Shock-Droplet Interactions and Reaction of Liquid RP-2 Fuel

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1 Introduction

Conventional deflagration combustion of liquid fuels has been the most prevalent topic of study in propulsion since the advent of the internal combustion engine. Characterizing the process of liquid fuel combustion from injection to burning is integral to the operation of a liquid-fed engine; thus, significant research has been pursued towards droplet vaporization and liquid breakup regimes [1], [2], thermal ignition [3], and burning rates [4]. However, with the advent of the pulse detonation engine (PDE) and rotating detonation engine (RDE), the combustion community requires a more unique understanding of liquid fuel interactions with shock waves, the shock-flame coupled phenomenon, and detonation waves.

Liquid fuel can be immediately ignited when interacting with a detonation wave, which has been seen to subsequently assist and sustain the detonation [5]. The liquid fuel was found to ignite when met with the detonation wave, thus continuing to thermally choke the propagating detonation wave as with a familiar gaseous detonation. Pertaining to both the PDE and RDE, research on liquid fuel assisting detonations increases the viability of detonation-based engines operating on liquid fuels for propulsion applications. Given the high dependence on reactant mixture for detonation propagation [6], [7], understanding how to consistently ignite the liquid fuel is crucial to maximizing detonation engine efficiency.

Outside of propulsion, droplet breakup is highly pertinent to other growing fields, such as gas atomization of liquid metals to produce metal powders. Additive manufacturing of metals through methods such as selective laser melting (SLM) necessitates the use of relatively spherical powders to ensure adequate density is achieved for which powder diameters ideally lie between 15 and 63 micrometers. The creation of such uniform particle size distributions and spherical particle shapes is closely related to the breakup mechanism of liquid droplets.

Building on the background of gaseous detonations [8], [9] and on gaseous fuel autoignition behind shock waves [10], this research attempts to quantify and characterize the effect of shock waves and detonation waves on liquid droplets and columns of RP-2 liquid fuel, continuing to characterize the breakup mechanism and ignition of liquid fuels in high-speed and varying reactive high-speed flows. This research is fundamental to the development of efficient liquid-fed detonation-based engines.

2 Methods

A stainless-steel turbulent shock tube (TST) was used to conduct the shock and detonation interaction experiments. This facility was designed to study deflagration to detonation transition for gaseous fuels [8] and thus could be adapted to produce a range of reacting flow cases from weak shocks to strong shocks, also leading up to strong detonations [11]. The TST facility consisted of three sections: the pre-

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detonator, the plenum, and the test section, each at a constant 45 mm square cross-section. A schematic is shown in Figure 1.

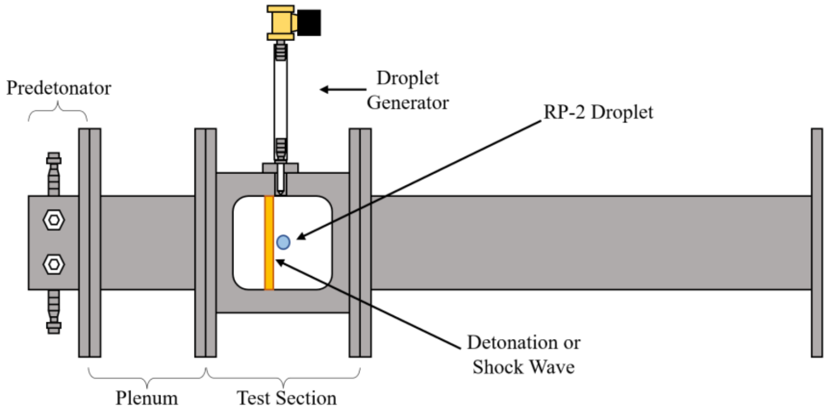

Figure 1: Schematic of TST facility, with liquid column and droplet generator in-situ.

The pre-detonator injects a stoichiometric hydrogen and oxygen mixture into a 30 cm length Shchelkin spiral to consistently produce detonations that can be input into the facility [12]. The pre-detonator fires the detonation into the 15 cm long plenum, which serves as an expanding volume that allows for the Shchelkin-based detonation to decouple into a M = 2.5 propagating shockwave and flame front. Depending on the pre-detonator flow rate, the detonation can remain decoupled, thereby passing a shockwave through the test section, or the detonation can reform. This control allowed for both shock and detonation interactions to be studied in this facility. The test section was composed of two 100 mm by 45 mm fused silica line of sight viewing windows on both sides of the test section for Schlieren diagnostics. The droplet generator was placed approximately 30 mm after the beginning of the viewing window such that the incoming flow could be examined pre and post-liquid interaction.

