Illuminated Spray from a Spray-Bottle

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Introduction

The image chosen for this first “Get Wet” assignment was a fairly simple one, the spray being ejected from a household spray bottle. This was chosen in part because with the droplets being ejected, the flow provides a method of visualization in itself. The flow is also familiar to most all viewers, making it relatable, and hopefully sparking interest.

The intent of the image was to freeze the spray in time, showing the developed turbulence and spreading of the spray. A secondary objective was to make the image colourful and eye-catching. For this reason, the freeze was achieved through flashes as opposed to shutter speed. Colour gels added to the flashes gave the image its desired colourfulness and made the image contrast well with the background. Several arrangements of the spray bottle, camera and flashes were tried before the final image was taken. Around 400 images were taken before the one with the desired lighting and visible flow pattern was shown. Special Thanks is given to Charles Bateman, who helped greatly in discussing flash orientation and operation.

Flow Apparatus

The apparatus was an unmodified generic spray bottle filled with water. The bottle was trigger action, and manually operated. For the images, the bottle was filled with tap water. The trigger is a simple lever, pressurizing a piston. The pressurized water flowed through the handle, and out a pressure swirl atomizer. (The apparatus was disassembled post photograph to determine the type, and dimensions of, the atomizer) Once ejected from the atomizer the flow broke down into the atomized spray seen in the image.

Visualization Technique

As mentioned, the flow, a mix of water droplets in flowing air, provides its own visualization. The smallest water droplets ejected tend to advect with the flow, whilst the larger particles are affected more by gravitational forces. The smaller particles, when illuminated show the flow created by the discharge of the spray bottle. A fairly powerful flash was placed below and behind the spray, allowing for a small instance in time where the water droplets front scattered light from the flash, and created the image. The position of the flash was chosen to best illuminate the particles while maintaining a clean background and minimal lens flare.

Photographic Setup

The setup used to capture the image consisted of the camera (Canon T3i with 18-55 f3.5-5.6) with the onboard flash operating as master, and a second flash (promaster FL190). The camera and flash were both tripod mounted. As shown in figure 1 the camera view was perpendicular to the spray. The master flash was front lighting the spray from the position of the camera. The slave flash was set behind and below the spray. This position allowed it to illuminate the flow without being present in the image. The photographer was to the side of the image, operating both the spray bottle and a cable release.

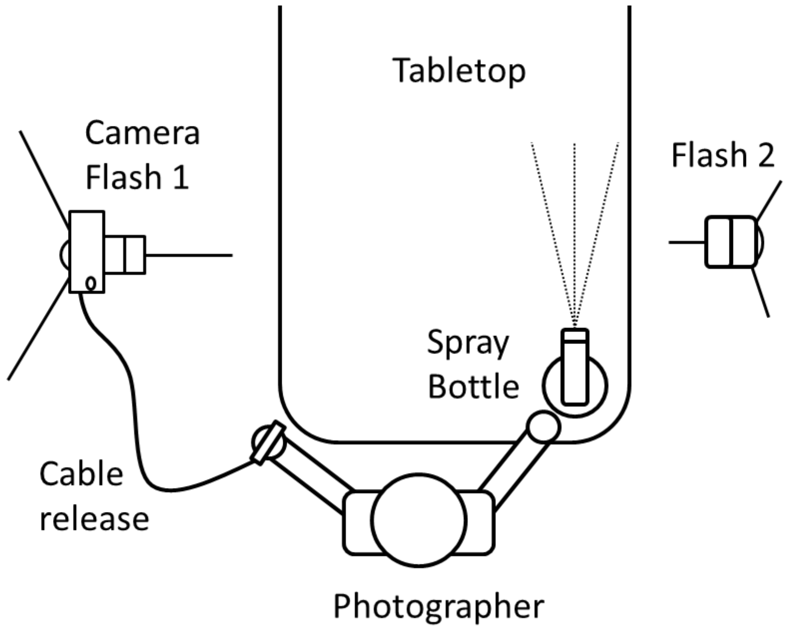

Figure 1

This figure shows the approximate arrangement of the camera, flashes, photographer, and spray bottle used to take the picture.

