

Team First Report

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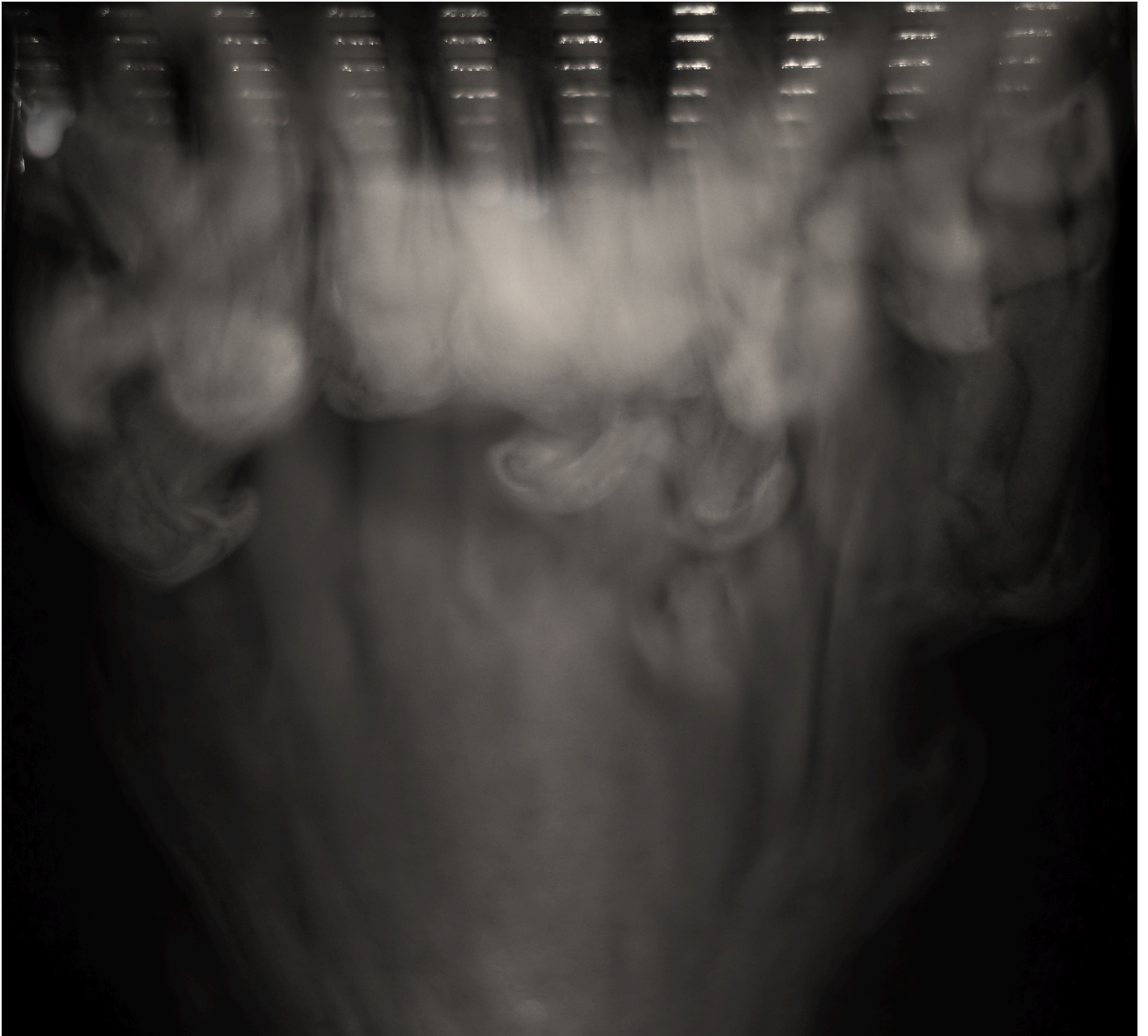


Figure 1: The final image taken for this project, displaying the leading plumes of water vapor as it falls through a square grid.

