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Spray Paint Visualization

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Abstract

Sprays play a very important role in everyday life such as in deodorant or paint as well as essential technical application like the internal combustion engine. As engineers we try to optimize the spray behaviour in order to achieve better efficiencies and lower engine emissions. In this exercise we examine how to visualize and analyze spray behaviour by studying two different techniques: Light-sheet Mie scattering imaging and Shadow imaging.

1. Introduction and Experimental Setup

Sprays

Dispersed liquid droplets dispersed in a gas is what we call sprays. They are generated most commonly by pressurized nozzles which atomize the liquid. This atomization process maximizes the surface area of the liquid and hence accelerates the reaction taking place (if desired). The most important factor for driving the primary breakup of the liquid is cavitation: A local pressure drop in the liquid causes instantaneous evaporation. The evaporated gas follows the liquid flow which returns to normal pressure causing the gas to condensate which in turn creates shock waves through the multiphase flow. The secondary breakup region is governed by the reduction of droplet size through velocity differences between phases. Surface instabilities such as Kelvin-Helmholtz (KH) and Rayleigh-Taylor (RT). Instabilities are amplified through such mechanisms and result in the catastrophic disruption of drops. The difference between these modes of instability are twofold: While KH instabilities affect surfaces parallel to the flow direction, RT instabilities influence surfaces perpendicular to the flow. Additionally KH instabilities originate from velocity differences between layers whereas RT-instabilities arise from density variations.

Light-Sheet Mie Scattering Imaging

As the name suggests we create a light sheet by sending a laser beam through a cylindrical lens which spreads the beam in one dimension. The sheet intersects the three-dimensional spray, more precisely it illuminates the spray particles as the light scatters off these particles.The camera is set up perpendicularly to the laser sheet such that the light that scatters off the spray can hit the sensor through the lens. Scattering is a rather different phenomenon than reflection. The direction of a reflected light beam is given by its incidence angle, scattered light however is redirected in all directions. Depending on the size of the particles that are affected a different kind of elastic scattering process occurs. When the particles are about the same size as the wavelength of the light we talk about Mie scattering, if they are much smaller its called Rayleigh scattering. The main difference between the two is that the strongest intensity signal is pointed towards the forward direction in the Mie case, whereas the Rayleigh scattering produces a much more evenly distributed signal around the particle. The diameter of droplets in our spray lies in the magnitude 0.1 micrometers to 10 micrometers, which means that we are mainly dealing with Mie scattering.

Shadow Imaging

Instead of projecting light onto the sensor, a gas (e.g. Xe) discharge lamp behind the spray causes the particles to cast a shadow onto the sensor. A diffuse plate between the lamp and the spray generates a diffuse light. The camera detects the shadow only as a difference to the bright background. As the camera, the spray and the light are all in one line this type of imaging method is called line of sight imaging.

Imaging Process

Since we try to understand how to capture the spray characteristics optically, we have to understand the effects of the parameters and essential definitions in our camera setup.

- The focal length f is adjusted in order to magnify our flame. The increase of the focal length on the other hand leads to a diminishing angle of view

- The lens aperture, also known as the f-number $N = \frac{f}{D}$ (notation: f/N, D = diameter of pupil), is similar to the iris of the human eye. It controls the amount of light which is able to travel onto our image sensor. In commercial cameras, these numbers follows a geometric sequence of $N = \left(\sqrt{2}\right)^n = 1,\ 1.4,\ 2,\ 2.8...$ for $n = 0,\ 1,\ 2...$

- The depth of field is defined as the "width" around the focal plane where the obtained images still appear clearly sharp. It follows for smaller f-numbers that the depth of field also decreases its size as well

- With scientific cameras, usually black and white images are made, thus intensities are measured rather than colors. In order to distinguish different wavelengths, one has to implement filters or an additional spectroscopical apparatus

- The linear n bit intensity range given indicates the resolution of steps which can be detected by a camera. These steps are given by 2^n, whereas a camera with an intensity range of $n = 16$ can resolve up to 16384 different intensities. The human eye can only resolve about 100 different gray-scales, therefore if we assign different colors to different levels of gray, nuances can be detected by eye. This process is called "false color rendering".

- Ideally, if we took pictures at complete dark conditions under laboratory conditions, images taken by a camera would still detect signals on the chip, also known as "Dark Signals". This problem can be resolved by either cooling the chip sufficiently or by subtracting background images with no objects present

Signal Scheme

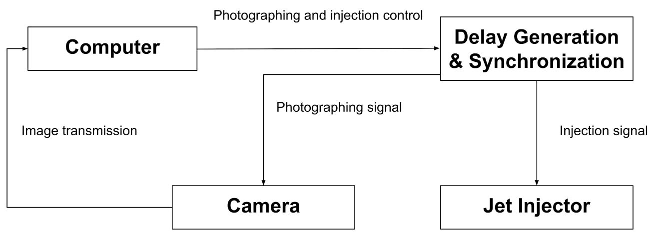

Figure 1: Illustration of the overall setup and signal flow used in the experiments

