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Flow Visualization, MCEN 5051 – 001

Image Video Assignment 1 Report

September 28th, 2020

This image intends to artistically visualize the atomization and spray pattern from an automotive fuel injector. An organic solvent solution is sprayed from the injector into open air. The image sets out to capture the speed of the flow, the shape of the spray, as well as the entrainment of particles into the high-speed jet. The primary photographic obstacles encountered were determining an appropriate shutter speed, setting up a dark backdrop, and achieving appropriate lighting.

The fuel injector used in this experiment is a Denso 23250-22030 from a Toyota 2ZZ motor. This injector is rated for 328 mL/min of fuel with a 14 ohm coil resistance.[a] Droplet size for this injector is specified to be 65 microns,[a] and it is intended for port injection. The yellow injectors can be seen outlined with a red rectangle in Figure 1 below.

Figure 1. Toyota 2ZZ motor with yellow fuel injectors highlighted.

To conduct the experiment, an 8” length of 3/8” ID Tygon tubing was affixed to the fuel rail side of the injector with a small hose clamp. The tube was oriented pointing slightly upwards with the injector clamped to the table. This allowed the tube to be primed with a small amount of injector cleaning fluid. This can be seen below in Figure 2.

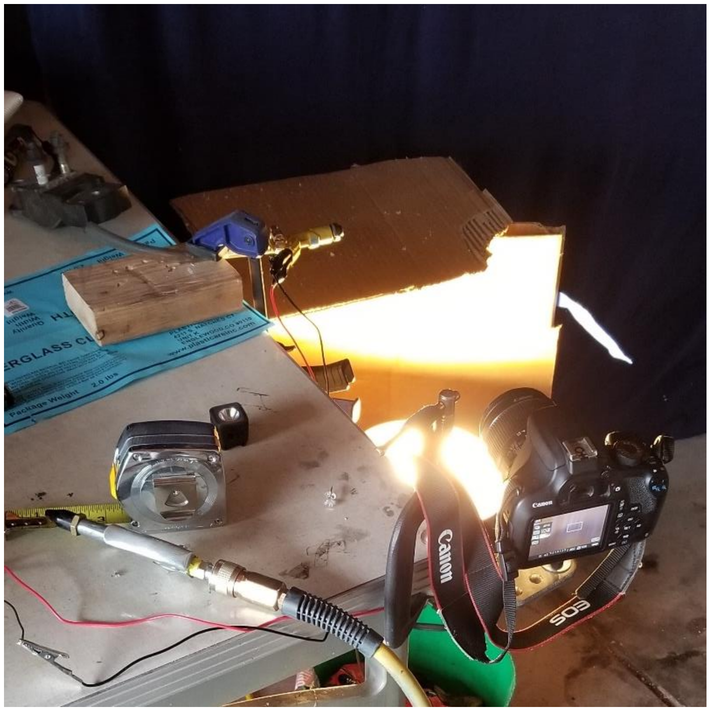

Figure 2. Experimental Setup

With the tube primed with a naphtha / isopropyl alcohol cleaning solution, the tube is pressurized to 35 psi using an air compressor. A 12 Volt, 2 Amp power supply is connected to the injector terminals through a foot switch. All connections near the injector are covered in electrical tape to avoid any sparks igniting the atomized solution. In addition, the experiment was conducted in a well-ventilated space to avoid inhalation of solvent fumes. With safety glasses on and a fire extinguisher nearby, the foot switch was triggered to release a short spray from the injector.

The Reynolds number for this flow can be roughly approximated with respect to the atomized fluid particles travelling through the air. Assuming an atomized fluid diameter of 65 microns,[a] air density of 1.2 [kg/m^3] and a dynamic viscosity of 18*10^-6 [N-s / m^2][b], the particle speed must be found from the image. As evident in the image as well as a video of the flow, particles may travel from the injector out of the frame within the 1/60 of a second exposure time. As seen below in Figure 3, this corresponds to a speed of over 400 [in/s], or over 10 [m/s]. Given these numbers, the air flow through the stream has a Reynolds number greater than 50. This implies that the air may be experiencing largely laminar flow.

Figure 3. A tape measure showing the scale of the image.

One of the regions of the image that stands out the most is the jet entrainment most clearly visible on the bottom right of the image. Fluid droplets most near the edge of the spray tend to break up before the more inner droplets. This is due to larger velocity difference between them and the ambient medium.[c] These particles then seed the flow which is likely to be entrained into the stream. This can be seen in Figure 4, showing the photo overlaid on a diagram from Lee and Park's paper showing ambient gas flow around the spray.[c] A similar counter-spray flow can be observed.