Context

The image above was taken as part of this class's "Team First" project, for which the goal assigned was to take a photograph clearly demonstrating a particular flow phenomenon in an aesthetically pleasing manner. Our team's initial intent was to observe the types of flow created as pressure- or temperature-driven airflow interacts with fine mesh screens, similar to those used in household windows, to see if there was any significant impedance to total flow. However, to optimize the setup for photographic clarity and to avoid complexities of techniques such as Schlieren imaging, the experimental scale was increased. By utilizing falling water vapor and a coarse, 3D-printed grid, we were able to capture the fundamental flow structures and turbulent patterns intended in our initial design in a manner more accessible to standard photographic methods.

This project was a collaboration between three team members: I, Maximilian Moiser, was responsible for the design and 3D printing of the grid and other structural components, while both Evan Zwicki and I co-constructed the final experimental setup, and Johnathan Pizarro provided and operated the oil diffuser. The team worked collectively to set up the lighting and initiate the flow for each individual's final image.

Flow Apparatus & Analysis

The apparatus used to create our flow consisted of several 3-D printed and paper components, along with an oil diffuser. The core of the setup featured a 100mm×100mm×100mm hollow reservoir positioned directly above a 1mm thick 3-D printed grid. The grid was designed with 4.48mm×4.48mm square openings, padded by 4.48mm of material. To provide a seamless backdrop whilst shielding the flow from lateral air disturbances, a vertical paper half-cylinder was positioned beneath the grid. A low-angle depiction of this is shown below, in Figure 2:

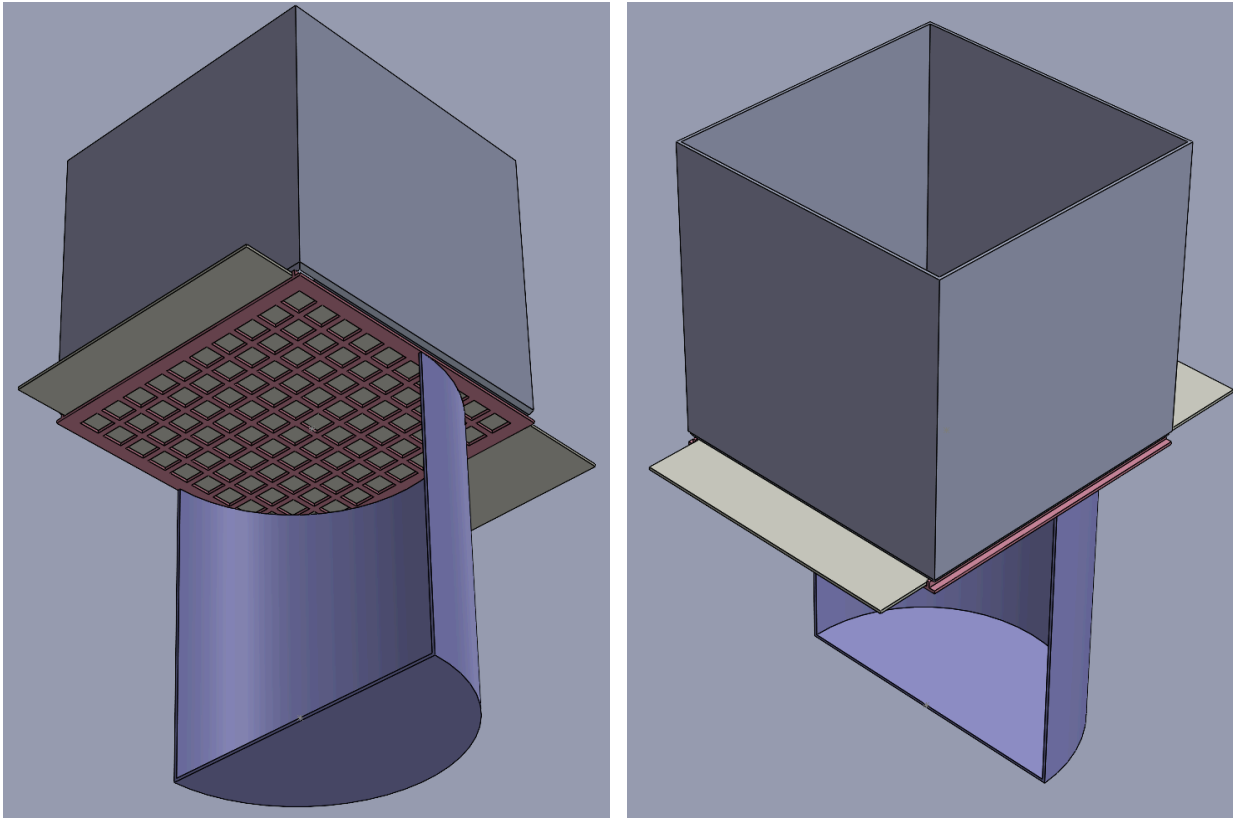


Figure 2: A depiction of the core elements of the apparatus, from lower- and upper-angle views: the reservoir is colored grey, the grid red, the paper cylinder blue, and the paper between the reservoir and grid yellow.

