

Simulation of Engine Expansion for Transparent Nozzle Combustion Research

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Abstract

A solenoid valve system and the ability to remotely control devices were added to the transparent nozzle experimental setup. The remote control of the devices allow a user to completely control the experiment via a computer interface. The user can collect data (low speed data acquisition of pressure and temperature and high speed data acquisition of voltage), set injection pressure of the system, and control timing of triggering solenoids, data collection, cameras and injection. The solenoid valve system was shown to work properly and allow for the simulation of engine expansion by cutting off the intake flow of pressure and opening the exhaust flow to a vent. The solenoid valve setup was also shown to help with the problems of splash back and air bubbles forming inside the sack and nozzle tip.

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I. BACKGROUND MOTIVATION

Current research being done at Sandia National Laboratories uses a transparent nozzle along with high speed cameras and LEDs to image spray injections for fuel to investigate the spray patterns of fuel injectors in car engines. The transparent nozzle allows researchers to see what is happening with the injection spray when an injection is triggered. An interesting discovery in the research is that after injection occurs the pressure differential in the system that the fuel is being injected into causes an air bubble to form. This phenomena, where an air bubble forms in the system, is called cavitation. Cavitation causes the system that the fuel is being injected into to be asymmetric and not uniform, which causes irregularities in the spray fluid dynamics, which can harm efficiency and performance for the injection and eventual ignition of the fuel.

The current experimental setup had the downstream (the part of the system after the injection) pressure set to a static, high pressure value. However, car engines are constantly expanding and compressing as the pistons of the engines move. Therefore, a more accurate experimental setup for a car engine and fuel injection needs to include the capabilities to simulate a dynamic downstream pressure system. The plan was to implement solenoid valves into the system that can be triggered on and off to simulate the changing pressure in a car engine and see how this would affect the experiment.

II. MATLAB CODE

The original system setup did not have any data acquisition or triggering control designed. The first step in designing the improved system was to add the ability to automate data collection. This was done with a slow (Keysight) and a high speed (Picoscope) data acquisition device. It also turned out the Keysight had the capability to perform digital triggering. Also, the goal was to add the ability to control the Teledyne (a syringe pump controller that pressurizes and distributes the fuel to the injector) via a MATLAB code as well.

A. Data Acquisition and Triggering

Setting up the system to acquire data from both the Keysight and Picoscope proved to be relatively simple enough. Both devices can be controlled simultaneously and set up to wait to be triggered to acquire data. The Keysight was also used to trigger devices and solenoid valves as it has digital TTL output capabilities. The important question in our triggering was the

jitter/uncertainty of the timing for our digital outputs. Originally, the jitter was around 25 ms, while the goal for the timing was within 5 ms. After some fine tuning, the jitter was eventually decreased to less than 3 ms.

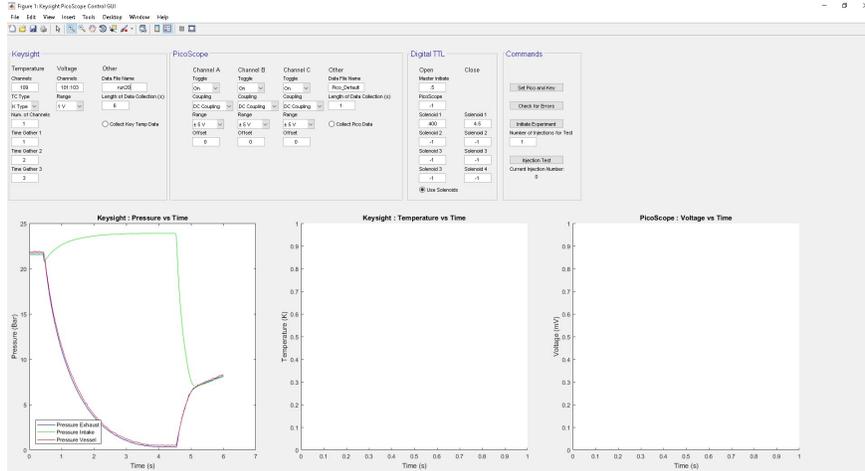


Fig. 1. MATLAB GUI for control of Keysight and Picoscope

B. Teledyne

Controlling the Teledyne proved to be a little difficult, as it required handshake methods to communicate. Eventually, it was also set up with the ability to be controlled remotely via a MATLAB GUI. With this code finished and setup, the system could be controlled entirely remotely and allowed users to be a safe distance from the high pressure system while running tests and collecting data.