Exposure was set so that the image was totally dark without the flashes, and almost all continuous light sources in the area were turned off. The master flash on the camera fired, but was significantly overpowered by the second flash, which provided most of the light in the image, and nearly all of the light for the flow itself. The settings used to achieve this are as follows: f8, 1/50, ISO 100, white balance 6000k, second flash power 1/4. This provided a well illuminated spray as well as a dark background.

To add the desired colour effects, gels were use over both flashes. A green gel was used over the first flash. This provided some light to the hand spraying the bottle, and helped accent the green lettering and the green plastic parts of the bottle. The second flash used a blue gel. This provided a distinct colour to the flow and even shone through the bottle giving it an intriguing glow effect.

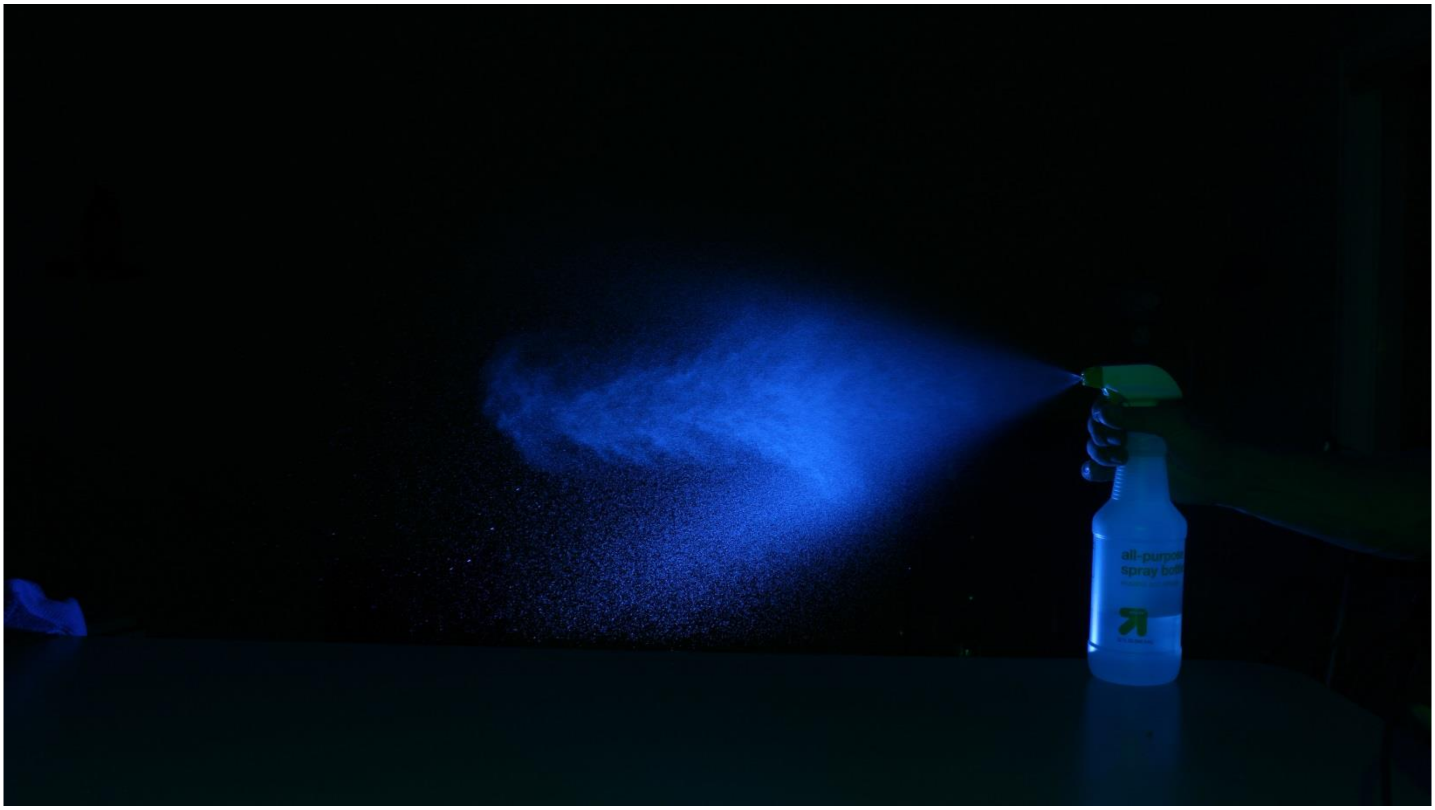

Figure 2

Figure 2 shows the unedited image taken from the camera.

The photo was then edited in Gimp2. Firstly, the image was cropped to just the area around the spray. This eliminated distracting artifacts near the edges of the image and allowed the action to fill the frame. Next, several small reflections from the master flash were painted over using a black paintbrush. The counter area was painted black, giving a clear area below the action. Lastly the curves tool was used to make the colours even more distinct. Since the colours green and blue were the primary focus of the image, the entire red channel was brought to 0. The