



Design Considerations and Imaging Setup for Liquid Fuel Droplet Detonation Wave Experiments

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Design considerations for a new detonation tube are presented to further improve detonation wave interaction research. The new structure consists of four independent portions: the deflagration to detonation initiation section, the transition expansion section, the operating test section, and the dump section. The initiation, transition, and test sections are designed to operate within a temperature limit of 150 °C and a maximum detonation pressure of 100 bar. The test section is comprised of interchangeable 155 cm 316 stainless steel plates assembled to create a 10x10 cm square hollow structure, sealed with longitudinal O-rings between plates and lateral O-rings between flanges and plate ends. The ports and windows are all sealed with O-rings. The current assembly has 30 circular ports for pressure measurements and ion gauge measurements. These same circular ports will also be used for laser spectroscopy measurements through 1.27 cm diameter circular windows. Two axial rectangular windows of 16.51 x 5.74 cm and two of 16.51 x 2.54 cm, with centers 52 cm from the downstream end of the test section, are used for various diagnostics and imaging techniques. Hydrostatic droplet release, piezo-actuated droplet release, and vibration-induced droplet release have been designed and discussed.

I. Introduction

Detonation waves (DW) are self-propagating supersonic combustion waves resulting from high-temperature chemical reactions travelling through a gaseous medium. The DW can sustain a sudden continuous surge in pressure and a decrease in entropy, releasing a large amount of energy in an extremely brief period of time. The 2-3 orders of magnitude between the velocity of a slow-burning deflagration flame versus the detonation wave makes them attractive for a wide range of applications where high energy release and high thrust are required [1]. The high pressure and temperature of the wave can be used to drive turbines, produce thrust, or generate electricity, making them useful for a wide range of applications in aerospace, power generation, and industrial processes. As such, research into pulse-detonation engines (PDEs) and rotating detonation engines (RDEs) has garnered significant interest.

In addition to their high energy release, detonation waves also have a number of unique properties that make them attractive for research. Under the correct conditions, they are highly stable and can propagate over long distances without losing their strength. They also have a well-defined front that can be easily studied using imaging and measurement techniques. Overall, the development of specialized experimental setups has played a crucial role in advancing our understanding of detonation waves and their interactions with different types of media. These setups, including shock tubes, cylindrical tubes, square or rectangular hollow structures, and other types of detonation tubes have allowed researchers to study the complex dynamics of DWs in a controlled environment. Helping to pave the way for the development of new types of engines and propulsion systems. High-pressure shock tubes used for combustion have also been adapted for detonation wave research [2, 3]. These structures allow researchers to control the parameters of the DW and study its behavior and interactions under a variety of conditions. New experimental investigations are necessary to better understand these interactions and improve our ability to develop efficient PDEs and RDEs that require the fuel to be stored in the liquid state and then ignited later. Understanding the interaction between DWs and liquid fuel droplets is essential to develop efficient PDEs and RDEs, and thus this paper outlines the recent work in developing a new facility to research DWs and their interactions.

II. Detonation Tube I

The first detonation tube (DT1) is a two-part 304 stainless steel 7 cm diameter cylindrical tube separated by a thin aluminum diaphragm. Its turbulator has a blockage ratio (BR) of 0.53, pitch of 1.95 cm between orifices, a post Deflagration to Detonation (DDT) expansion ratio and a length of 10.9 and 10.2 cm respectively. The turbulator is a sliced pipe with welded washers evenly spaced to create the internal fuel pockets required for DDT. After expansion, the wave passes four evenly spaced ports (3.81 cm apart), where the furthest downstream port, 12.07 cm from the flange/diaphragm, is used for droplet introduction. Depending on the available ports, piezoelectric pressure sensors (PCBs) and ion gauges are used to measure the pressure and velocity of the DW. At the downstream port, there are two pairs of 1.27 cm diameter sapphire windows axially mounted (labeled line of sight L.O.S. Windows Figure 1), which are used for droplet imaging and lasers.