An ultrasonic transducer within the oil diffuser was used to atomize some room-temperature filtered water, which notably created a fine aerosol rather than a pure gas. To ensure a controlled release, a strip of paper was slotted between the reservoir and the grid, preventing any flow between them. The aerosol was allowed to accumulate within the reservoir, and once full, we let it settle for a few seconds. To initiate the flow, the paper strip was manually removed, allowing gravity to drive the aerosol through the grid. A burst of photographs was taken immediately afterwards, with that shown in Figure 1 being within 1 second of release. Figure 3 below demonstrates the process described here:

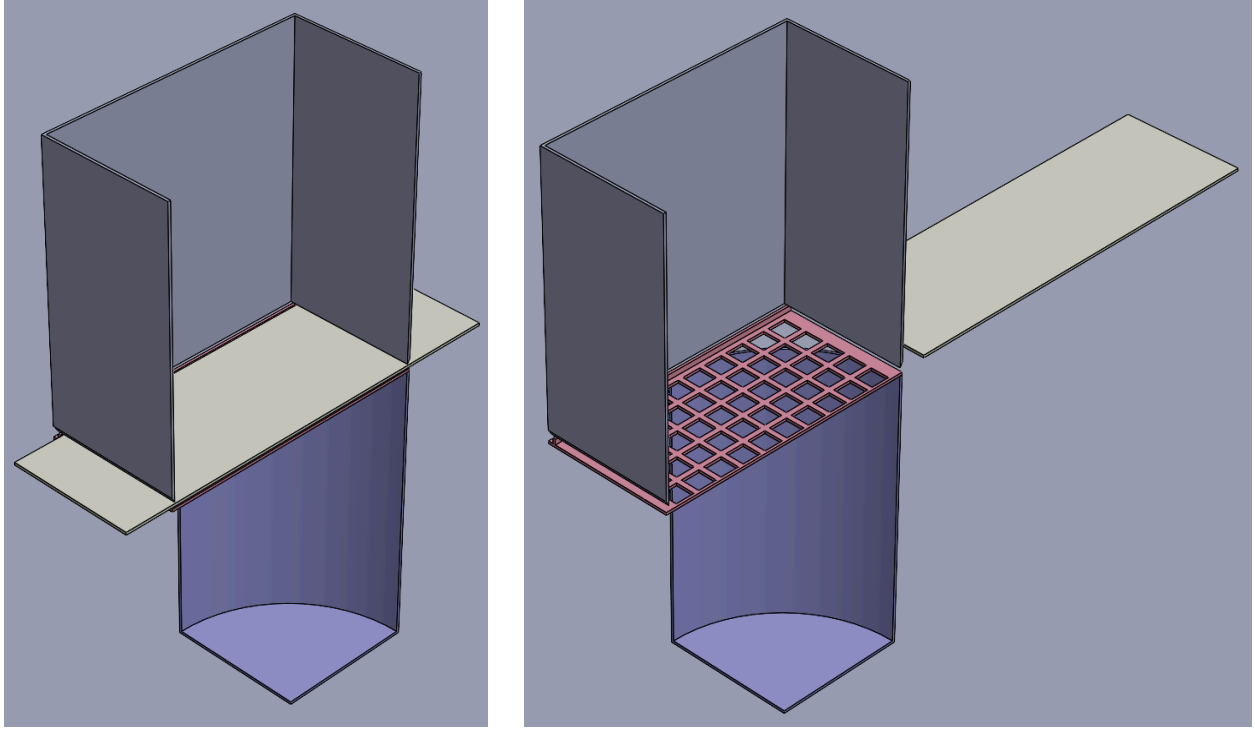


Figure 3: A cross-sectional view of the apparatus before and after the paper strip is removed.