III. WIRING FOR SYSTEM

Installing the capabilities for digital triggering and automated data collection greatly increases ease and quality of use for researchers, but it also can create a mess of wiring. To improve functionality and organization, a rack mount and a relay box were installed.

A. Relay Box

The relay box is powered in the back panel via any voltage source that is between 0-50 V and 0-10 A. The internal printed circuit switching boards require a 12 V source. Once these are setup, the box can either switch a channel to On, Off, or remote. On just allows the power source to flow to the output of the channel, and off does not allow the power source to flow. Remote

has the output switched off until it receives a 5 V input into its remote TTL connector. Then, the voltage at the output will stay on until the voltage returns to 0 V. The relay box also has fuses installed as a safety measure in case of over supply of current. The solenoid valves are connected to the box to be powered on and controlled via digital triggers.

B. Panel Mount

The Keysight digital outputs and data acquisition channels are inside long modules plugged into the back of the device's box, and the channels require wires fed into the module and clamped down with ring clamp terminals. To make it easier and more functional, a panel mount interface was designed with BNC and thermocouple feed through connectors. The feed through panel was designed using a 2D cad software and then machined in the in-house machine shop with a 2D mill.

IV. PRESSURE SYSTEM CONSTRUCTION

The pressure system needed to be able to be externally triggered and fast acting. The relay box and Keysight digital output allow for the external triggering to setup the timing of the pressure system. Originally, only the downstream side of the system had a solenoid valve to control flow, but the intake into the system kept the pressure too high in the system. A second solenoid valve was added upstream to switch off the supply while simultaneously allowing the pressure to vent to rapidly decrease the pressure of the system.

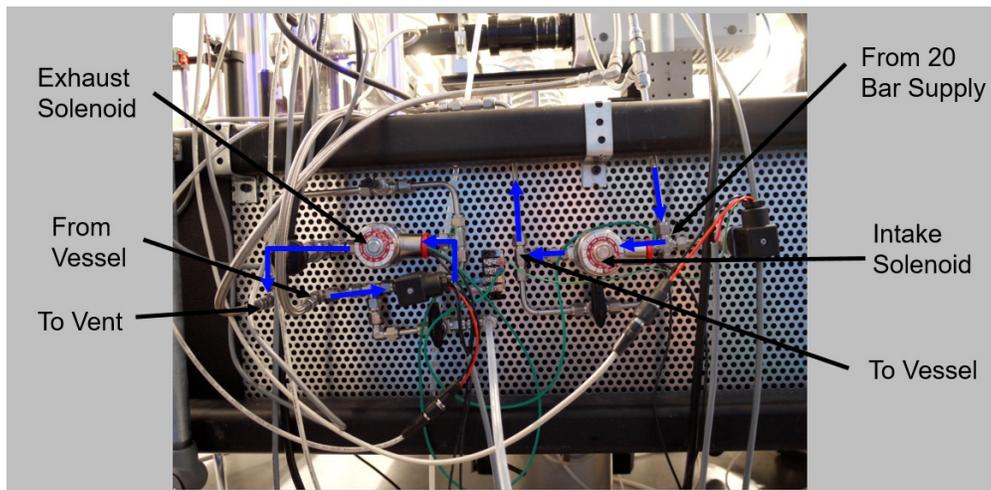


Fig. 2. Solenoid Valve Panel (Blue Arrows show Air Flow for all Solenoids Open)

V. FINAL NOZZLE TESTING

Figure 3 shows the scale of the injection photos and labels the names used for various parts in the images. The system works by having a large amount of pressure in the fuel behind the injector (on the order of magnitude of hundreds of bar). A trigger is sent to the injector driver, which allows the injector to slide back and have the fuel flow around the injector and into the sack and beyond. The liquid fuel escapes out of the nozzle tip at high enough velocity that the liquid forms into an aerosol spray. In the images, a clear area in the sack and nozzle tip indicates liquid is present and a shadowed area indicates that air or vacuum is present. In the spray chamber it is vice versa. Liquid is dark and air is clear.