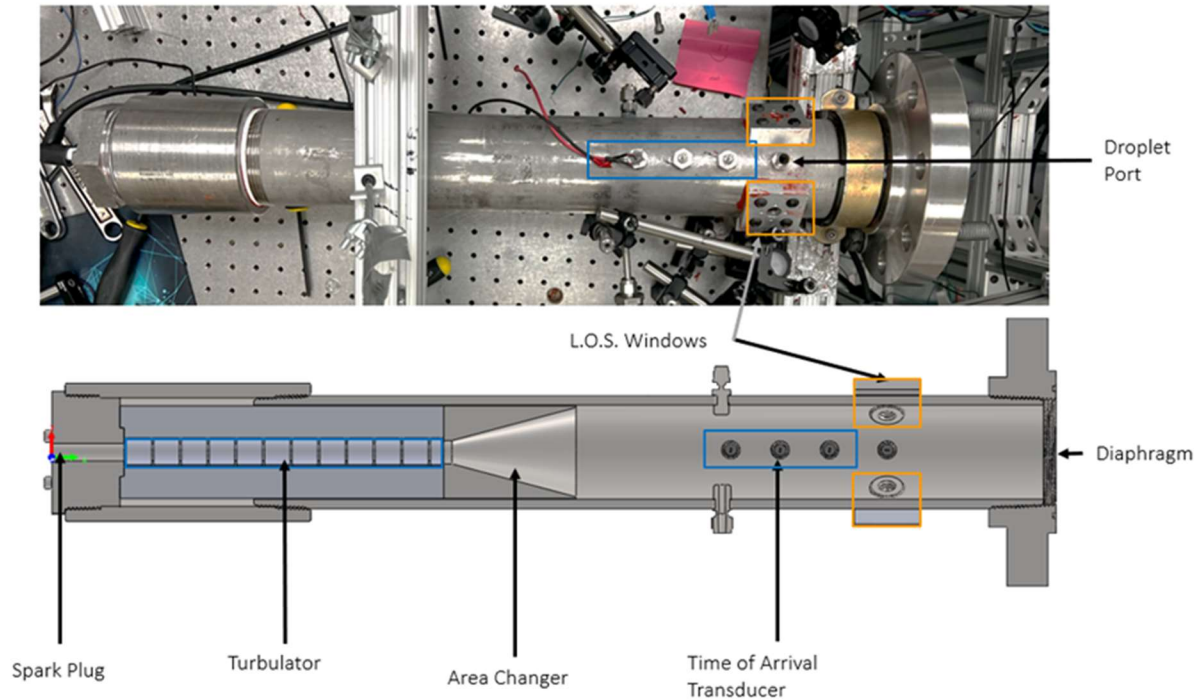


Figure 1: Detonation Tube I Test Section

III. Detonation Tube II

The facility's newly constructed detonation tube (DT2) comprises four independent portions: the DDT initiation section, transition expansion section, operating test section, and dump section. These sections allow for greater serviceability. The initiation, transition, and test sections are designed to operate within a temperature limit of 150 °C and a maximum detonation pressure of 100 bar. The expansion section measures 21.26 cm in length and has an expansion ratio of 7.16. The test section consists of four 316 stainless steel plates measuring 155 cm in length and either 3.18 cm or 2.92 cm in thickness, depending on the plate. The plates are joined by dowels and hex socket bolts to form a 10x10 cm hollow square tube. Similar to before, a scored aluminum diaphragm is located between the test section and the dump section, with the option to have one between the expansion section and test section if a different

mixture to initiate the detonation is preferred. The whole internal assembly, save for the dump section, has been finished to 32 RMS and electropolished. The dump section is again used to safely expand the gases.

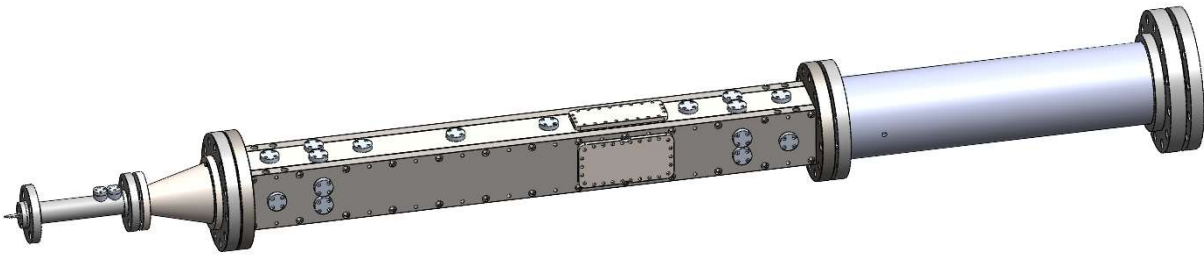


Figure 2: Detonation Tube II Full Assembly

Longitudinal sealing is achieved using four O-ring cord stocks that are fit into straight grooves opposite lengthwise sides of the thicker plates, as shown in Figure 3. Lateral sealing is achieved using two circular O-rings that are fit into rectangular grooves on each flange, between the flanges and plate ends, as described in [4]. The lengthwise O-rings meet the flange O-rings in each corner, creating what can be imagined as a wire enclosure between all the parts ensuring proper sealing. This separable plate system facilitates disassembly and servicing of the equipment, as well as the future opportunity for simple plate modifications post-initial manufacturing.