Given that our apparatus was designed to isolate the flow from ambient air disturbances while starting the mist in a stagnant state, the downward flow observed in Figure 1 can be attributed mainly to the density differences between the aerosol and surrounding air. This negative buoyancy drove the aerosol through the grid, where it initially formed discrete, bulbous plumes. As these plumes accelerated due to gravity, they began to exhibit instabilities which led to distortion of those bulbous shapes. At the moment of capture, we see this transition from coherent, nearly spherical structures near the grid to more complex turbulent structures further downstream. Figure 1 plainly shows how the furthest advanced plumes exhibit distinct vorticular structures, while those closest to the grid maintain a more cohesive, undisturbed shape.

To quantify this transition from coherence to turbulence, the Reynolds number (Re) can be used, as it indicates whether the flow is in a turbulent or laminar domain. This is calculated using the equation

$$Re = \frac{UL}{\nu},$$

where $\mathbf{U}$ is the plume head velocity, $\mathbf{L}$ is the characteristic length, and $\mathbf{v}$ is the kinematic viscosity equal to the dynamic viscosity divided by the density.

Since each plume is still visibly isolated from the others, we can consider the characteristic length to be the distance from a given opening to the head of a plume. By counting pixels in this image using the in-focus grid cells whose known dimensions provide a size reference, and assuming the grid to be on a plane completely perpendicular to the camera's sensor, I derived the plume length measurements shown in Figure 4, below:

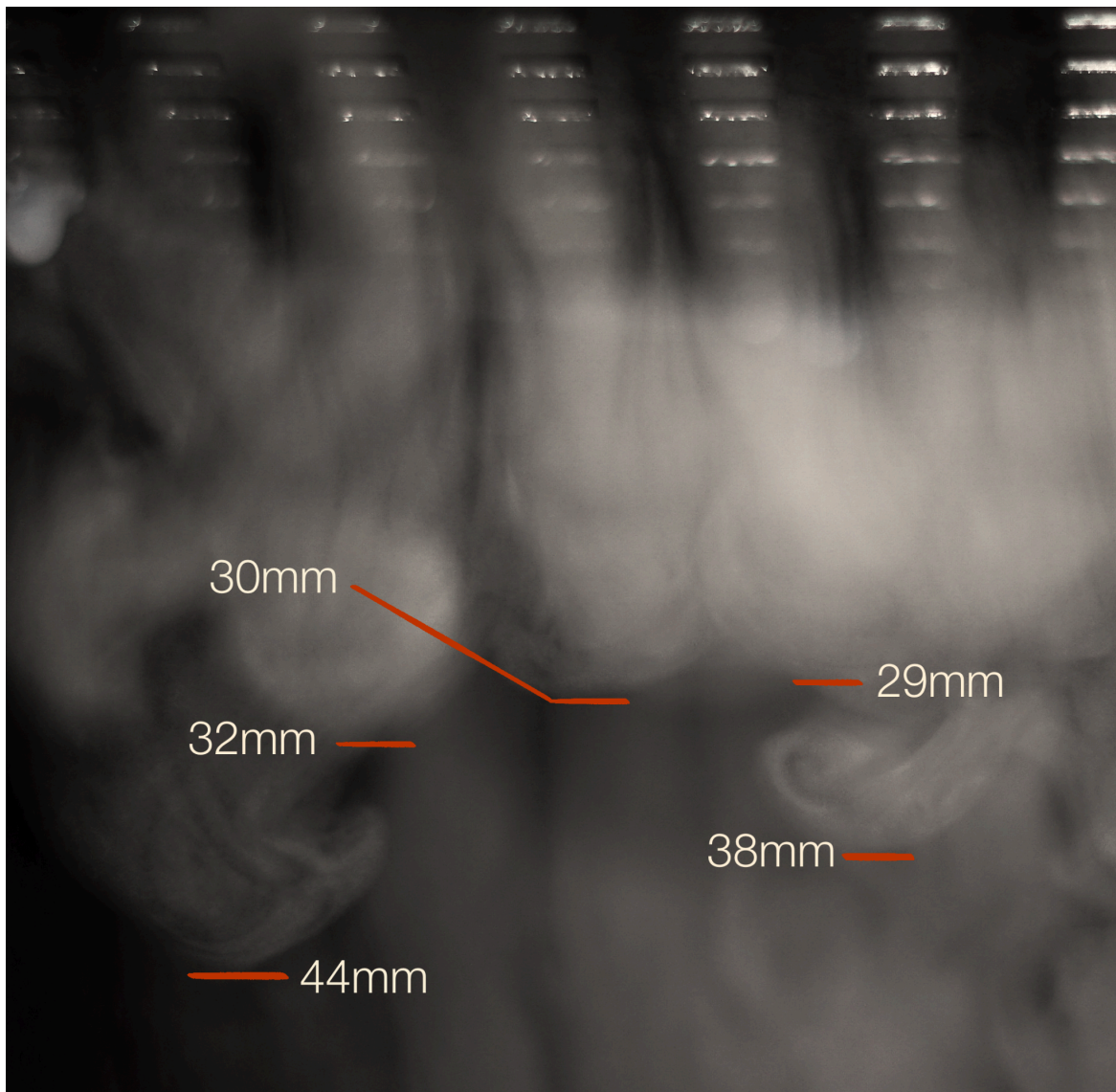


Figure 4: Five plumes heads labeled with their approximate total lengths, in mm.

These measurements were made only on the plumes that were in-focus, as that allowed for measurement of their distances to the corresponding in-focus grid holes above. Measurement was made to the very end of each plume, to the extent I could distinguish them, and was done using the original unaltered image. Note the 38mm and 44mm plumes are significantly more turbulent than the other shorter ones. For calculation, we'll use the two extremes $L_{MIN} = 29mm = 0.029m$ and $L_{MAX} = 44mm = 0.044m$, for our characteristic lengths.

Our team did not get enough images with precise enough timing to derive the velocity for the particular instance of our experiment in which Figure 1 was captured. However, by taking some rapid successive shots of a similar setup later, I found the velocity of a plume at 29mm to be approximately

$$U_{MIN} = 250 \frac{mm}{s} = 0.25 \frac{m}{s}, \text{ while that of a plume at 44mm was approximately}$$

$$U_{MAX} = 350 \frac{mm}{s} = 0.35 \frac{m}{s}.$$

Using a kinematic viscosity of $\nu = 1.85 \cdot 10^{-5} \frac{m^2}{s}$, scaled from the standard room temperature sea level value to match Boulder's, we get the following values for our Reynolds numbers:

$$Re_{29mm} = \frac{0.029m(0.25 \frac{m}{s})}{1.85 \cdot 10^{-5} \frac{m^2}{s}} = 391. \overline{891} \approx 3.9 \cdot 10^2$$

$$Re_{44mm} = \frac{0.044m(0.35 \frac{m}{s})}{1.85 \cdot 10^{-5} \frac{m^2}{s}} = 832. \overline{432} \approx 8.3 \cdot 10^2$$

While for a situation such as pipe flow, these Reynolds values of 390 for the shorter plumes and 830 for the longer plumes would be well within the laminar range, it's important to consider the fact that these plumes are surrounded by air as opposed to something more rigid: the presence of disturbances in this ambient air can lead to a lower transition range between laminar and turbulent flow (Leishman, 2022), giving a possible explanation for why the $Re = 830$ plume appears turbulent while the $Re = 390$ does not.

Visualization & Photographic Methods

Because our flow involved inertial water particles suspended in air, it is arguable as to whether or not we were visualizing the flow of the aerosol itself, or the air they affected: in the absence of air's influence on the particles, they would

have followed simple projectile paths and fallen straight down. Without the particles, the air would not have been disturbed by anything more than the ambient disturbances, and the particular flow we saw would not have occurred. Ultimately, it is most useful to consider this to be a coupled system, in which the aerosol functions both as a driver of the flow and as an accurate tracer.

Given that, the visualization technique we use here could be described as a marked boundary technique which relies on light scattering caused by the water droplets. A warm LED ring light was held immediately above the camera and pointed towards our apparatus in an orientation which seemed to maximize the amount of light reflected back at the camera (See Figure 5). This technique led to the higher densities of water particles corresponding to the brightness of the visualized flow, given that the transparent air remained dark against the black background.