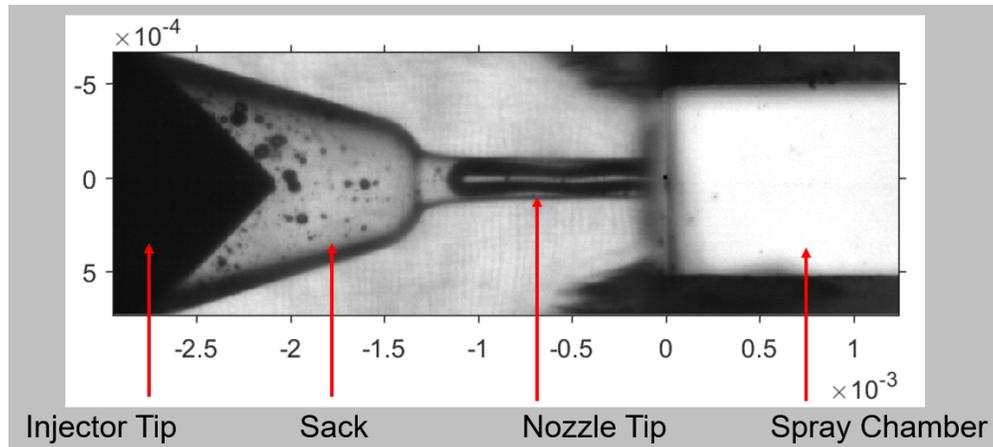


Fig. 3. Image with Scale (x-axis and y-axis in meters) and Labels

A. Non-Expansion Simulation Results

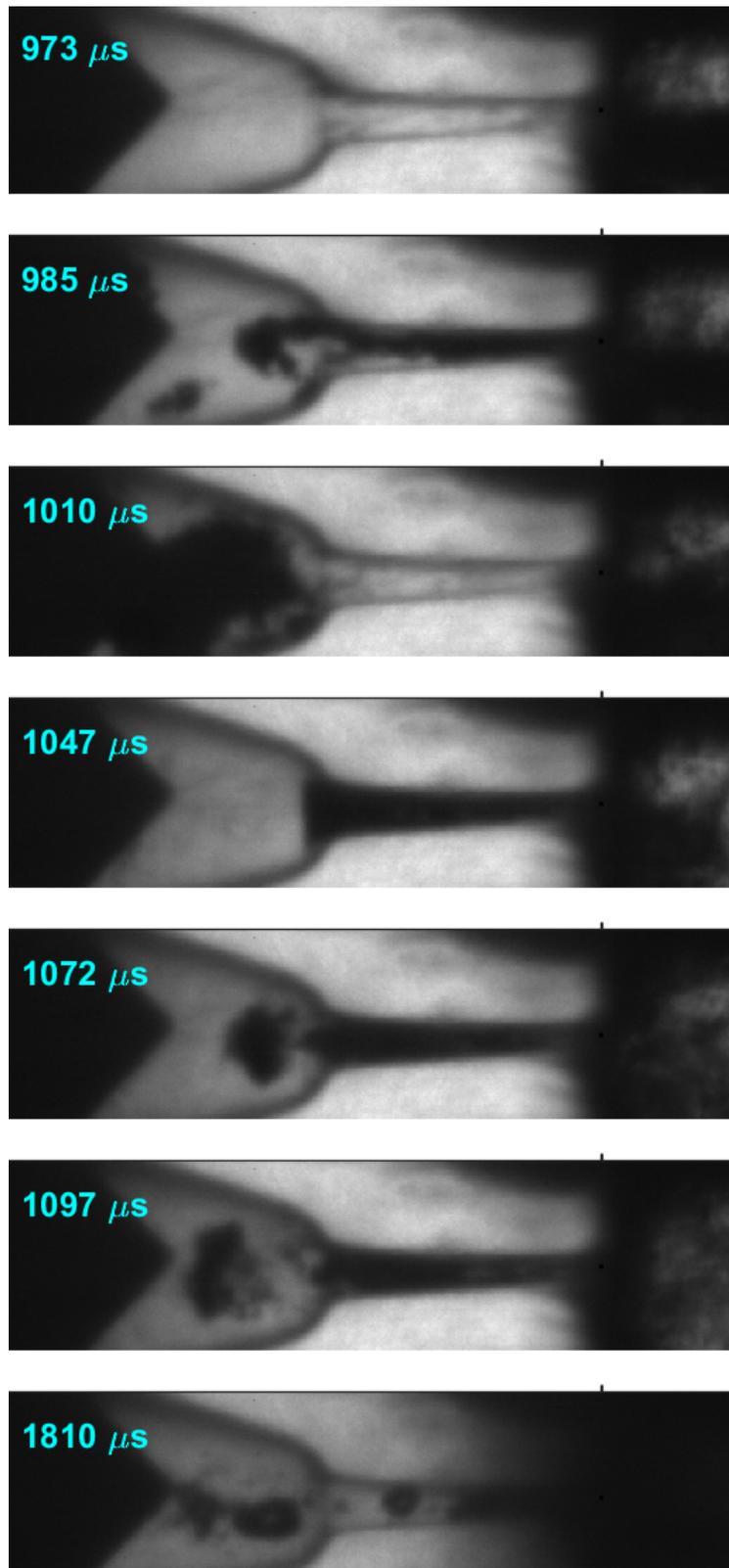


Fig. 4. Images of Cavitation and Splash Back for Old System

Figure 4 shows the images for a run of the system before adding the low speed and high speed data acquisition units and the solenoid valve panel to allow expansion simulation. In the figure, it can be seen that the splash back on the system is significant. The spray chamber is clouded beyond visibility by the end of the images. All of the images are within 100 ms of injection.