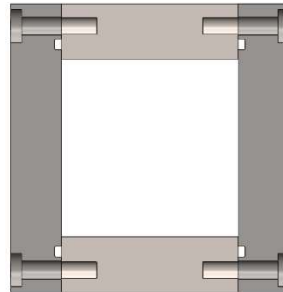


Figure 3: Detonation Tube II Test Section, Plate Cross Section

The DDT section features a new turbulator design assembled of washers and spacers along threaded rods as shown in Figure 4. The modularity of the new turbulator section in the DDT allows for experiment-specific turbulators to be used based on the mixture and experimental needs. The turbulator can easily be modified by replacing the washers with different openings to change the BR, or the pitch could be decreased or increased by increasing spacer lengths. The first configuration of the new turbulator will consist of an internal tube diameter of 4.28 cm with a BR of 0.5, and a pitch of 2 cm between orifices to match Detonation Tube I's turbulator to have a baseline to compare to.

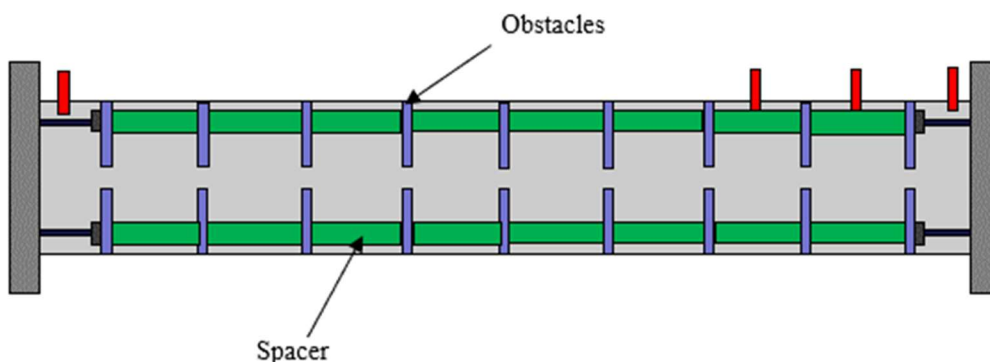


Figure 4: Detonation Tube II Turbulator Section

The test section assembly includes 30 circular ports that can be utilized with plugs for accommodating either 1.27 cm spectroscopic windows, or PCBs. If the circular plug is a window, then an inner hole has been drilled through, with a piece of wedged sapphire glass inserted at the bottom of the plug. The tolerancing for the windows is quite stringent, primarily utilizing a slip fit to prevent any disruptions to the flow field and minimize leaks. Finally, Epotek 353-ND is used to epoxy the sapphire glass in place to the 316 stainless steel window assemblies.

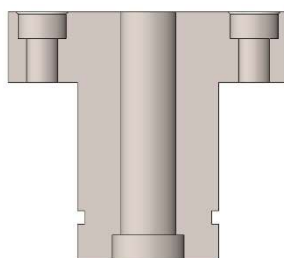


Figure 5: Detonation Tube II Circular Window Design

Four rectangular ports, with centers 52 cm from the downstream end, are used as windows to image the DW and droplets through a 16.51 x 5.74 cm or 16.51 x 2.54 cm viewing area, depending on the plate. The large window assembly, shown in Figure 6 below, introduces a cavity along the test section wall and is an unintended design result from the required pressure ratings of the windows. In experiments without the need for imaging, plugs are used to seal these rectangular ports and create a flush surface. The plugs were attached and finished simultaneously to their respective plates during machining to lower potential flow turbulence. An additional rectangular plug was created to accept a droplet introduction method used to release a droplet within the test section.