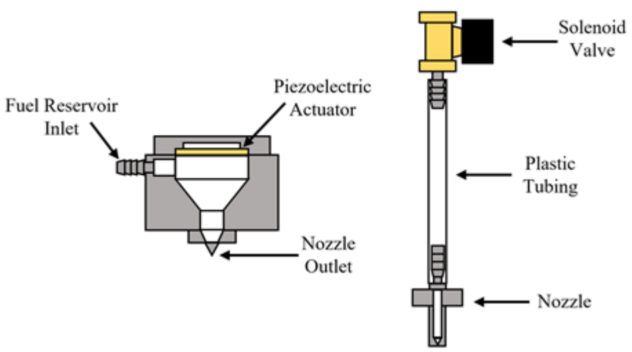

Figure 2: 3D printed droplet generator designs, Ionkin (left) and UCF TST (right).

To form the droplets or liquid columns, a 3D printed system based on Ionkin's design was used [13]. The dimensions of the nozzle geometry remained consistent with Ionkin, but used a different actuation system. Both designs are compared in Figure 2. In lieu of a piezoelectric actuator, a solenoid valve was used to initiate the liquid injection. The system would be filled with fuel, then depressurized with the solenoid valve, creating a vacuum. The solenoid could then be opened for varying times to release the system, forcing the liquid down into the nozzle and forming a droplet or column. A pulse width of 5 ms was found to be sufficiently small to create a short liquid column followed by consistent droplets, with dimensions shown in Table 1. Smaller pulse widths were desirable, such that singular droplets could be formed, but further fidelity was severely limited by the actuation response time of the solenoid valve and the brief resonance time of liquid fuel in front of the propagating shock or detonation within the test section.

To characterize the interface between the liquid droplet or column and the incoming shock or detonation, a double mirror, Z-configuration Schlieren imaging setup was used. Both the liquid breakup mechanism and burning initiation could be comprehensively captured with a Photron SAZ camera imaging at 80 kHz. Additionally, PCB Piezotronics ICP high-frequency pressure transducers were placed upstream and downstream of the test section to validate shock and detonation regimes, and propagation speeds passing the windows. Pressure transducers were sampled at 1 MHz, as per previous TST experiments.

3 Results and Discussion

This work seeks to characterize and understand liquid breakup,ignitionand subsequentsupersonic reacting flow at varying speeds. It has been theorized that with a strong enough shock a liquid droplet can instantaneously breakup, ignite, and transition to a detonation [5]. While this work does reveal ignition of the liquid fuel, it is assisted with a stoichiometric hydrogen-oxygen reacting mixture. The results from this study are revealed in Figure 3. The gaseous mixture in the chamber is maintained at a stoichiometric mixture however the composition mixture of the pre-detonator mixture pressure is increased to create stronger shocks in varying flow regimes. The resulting interactions were then characterized through velocity measurements and normal shock relations.

In Figure 3a, a slow deflagration with a shock traveling around Mach 1.1 passes through a 1.37 mm column and a 2.38 mm droplet. The liquid breakup is observed in these images, however, with the 473K autoignition temperature of RP-2 and the post-shock gases calculated to be at 325 K, ignition does not occur. It is noted that the stream does appear to act as a barrier, nearly quenching the subsequent subsonic flame and causing significant deceleration. The following column, Figure 3b, reveals a fast deflagration crossing through a 1.74 mm RP-2 column. In this fast deflagration case, the slightly faster Mach 1.5 shock leads to a post-shock temperature of 360 K. While this is still not enough to cause ignition, significantly more breakup is witnessed. Again, the flame appears to slightly decelerate coming into the frame, likely from the opposing shockwave stemming from the column. However, the breakup, in this