B. Experimental Setup

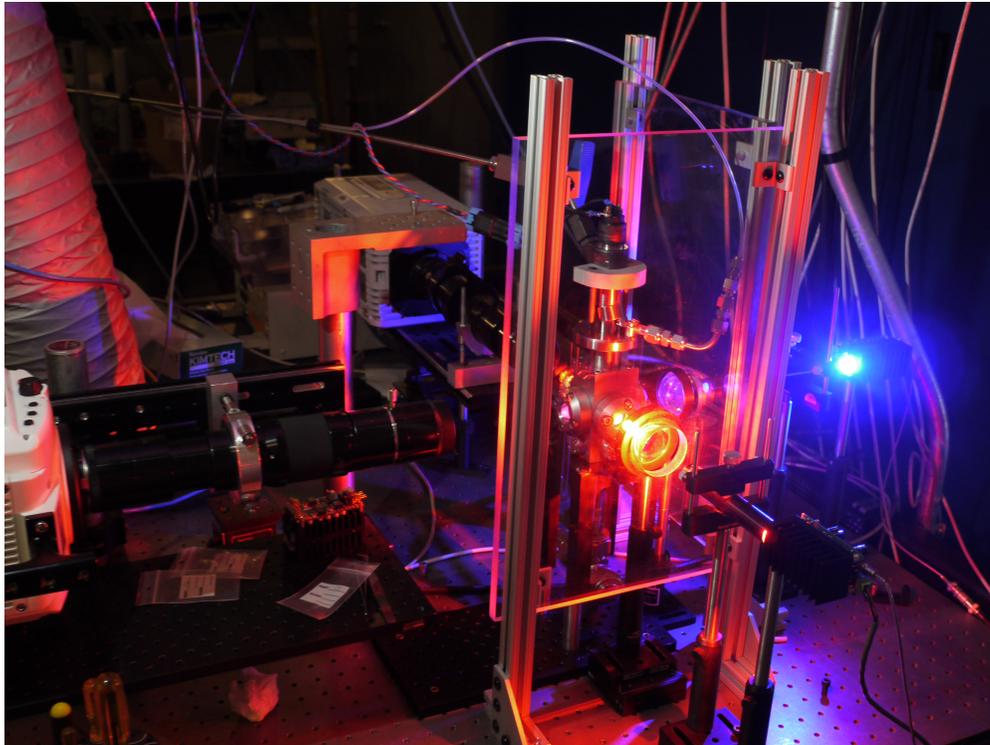


Fig. 5. Experimental Setup for Transparent Nozzle Testing

Figure 5 shows the experimental setup used for the transparent nozzle testing system. Blast doors are used to protect users from any possible explosions due to the high pressure used in the system. The blue and red LEDs are placed opposite cameras in order to flash on synchronously with the camera opposite taking a picture and flash off with the camera to the side taking a picture. The LEDs work as a backlight for the events occurring inside the vessel. Camera speed varies with each run depending on user's settings, but a typical speed for the cameras is 100k pictures per second and the LED opposite is set to pulse at 200kHz.

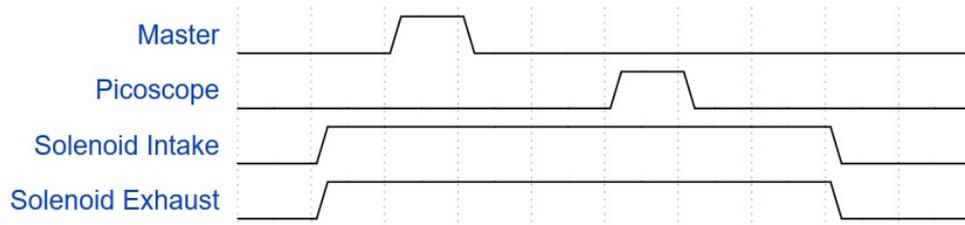


Fig. 6. Timing Diagram for Triggering System

Figure 6 shows the timing diagram used for the system. Originally, the solenoids were set to trigger simultaneously with the master trigger (cameras, LEDs, injection). However, the solenoids have about a 20ms delay to open and 70ms delay for steady flow through the valve. Therefore, the solenoids were opened 100ms prior to the injection triggering to allow the depressurization to start and stabilize.

C. Expansion Simulation Results

1) *Injection:* Figure 7 shows the progression of the system during injection. The initial pull of air into the nozzle tip is visible in the top two photos of the figure. Then, the high pressure fuel flows from behind the injector and out the nozzle tip. The initial air being pulled into the tip creates a blockage that has a two headed cloud form at first as seen in the third image. The beginning of the spray has a large liquid core (the clear area inside the black cloud in the fourth image), but by the end the spray only has a small liquid core (bottom image). The spray appears symmetric and smooth and the system is shown to run proficiently for injection.