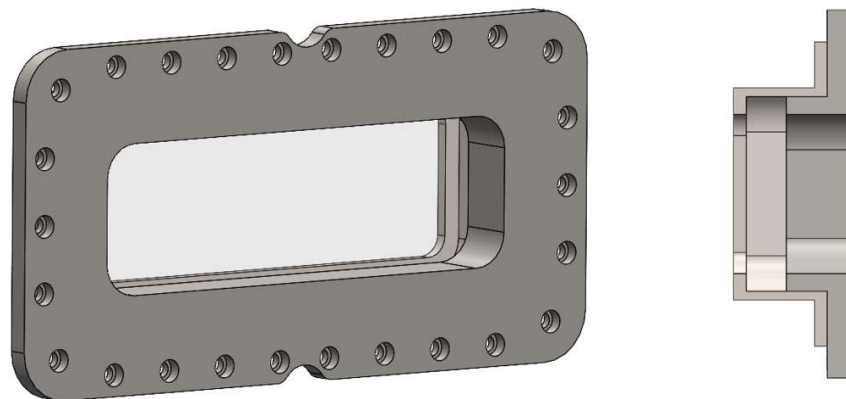


Figure 6: Detonation Tube II: Large Window Assembly and Large Window Assembly Cross Section

Four triggering/timing mechanisms have been used previously, the first being a step-based timing sequence that had the DW dependent on an experimentally inconsistent gravitationally induced droplet release time frame. With this method, a solenoid is opened on a timer, and the DW is triggered after a delay, assuming a droplet has fallen. Due to these inconsistencies, droplets were either out of frame by the time the DW arrived, or never released on time. The next setup used a laser-based triggering system that would trigger the DW based off a droplet interrupting the beam path. This method being much more accurate was sufficient with droplet sizes of 5 mm; however, as the droplet sizes were decreased to 2 mm, aligning a 532 nm laser to the droplet's path became difficult. Any misalignment with the droplet path, such as the needle's orifice's orientation, would have the droplet miss the path. The third attempt consisted of in-house image processing software to observe the window in real-time, but that had too much delay in triggering. The fourth and current mechanism is a light detection system (a simpler version of the third method) where a visible light detector, outputting a voltage based off light intensity, detected a decrease in light when the droplet obscures the light source. Here, the source was a 530 nm light, used to illuminate the droplet and be the light the detector was observing, as shown in Figure 7. Current and future experiments still do and will continue to use the fourth method due to good consistencies with small windows and 2-5 mm droplets; however, with interest in fuel sprays and smaller droplets, this current light detection-based system may become harder to use.

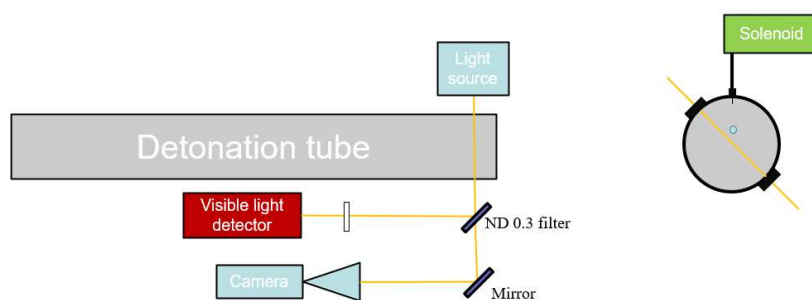


Figure 7: Detonation Tube I, 530 nm Path (left) Droplet Crosses Light Path (right)

In DT1, the furthest downstream port is used to inject the droplet through a needle connected to a fuel reservoir by a solenoid. During an experiment, the solenoid orifice (0.635 mm) is opened, allowing the hydrostatic forces to pool a droplet at the 23-gauge needle tip. When enough mass has accumulated on the needle tip, gravity overcomes the surface tension forces, and the droplet falls into the window's path. This has been sufficient in creating droplets down to 2 mm, but one concern for DT2 has been the limitations on droplet creation regarding the current method of introduction, as smaller droplets will be investigated. A second design of droplet introduction will pool a certain amount of fuel on the tip of the needle within view of the camera. When the size of the droplet is sufficient, a trigger signal will vibrate the needle at the correct frequency to dislodge a droplet and initiate the DW, leaving the

droplet midair before the DW arrives. The third design is pictured in Figure 8 and will actuate a piezo ring within a reservoir to briefly increase the pressure and force a droplet out, followed by a decrease in pressure when the piezo contracts to “cut” the droplet. The impression is one of these will be sufficient to trigger a detonation with the intended size of the droplet; this will need to be seen. Commercial droplet devices are being considered for even smaller droplet sizes. Regardless of the method, a triggering mechanism will be used to close the solenoid and start the detonation process, allowing the DW to reach the droplet mid-flight. This, in turn, will prevent any flame from reaching the reservoir, increasing the accuracy of droplet introduction and lowering the amount of liquid introduced into the facility.