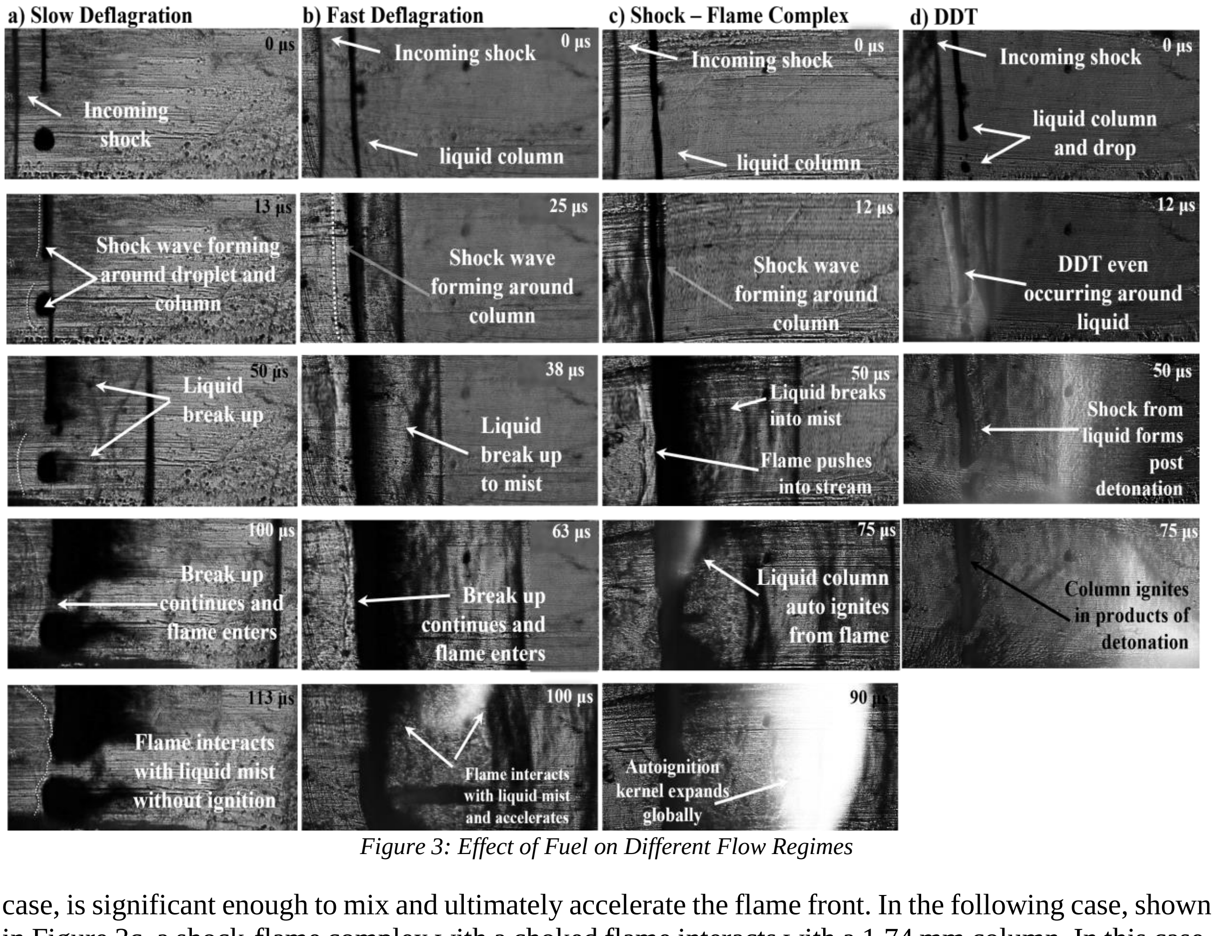

Figure 3: Effect of Fuel on Different Flow Regimes

case, is significant enough to mix and ultimately accelerate the flame front. In the following case, shown in Figure 3c, a shock-flame complex with a choked flame interacts with a 1.74 mm column. In this case, although the initial Mach 1.7 shock is not strong enough to ignite the column, it does promote breakup as it is within 15% of the autoignition temperature. Following the breakup, a flame and compressed region traveling at nearly 1,600 m/s, with a corresponding temperature of 754 K ahead of the reaction front driven by compressibility [11], does initiate ignition in column mist. This reaction then rapidly propagates throughout the liquid field causing the bulk flow to reach Chapman-Jouguet (CJ) detonation conditions. In the final column, Figure 3d, a stoichiometric hydrogen-oxygen deflagration to detonation transition event occurs around a 1.37 mm column and 2.38 mm droplet. The column forms a strong shock and then ignites 25 µs later, likely due to the high temperatures driven by the detonation.

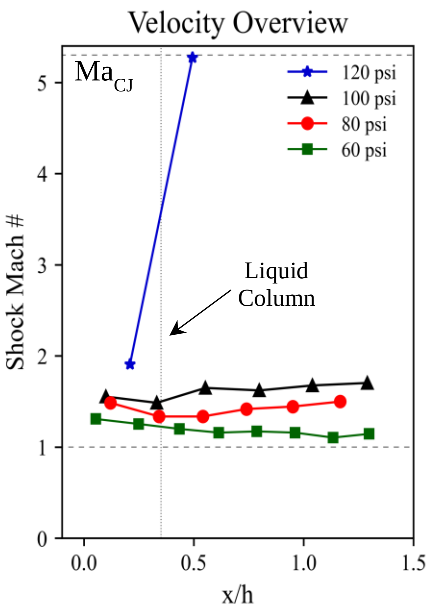

Figure 4: Mach Number in Test Section at Various Pre-detonator Pressures

Figure 4 shows a comparison of varying initial pre-detonator pressures with their corresponding shock Mach numbers over the length of the test section. The lower dashed line at a Mach number of 1 signifies the sonic condition for the plenum mixture, 540 m/s. The upper horizontal dashed line represents the CJ detonation velocity for the same mixture, 2,800 m/s. The vertical line denotes the x location of the liquid column and occasionally the droplet. This figure conveys both the increasing velocity correlated to the increasing pre-detonator pressure along with the slight decrease shown in almost all cases when the flow first interacts with the column. It offers quantitative confirmation of the phenomenon observedin Figure 3. Additionally, Table 1 presents an overview of the data collected.