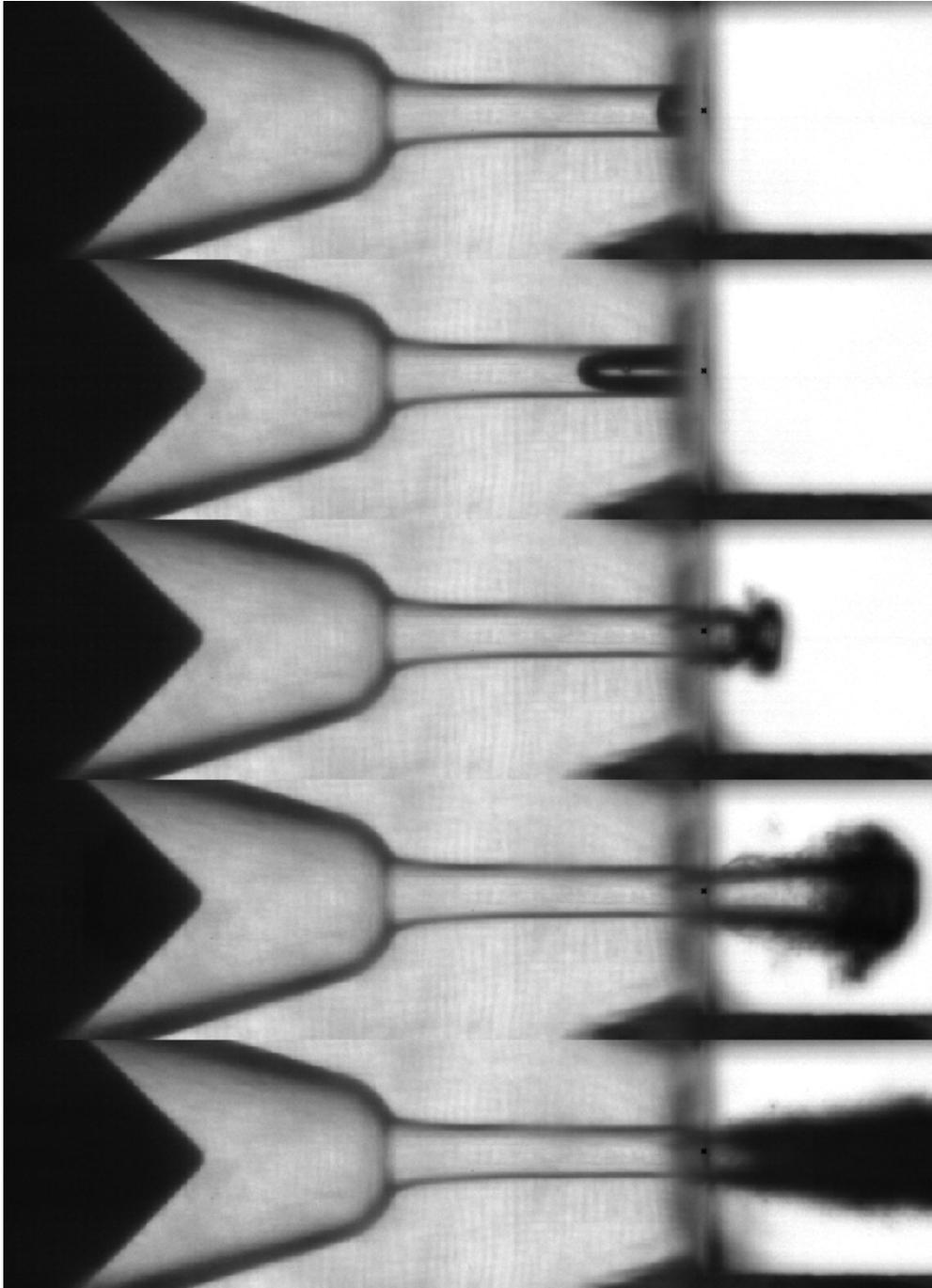


Fig. 7. Images for Injection Spray

2) *Cavitation*: An interesting discovery that occurred with the transparent nozzle project is cavitation happening when the injector closes. As the injector closes, the flow of high pressure fuel supplying the sack with liquid is decreased and then cut off. However, the fuel in the sack is still at a high enough pressure and moving at a fast enough velocity that even as the injector

is closing, fuel is still ejected from the nozzle tip. The rapid movement of fuel out of the nozzle tip and sack creates areas of vacuum since there is no longer fuel upstream (since the injector is closing/closed). This progression is seen in the top three images in figure 8. Initial formation of cavities can be seen in the top image, in the bottom left of the sack. A small, black cloud is starting to form. The dark area here represent a vacuum. As the injector continues to close, a larger area of the sack forms vacuum pockets as seen in the middle two images. The fuel in the sack then moves into these vacuum areas, which pulls fuel from the nozzle tip into the sack, which subsequently pulls air from the spray chamber into the nozzle tip. This phenomenon is seen the third image as the nozzle tip starts filling with a dark cloud. This darkness is air from the chamber being pulled into the nozzle tip. Finally, in the last image, all of the vacuum pockets in the sack have been filled and air has now completely occupied the nozzle tip.