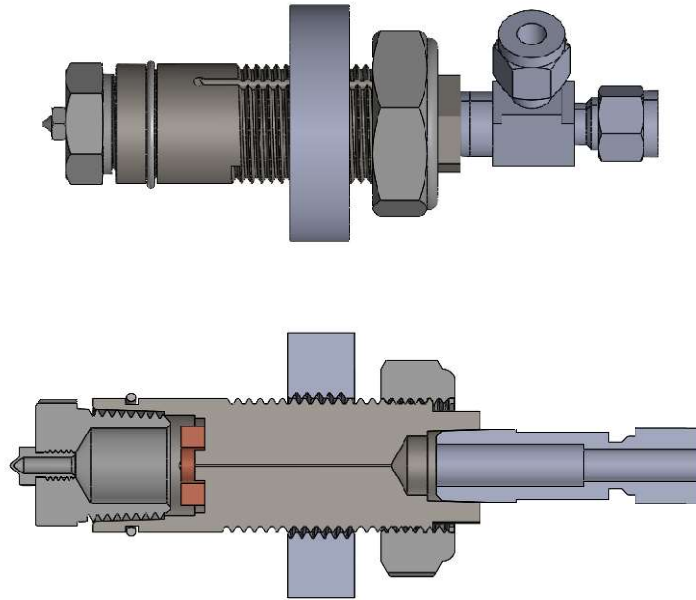


Figure 8: Detonation Tube II Piezo-Actuated Droplet Injector

DT1 and initially DT2 will use shadowgraphy to image the droplet by illuminating it with a 530 nm light source. For DT1 a lens is used between the ND filter and light detector to focus the light on the sensor. This light source is directed into the tube on one side and after passing through the tube, is split to a light detector by a neutral density (ND) 0.3 filter and directed to the camera through more mirrors as seen in Figure 7. Initially, low-frequency light sources caused problems as the camera's high frame rate captured moments the light source would be off during droplet interaction, but stronger and faster sources such as Mightex's BLS-LCS-0530 solved this problem. However, with the lab acquiring a Shimadzu high-speed camera, the Mightex does not seem sufficient and instead a Prizmatix light source has shown promising results.

As of now, all the parts have been received to assemble DT2. The figures below show individual parts of the already machined DT2 as we wait to receive the support structure for the final assembly.



Figure 99: Detonation Tube II Turbulator Section, Expansion Section and Flanges

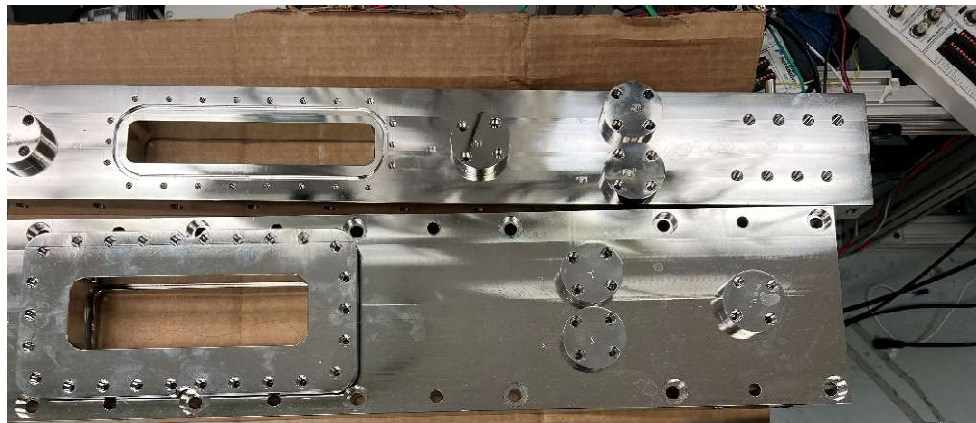


Figure 1010: Detonation Tube II Clamping Wall and Clamped Wall. Large Window Assembly is Installed in Clamping Wall.

VI. Conclusions

The goal of the facility's first attempt with DT1 was only an initial attempt at creating a detonation tube. It has succeeded well beyond expectations and will be used onward. DT2 is DT1's successor and will initially be characterized in comparison to work already done with DT1. The facility also plans to further these initial investigations of detonation-induced fuel droplet breakup, investigating more types of fuels and various additives. Different imaging tools will be used to resolve temperature and spectroscopy. Overall, the facility will characterize more gaseous fuel types to provide various sets for future experiments moving forward.

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