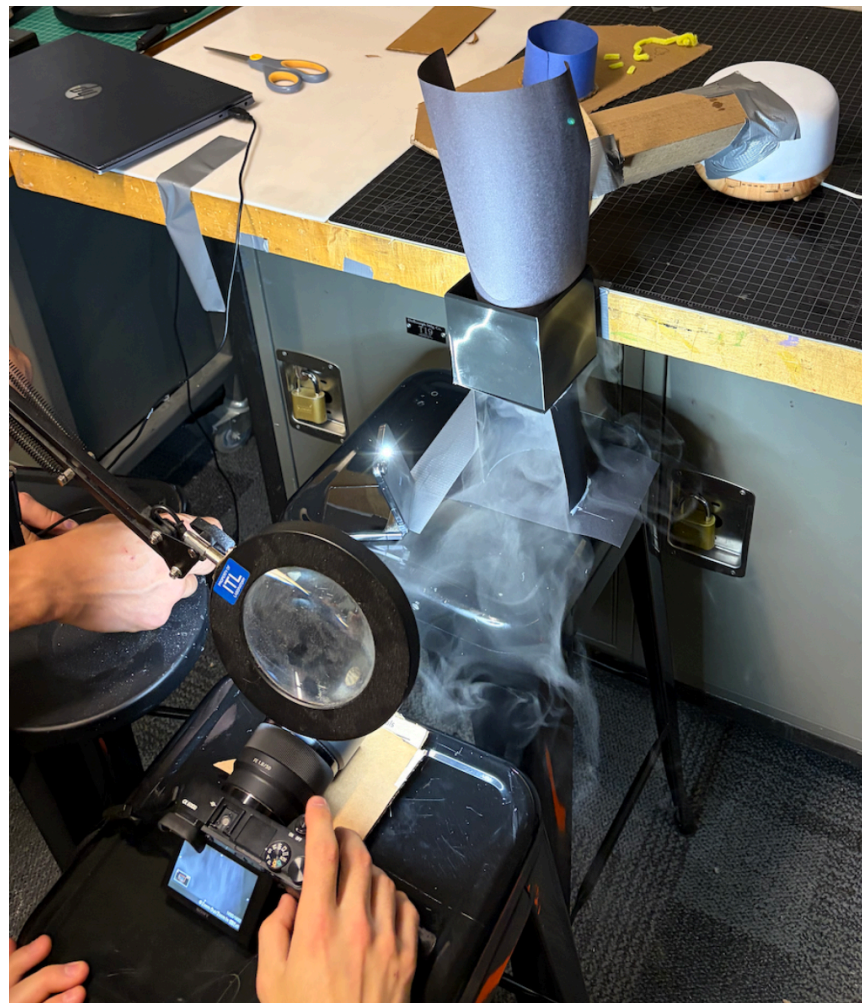


Figure 5: The lighting setup used. In this image, there is a cell phone flashlight present, which was not used in the capture of Figure 1. Image taken by Johnathan.

Though this could also be considered a particle tracing technique, most of the particle paths are not visible in the final image. Our exposure time was relatively short at 1/160th of a second, and the size of the particles was too small for most to be distinguishable at the camera's zoom and resolution, regardless.

The water used in this experiment was filtered water which started near room temperature in the diffuser, though it is likely the temperature of the vapor differed from the temperature of the diffuser due to evaporative effects and energy introduced by the transducer. The room was also room temperature, and had no significant net airflow.

To capture the image in Figure 1, I used a digital Sony a6000 camera equipped with a Sony FE 50mm f/1.8 lens set to manual focus, placed approximately 32cm from the frontmost part of the grid. This lens was selected because it was the best I had for achieving focus at the scales we were working with. My other option was a lens which could not focus clearly on the subject when placed at a distance where the flow took up most of the frame. With the Sony a6000's sensor dimensions at 23.5mm×15.6mm, this lens had a horizontal field of view of

$$2\tan^{-1}\left(\frac{23.5\text{mm}}{2(50\text{mm})}\right) \approx 26.4^\circ$$

and a vertical field of view of

$$2\tan^{-1}\left(\frac{15.6\text{mm}}{2(50\text{mm})}\right) \approx 17.7^\circ.$$

This particular image was taken using an ISO of 100, which was the lowest available setting, and which was chosen to minimize sensor gain noise. The corresponding exposure time that best maximized the range of values in the image while minimizing blurriness due to flow motion was 1/160 seconds. Because this lens's aperture could not be adjusted, an f-stop of f/1.8 was used.

