-speed camera, the frame spacing 2.94 * 10^{-6} s, We = 359*10^3 for top droplet (diameter = 1.2 mm) and We = 666*10^3 for bottom droplet (diameter = 2.3 mm). DW travels from left to right with a CJ velocity=2391.2 m/s.

A similar picture can be observed with a bigger droplet (6.8 mm in diameter) interaction with a detonation wave, as can be seen in eight frames in Figure *4*. This droplet was recorded using a Photron SA-Z 2100K camera using the same methane-oxygen mixture with a 0.9 equivalence ratio. A detonation wave going from left to right can be seen passing the droplet on frame 2. The bright spot seen in the first two images are reflections of the flashlight from the droplet, which disappears as the detonation wave begins to strip away at the droplet, and the surface is distorted.

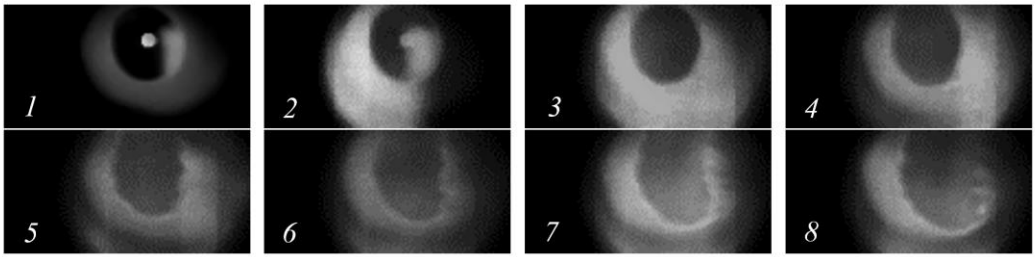

Figure 4: Series of photographs obtained with the Photron SA-Z 2100K high-speed camera, the frame spacing 5.55 * 10^{-6} s, We = 1.92*10^6 (diameter = 6.8 mm). DW travels from left to right with a CJ velocity= 2337.6 m/s.

A few experiments were obtained at very high speeds for the interaction of a shock wave with reacting droplets. Figure *5* presents the images of a shock wave crossing the droplet (5.8 mm diameter) at a time interval of 0.83 µs (obtained at 1.2 million frames per second). The mixture is a stoichiometric mixture of methane (CH_4) and oxygen (O_2), This is just a normal shock as a result of the (fast) deflagration occurring in the mixture. Frame 4 shows the shock wave about to hit the droplet, while frame 12 is when the wave leaves the droplet. In frame 6, a bright reflected shock can be seen leaving the droplet towards the left.

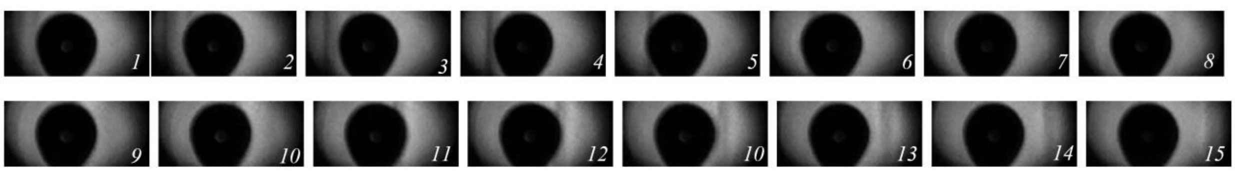

Figure 5: High-speed images of a shock wave crossing a fuel droplet (diameter = 5.8 mm) obtained with the Photron SA-Z 2100K high-speed camera, the frame spacing 0.83 * 10^{-6} s, We =230*10^3 (wave travels from left to right with a velocity = 900 m/s*)*.

Current results are comparable to the study conducted by Nicholls and Ranger on the interaction (non-reacting) between water droplets and shock waves. For instance, they also observed the initial deformation of the droplets as "planetary ellipsoids" which become more eccentric over time. In addition, they observed the formation of a micro-mist as the convective flow acted upon the droplet [16]. These observations are confirmed by Kauffman et al. [17], including the drop deformation, stripping mechanism of the surface of the droplet, and the acceleration of the droplet, however, they were also able to observe bow and wake shocks. This shows that the detonation wave is quite similar to a normal shock in terms of droplet deformation, which is interesting considering that combustion is expected to occur somewhere in the droplet wake (not seen). This could imply that the droplet disintegration process may be largely independent of the presence of combustion of the micro-mist wake. Larger window size and refined optical setup may help in the future to confirm this while allowing the ability to see additional characteristics (i.e., bow and wake shocks). Future work will also include comparisons with simulations.

Summary

The current study investigated the effects of a sustained detonation wave on an isopropanol droplet in a detonation tube environment. The detonation waves were initiated using a methane-oxygen mixture at an initial temperature of 293 K and pressure of 1 atm. The results show that the isopropanol droplets' displacement, deformation, and disintegration are comparable to previous studies investigating the interaction of shock waves on water droplets and on liquid fuel droplets. This may imply that the droplet disintegration process may be largely independent of the presence of combustion. The current investigation of detonation wave-droplet interaction is the first of its kind in recent times. This study highlights many similarities with literature studies (non-reacting experiments with water droplets and shock waves) and validates the fundamental information currently available regarding interactions between shock waves and droplets while contributing more information regarding the impact of reacting droplets by detonation waves.

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