2. Measurements

The goal of this experiment is to obtain the best possible representation or more precisely visualisation of the spray. In order to achieve this we adjust the recording parameters of our camera as well as the imaging technique and the spray itself. First of all we need to make sure that that the spray is visible while the camera is exposing. Because the internal delays of the camera and the jet are different, the actual timing of the exposure and the spray do not match the signal timing on the oscilloscope. We adjust the delays manually until we can see that the camera captures the spray optimally. As we begin with Mie imaging the continuous laser-sheet does not need to be synchronized. The aperture is fully open to capture as much light as possible. In our first subset of images we set the exposure time to 1000 microseconds (Fig. 2). In all the following figures the left picture depicts the raw data while the image on the right has a false-color modification and the average background subtracted. As the eye can only distinguish so many gray scales we need the false-color mode in order to differentiate more values. In every series of 25 pictures we pick a single image which visualizes the spray the best.

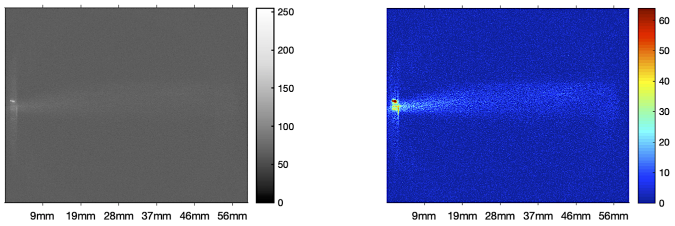

Figure 2: Recording obtained by Light-Sheet Mie Scattering with exposure time set at 1000 μs

What we can observe is that the unmodified picture has very low contrast. In false-color it is clear that the spray spreads in a cone in the first stage and then steadies itself in a beam shape. Where the diameter of the cone is low, the measured intensity is higher. The noise level is moderate. In the next set of images, we expose for 100 instead of 1000 microseconds, shown in Fig. 3.

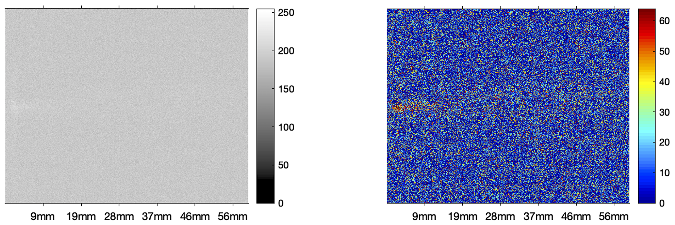

Figure 3: Recording obtained by Light-Sheet Mie Scattering with exposure time set at 100 μs

It is immediately apparent that the noise level is very high in this set and the spray is almost invisible. In the first few millimetres we are able to see the spray unfurl itself but it fades very quickly and is indistinguishable from the noise level. In the next set we start binning, which means we pool multiple pixels together, their measured intensity adds up into one remaining "superpixel". First we start with 2×2 binning, which means the resolution will be four times lower than before.

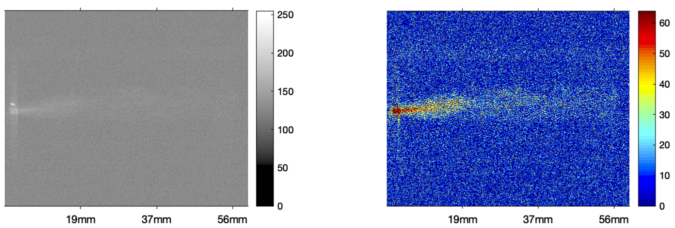

Figure 4: Recording obtained by Light-Sheet Mie Scattering with exposure time set at 100 μs, additionally 2×2 binning is executed

The lower resolution stands out, we can easily distinguish every single pixel, however the spray is visible throughout its trajectory. We measure very high intensities at the vicinity of the nozzle. In the next set we increase the binning to 4×4, meaning we decrease the resolution by four again.

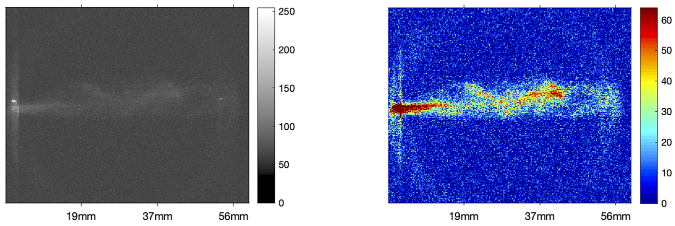

Figure 5: Recording obtained by Light-Sheet Mie Scattering with exposure time set at 100 μs, additionally 4×4 binning is executed

The spray stands out from the background very well. As a first there are higher intensities not only at the nozzle but further down the trajectory, the camera captured something that could be described as a streak. The noise level in the background is low. We continue by changing the imaging technique to shadow imaging. In the first set we lower the exposure time to five microseconds and set the aperture to $f3.5$.