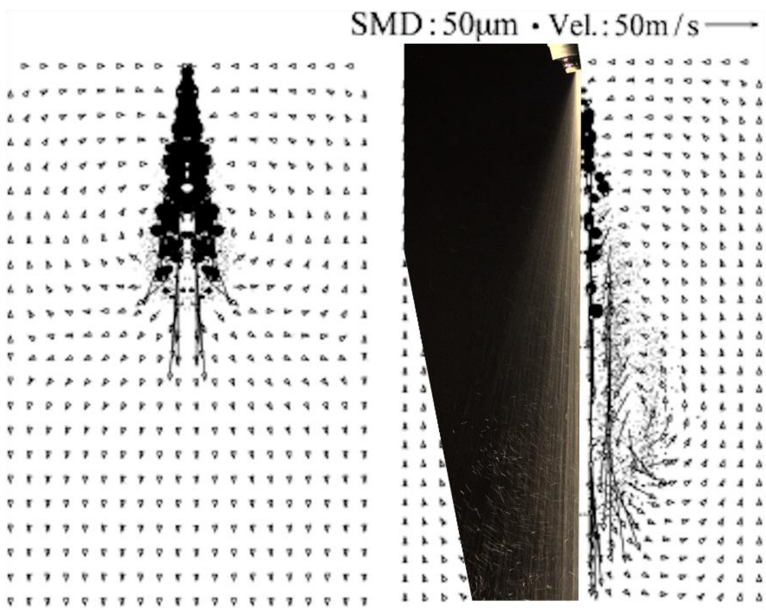

Figure 4. A composite image of the spray photograph compared to a simulation of spray induced gas entrainment.[c]

An important design consideration as well as testing parameter for fuel injectors can be the cone angle, and the separation angle of the cones.[d] While best determined by observing the spray pattern onto a surface, this can be approximated from the image. The separation angle is the angle between rays tracing the cross-sectional centroid of each spray. The cone angle is the angle between rays of the outer most part of each cone.[d] In this case, the separation angle is about 25 degrees, while the cone angle is approximately 15 degrees.

For reference, the cone angle is shown below designated by black lines, and red lines designate the separation angle.

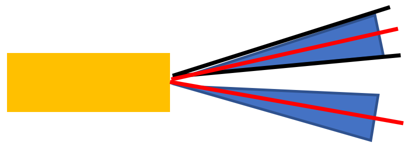

Figure 5. The distinction between cone angle and separation angle.

The flow in this instance was unchanged for visualization. Despite the atomized fluid being easily visible to the naked eye, the spray was illuminated from directly underneath with a 19 Watt, 1600 lumen LED as the only non-diffuse light source. A LED bulb was used as it remained cool to avoid a potential ignition source. A partial cardboard enclosure was created to shield the dark blue backdrop from the light. This can be seen in Figure 2.

The image was taken using a Canon EOS Rebel T5. The camera was manually focused to a ruler set along the axis of the injector. The image was shot from about 20 inches away from the spray with an exposure time of 1/60 seconds. The focal length of the lens is 34mm with a F-stop of 4.5. ISO was set to 3200 and an image with a resolution of 5184x3456 was taken. This image was cropped to 4136x3170 pixels and rotated to align the injector to horizontal. The tone curve was manipulated to achieve the full dynamic range, darken the background, and provide more contrast within the flow. The white balance tint was slightly modified to give a cooler color to the flow. A comparison between the original and edited photo is below in Figure 6.

Figure 6. A comparison of pre editing on the left, post editing on the right.

This image reveals what is happening thousands of times per minute in a car motor. While the flow physics are largely observable, it may be more descriptive with a larger field of view to better show the jet entrainment. In addition, fuel injection is inherently an incredibly transient process. A logical development of this idea would be to capture an entire injection cycle using a high-speed camera. This would document the critical start and end effects. As a single image it does however provide some insight into the steady state spraying condition.

References

[a] "Denso Fuel Injector Specifications." Injector Rx, 29 Sept. 2019, www.injectorrx.com/fuel-injector-cleaning-and-flow-testing-service/fuel-injectors/fuel-injector-data/denso-fuel-injectors/.

[b] Engineering Toolbox, (2005). Dry Air Properties. [online] Available at: https://www.engineeringtoolbox.com/dry-air-properties-d_973.html [Accessed 28 9. 2020]

[c] Lee, Chang Sik, and Sung Wook Park. "An Experimental and Numerical Study on Fuel Atomization Characteristics of High-Pressure Diesel Injection Sprays." Fuel, vol. 81, no. 18, Dec. 2002, pp. 2417–2423., doi:10.1016/s0016-2361(02)00158-8.

[d] Hung, David L.S., et al. "Gasoline Fuel Injector Spray Measurement and Characterization – A New SAE J2715 Recommended Practice." *SAE International Journal of Fuels and Lubricants*, vol. 1, no. 1, 2009, pp. 534–548. *JSTOR*, www.jstor.org/stable/26272030. Accessed 28 Sept. 2020.