blue and green channels were modified individually to make the spray lighter and more distinct, as shown in figure 3. After these modifications, what was left was the bright and colourful flow from the spray bottle over a clean black background.

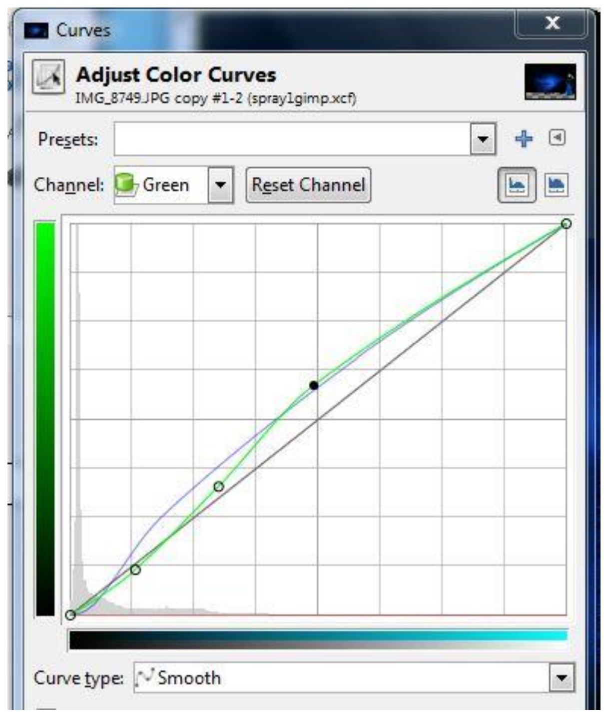

Figure 3

This shows the adjustments made using the curves tool.

Discussion of Flow Phenomena

Depressing the trigger of the spray bottle, through a simple lever mechanism pressurizes a reservoir in the handle. This pressurized water then flow up the handle and out the nozzle through a pressure swirl atomizer. The water stream once in a free gaseous environment breaks down into small droplets, imparting momentum on the surrounding air, creating a current similar to an impulsively started turbulent jet. This is the main flow captured by the image.

The trigger of the bottle, when depressed is done so with an estimated (by photographer) to have a force around 12lbf, or rounded to 50N when converted to metric. The piston has a diameter of 1.5 cm and a stroke of .75cm, giving a total discharge of 1.325CCs. With the trigger being a lever, there is about a 3:1 mechanical advantage on depressing the piston, meaning a force around 150N is applied, meaning the system is pressurized to around 85kPa, assuming small losses in the short tubing to the inlet of the nozzle. The trigger depression occurs over about a 1/3 second timeframe, this can be used to find volumetric flowrate, 3.975CC/s, and then mass flow rate, 3.975g/s of 4E-3 kg/s. This can expressed as a dimensionless flow number FN:

$$FN = \frac{\dot{m}}{\sqrt{\rho_l P}}$$

Where $\dot{m}$ is mass flow rate, ρ_l is liquid density, and P is pressure. For our case, the flow number is 4.3E-7. The mass flowrate can then be used to estimate the discharge coefficient C_D . Using rough measurements of the swirl chamber of the atomizer, the theoretical pressure can be determined, and is on the order of 80Kpa, confirming the earlier estimate. C_D for a pressure swirl atomizer can be determined by the following:

$$C_D = \frac{\dot{m}}{A_o\sqrt{2(\rho_l P)}}$$

Where A_o is orifice area (measured at .5mm). C_D here is calculated to be 0.4. This discharge coefficient represents a ratio of the actual flow rate to a theoretical flow rate; this arises from pressure losses and effects of the nozzle geometry.

Once the flow exits the nozzle of a pressure swirl nozzle, a thin film forms and quickly disintegrates. This can be seen in the image, when the nozzle outlet is magnified. The thickness can be estimated as

$$t = \frac{.00805 * FN * \sqrt{\rho_l}}{d_o * \cos(\theta)}$$

Where d_o is the orifice diameter, and θ is the cone angle (measured from image at 60^o). Thickness is estimated at .45 mm. This thickness is critical in how the sheet breaks down, and ultimately is a determining factor in droplet size. Further discussion ov particle velocity and size distributions is probably beyond the scope of this paper, however the topic is well discussed by Babinsky and Sojka.

Looking carefully at the image one can see the breakdown of the fluid sheet out of the nozzle. Though not particularly well resolved in this image, on can see a difference in the flow of the first centimeter, or so, of the jet. This is the fluid sheet ejected from the orifice before it breaks down into droplets. This represents the above discussion of parameters defining the formation of this sheet, and presents an opportunity for follow up work in the form of a macro image of the fluid jet forming.

Several other effects can be seen in the image. The path of droplets appears to be dependent on size. Assuming the droplets are approximately spheres, or at least of shapes which one can draw an equivalent radius to define a volume and projected area. Looking at the forces of momentum, gravity and aerodynamic force or drag on the particle, all scale in a way which matches what is seen in the image.

Momentum and gravitational forces both rely on mass, which scales with volume or r^3, and drag forces rely on projected area, which scales as r^2. This scaling implies that larger droplets will have more influence of momentum and gravity, whilst smaller particles will tend to advect with the flow. Looking at the image, one can see this split in particle sizes. The center of the jet appears to consist of smaller particles, whilst the bottom of the cone appears to consist of larger droplets. At the bottom left of the image, several large droplets can be seen. These are likely from the initial forming of the flow, before the fluid sheet from the nozzle was of a sufficient form to disintegrate into smaller droplets. These large droplets, of sufficient velocity, would follow a parabolic path determined most by gravity and less by advection in the moving gas, thus end up in a position below the jet, as seen in the image.

Also in the image is a vortex ring, near the front of the jet. This appears to be created as the jet is formed, and appears to be a result of the velocity gradient between the originally stagnant air and the forming jet. The smaller particles advect with the vortex ring as if moves forward and develops. The pair of circular shapes are seen in the mid left of the image, similar in shape (and originating forces) to a small mushroom cloud.

Discussion of Image

Overall the image realized the desired vision. The flow was well frozen in time and in focus. The flow was coloured and in good contrast. Peer critiquing was mostly positive, again with mostly positive feedback about the colours, contrast and focus. Some suggested removing the spray bottle from the image. However, the original intent was to make a familiar image, and the bottle and hand add the source of the flow as well as the desired familiarity for the viewer. Some suggested having the flow interact with some obstacle, which would be a great way to move forward for similar images. Perhaps a follow up image could include the flow impacting perpendicular to a surface, again a familiar and common example of a flow from a spray bottle.

Works Cited

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