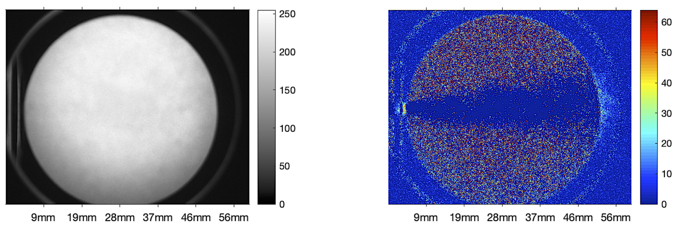

Figure 6: Recording obtained by Shadow Imaging with exposure time set at 5 μs and aperture set to $f3.5$

As the name suggests, the spray particles are now represented by low intensity light (shadow). The spray forms a cone throughout the whole frame. The areas without any spray particles are well defined but very noisy. Also what appears to be an almost empty unmodified frame shows a very distinct spray when false-colors are assigned to the intensity values. We close the aperture further to $f8$ in the next series.

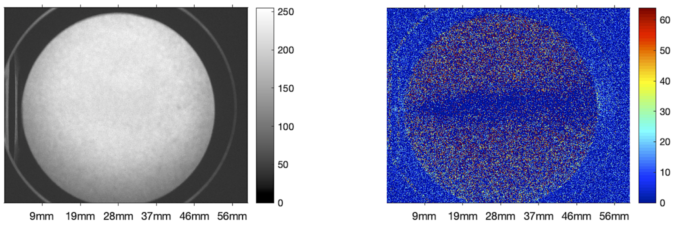

Figure 7: Recording obtained by Shadow Imaging with exposure time set at 5 μs and aperture set to $f8$

The noise level increases, which makes it harder to assess the shape of the spray. It still is conical but the line between spray particles and noise is increasingly blurred the further along the spray direction. At last we increase the flow rate of the spray.

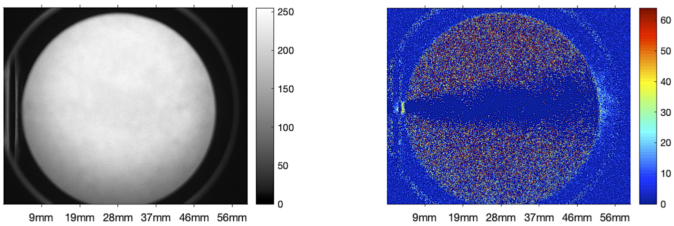

Figure 8: Recording obtained by Shadow Imaging with exposure time set at 5 μs and aperture set to $f8$ while flow rate is increased

The raw picture shows the cloud of the spray clearly, the false-color background subtracted picture however does not seem to match its original at all. Its diameter seems way broader and the cone angle appears to be way lower.

3. Discussion and Conclusion

The exposure time determines for how long the camera captures light, which means that the fast moving spray particles influence the sensor at many locations until the exposure time is over. This is what happens in our first set, it is not really a momentary capture of the spray. The long exposure time blurs the motion, which is why we reduce it to a tenth in the second series. The second set is much worse than the first, which at least us shows us a long time trajectory of the spray. The signal to noise ratio is so low the spray is almost not visible. This is why we now introduce binning, we are able to catch more light per pixel as we add the measured intensity of multiple pixels together to a bigger pixel-block. 2×2 binning means that two row and two column pixels are summed together, the resolution is therefore reduced by a factor of four while the amount of light per pixel is multiplied by four. The resulting image set shows that this tradeoff makes sense, we can see the outlines of the spray again, while the general noise level is still high the signal stands out a lot more. Applying the same principle again with 4×4 bins we get an even better result. The instantaneous spray distribution is clearly visible and the signal to noise ratio is even higher. However the resolution is now a sixteenth of the first sets and the pixel-blocks are easily perceptible. Even higher binning would make the images too coarse. This is where we would benefit from using a better camera with higher resolution, the binning factor could be increased without losing as much image quality. The diffuse light behind the spray casts a shadow on the sensor, therefore the lower intensities indicate the presence of droplets. As the background light is very bright in comparison to the rest of the scene we can decrease the exposure time even more to five microseconds and set the aperture to $f3.5$. The resulting image is very noisy, yet the spray outline is still well defined, but there is no distinction in the spray itself. It appears like the spray itself is two dimensional. Setting the aperture to $f8$ allows even less light to hit the sensor which in consequence lowers the difference between the background and the spray. The image reflects exactly that, the contrast is very low. In order to increase the contrast again we raise the flow rate of the spray which means there are more droplets blocking the line of sight during the exposure. To conclude in terms of clarity and image quality, Mie scattering is the preferred method. However, its setup is more complex, several optics and a laser are needed as well as more space in general. All you really need for shadow imaging is a camera and a light and the experiment is ready to go, which makes it a lot cheaper, compact and flexible. The image quality tradeoff however is considerable.