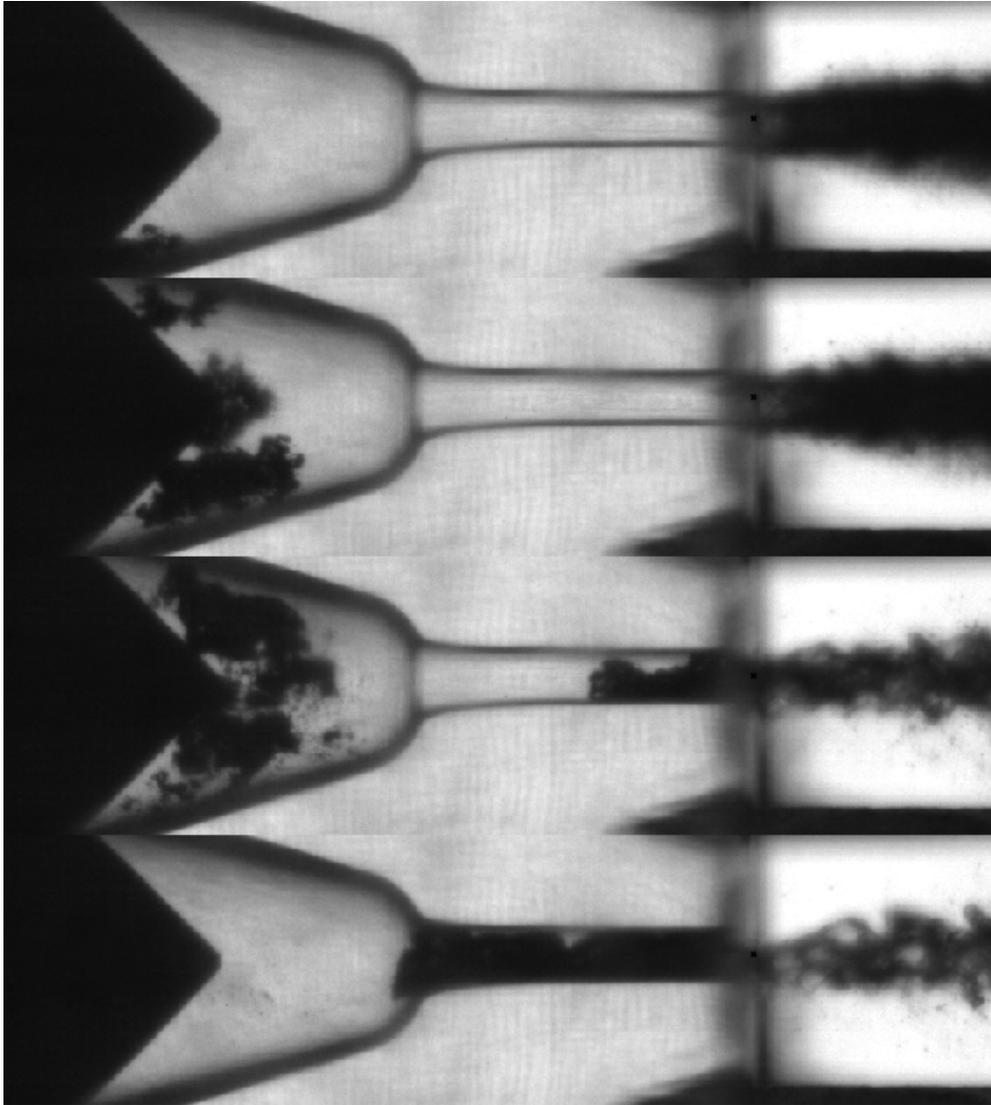


Fig. 8. Images for Cavitation Following Closing of Injector

3) *Splash Back*: Figure 9 shows the splash back of the system with the added depressurization feature to the experiment. Comparing figure 9 and figure 4, it becomes evident that the new system has significantly limited the previous problem of splash back after injection. The images are no longer obscured by a large cloud via splash back post injection.