Regime	*Pre-detonator Pressure (psi)*	*Stream Width (mm)*	*Droplet Diameter (mm)*	*Shock Mach #*	*Post- Shock Temperature (K)*
Slow Deflagration	60	1.37	2.38	1.1	325
Fast Deflagration	80	1.74	-	1.5	360
Shock-Flame Complex	100	1.74	-	1.7	400
DDT	120	1.37	2.38	5.3	460

Table 1: Dimensions of droplet and column

4 Conclusion

This experiment attempts to characterize and describe the effect of shock waves and detonation waves interacting with liquid fuel columns and droplets of RP-2; demonstrating the influence that liquid fuel has on different reacting flow regimes. It was determined that liquid RP-2 reacts more favorably as the shock Mach number is increased; ignition can occur in Mach numbers as low as 1.7, allowing detonation waves to be sustained. This research will help to advance RDEs and other liquid-fed detonation-based propulsion methods by enabling detonation waves to be more easily sustained.

References

[1] W. A. Sirignano, “Fuel droplet vaporization and spray combustion theory,” *Prog. Energy Combust. Sci.*, vol. 9, no. 4, pp. 291–322, Jan. 1983, doi: 10.1016/0360-1285(83)90011-4.

[2] A. A. Borisov, B. E. Gel’fand, M. S. Natanzon, and O. M. Kossov, “Droplet breakup regimes and criteria for their existence,” *J. Eng. Phys. 1981 401*, vol. 40, no. 1, pp. 44–49, Jan. 1981, doi: 10.1007/BF00825066.

[3] C. K. Law, “Theory of thermal ignition in fuel droplet burning,” *Combust. Flame*, vol. 31, no. C, pp. 285–296, Jan. 1978, doi: 10.1016/0010-2180(78)90141-4.

[4] G. M. FAETH and R. S. LAZAR, “Fuel droplet burning rates in a combustion gas environment,” *https://doi.org/10.2514/3.6490*, vol. 9, no. 11, pp. 2165–2171, May 2012, doi: 10.2514/3.6490.

[5] J. A. Nicholls, “Two Phase Detonations and Drop Shattering Studies: Second Annual Progress Report,” *NASA Office of Research Administration*, Jan. 1966

[6] P. A. T. Cocks, A. T. Holley, and B. A. Rankin, “High fidelity simulations of a non-premixed rotating detonation engine,” *54th AIAA Aerosp. Sci. Meet.*, vol. 0, no. January, pp. 1–18, 2016, doi: 10.2514/6.2016-0125.

[7] S. Prakash, R. Fiévet, and V. Raman, “The effect of fuel stratification on the detonation wave structure,” in *AIAA Scitech 2019 Forum*, 2019, p. 1511.

[8] P. A. Urtiew and A. K. Oppenheim, “Experimental Observations of the Transition to Detonation in an Explosive Gas,” *Proc. R. Soc. Lond. A. Math. Phys. Sci.*, vol. 295, no. 1440, pp. 13–28, 1966, Accessed: Oct. 08, 2021. [Online]. Available: https://www.jstor.org/stable/2415508?seq=1#metadata_info_tab_contents.

[9] I. B. Zeldovich, G. I. Barenblatt, V. B. Librovich, and G. M. Makhviladze, *Mathematical theory of combustion and explosions*. Consultants Bureau,New York, NY, 1985.

[10] O. G. Penyazkov, K. A. Ragotner, A. J. Dean, and B. Varatharajan, “Autoignition of propane–air mixtures behind reflected shock waves,” *Proc. Combust. Inst.*, vol. 2, no. 30, pp. 1941–1947, 2005, doi: 10.1016/J.PROCI.2004.08.122.

[11] R. Hytovick, H. Chin, and K. Ahmed, “Investigation of controlled deflagration-todetonation transition of hydrocarbon fuels,” *AIAA Scitech 2021 Forum*, pp. 1–6, 2021, doi: 10.2514/6.2021-1146.

[12] J. H. S. Lee, “Initiation of Gaseous Detonation,” *http://dx.doi.org/10.1146/annurev.pc.28.100177.000451*, vol. 28, no. 1, pp. 75–104, Nov. 2003, doi: 10.1146/ANNUREV.PC.28.100177.000451.

[13] N. Ionkin and D. M. Harris, “Note: A versatile 3D-printed droplet-on-demand generator,” *Rev. Sci. Instrum.*, vol. 89, no. 11, Nov. 2018, doi: 10.1063/1.5054400.