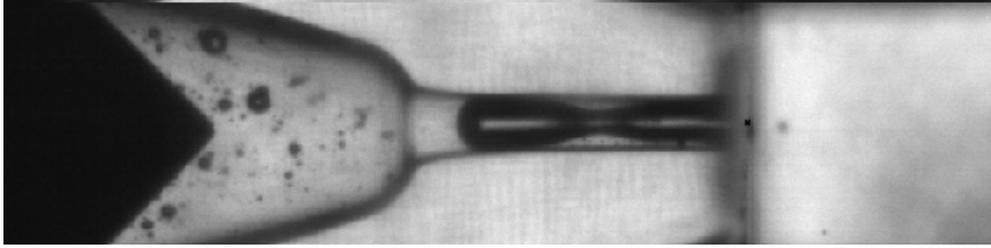


Fig. 9. Image of Splash Back with Expansion Simulation System

4) *Air Bubbles*: Figure 10 demonstrates the ability of the expansion simulation to pull air bubbles out of the nozzle tip and sack. The top image is about 20ms after injection. There are various small air bubbles in the sack and two air bubbles in the nozzle tip. The middle image is 300ms after injection. Most of the air bubbles in the sack have been merged into the second air bubble in the sack and the first air bubble has already been sucked out. The second air bubble can also be seen to begin stretching as it is being pulled out of the nozzle tip. The bottom image is 800ms after injection. The second air bubble is now completely stretched to the opening of the nozzle tip and is being pulled out of the nozzle tip by the depressurization of the spray chamber.

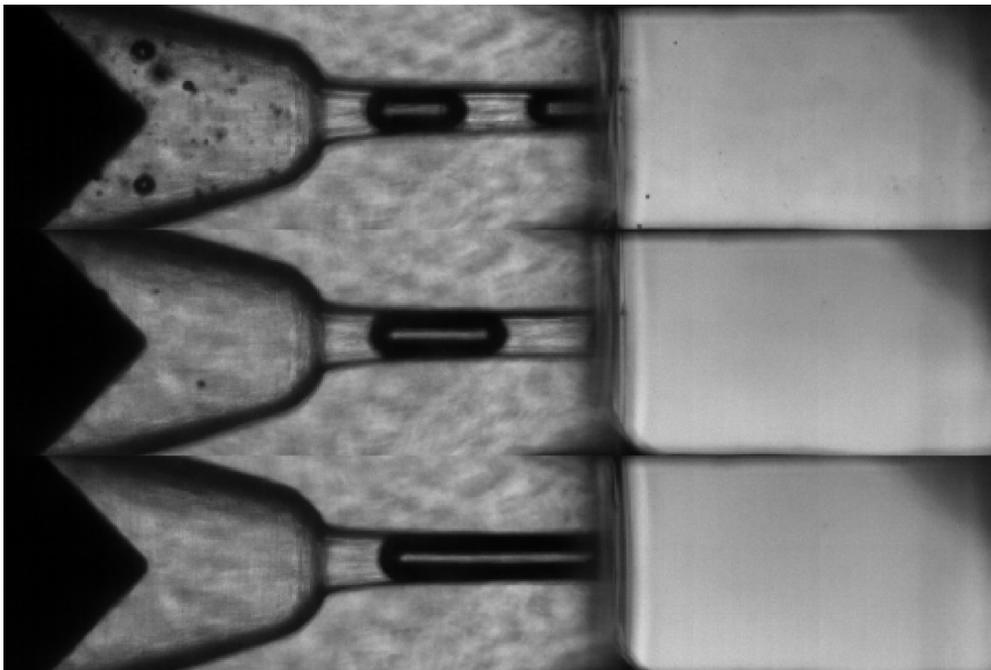


Fig. 10. Images for Pull on Air Bubbles in Sack and Nozzle Tip via Depressurization

VI. CONCLUSION

A solenoid valve system was successfully added to the system such that users can control the intake and exhaust pressures for the experiment. This allows for the ability to include expansion and compression simulation in the transparent nozzle experiments. Furthermore, MATLAB GUIs were created to control the devices of the system remotely and to collect data from the system. The final setup was proven to collect pressure data and trigger the system as expected. Moreover, it was shown that the problem of splash back was greatly minimized and that there is now the added ability to pull air bubbles out of the sack and nozzle tip. The new system allows for a more in depth and accurate investigation of the transparent nozzle with the addition of engine expansion simulation.

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