The camera was set to store images using the largest resolution it could, at 6000×3376 pixels. However, because the camera could get no closer to the subject, much of the original image consisted of our setup's background, and the final image, once cropped to show only the flow apparatus, was 3601×3294 pixels.

Beyond that cropping, the final image was processed to increase contrast and highlights, while reducing brightness, exposure, and shadows, to obscure the background's noisy texture while emphasizing originally low-contrast details in the vapor. Additionally, the image warmth was slightly increased, and its saturation decreased, in order to hide some distracting bluish hot glue blobs that were present in the background. All editing was done in Windows Photos. Figure 6 below shows the original image.

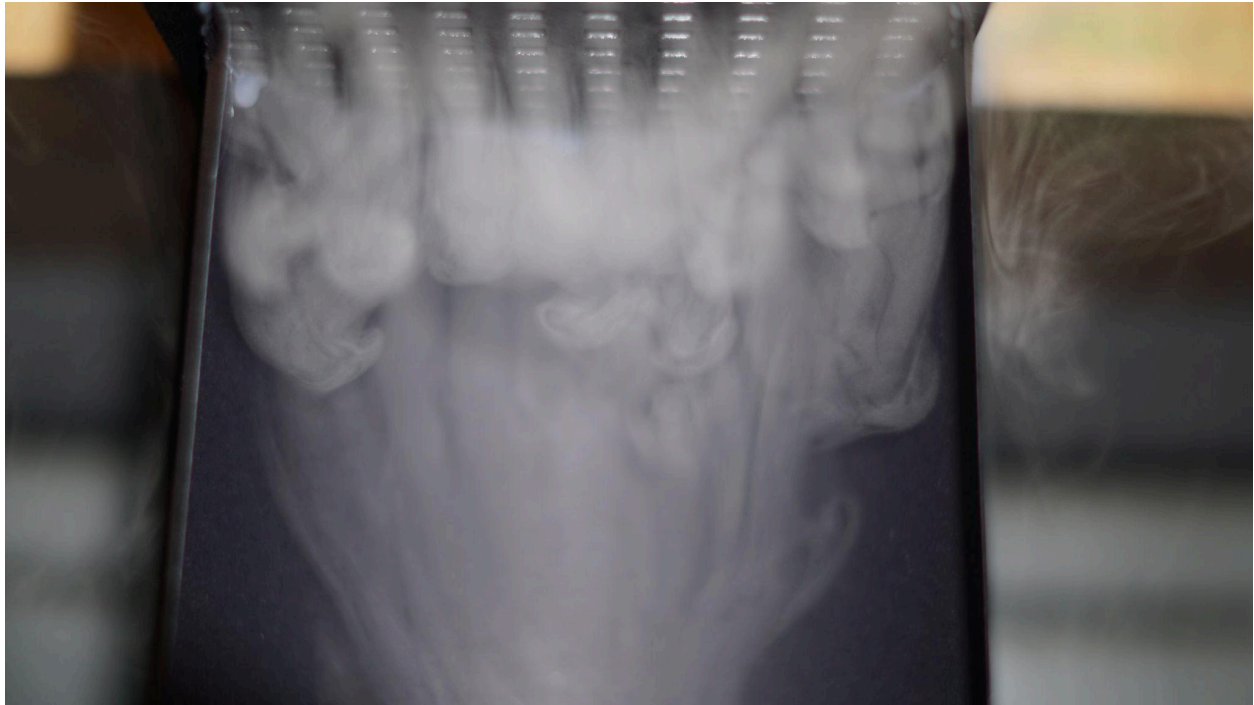


Figure 6: The original photograph, later edited to create Figure 1

Discussion & Conclusion

As mentioned at the beginning of this document, our initial motivation in designing this experiment was to investigate potential airflow impedance through fine-mesh screens caused by flow structures formed at screen boundaries. However, the flow drive method and experimental scale used did not make this an accurate model for that phenomenon. While this setup was not ideal for studying such ventilation rates, it did prove to be an effective model for observing the evolution of discrete gravity-driven plumes. Figure 1 provides a clear depiction of the transition from laminar to turbulent flow regimes, and how that corresponds to the length of a plume. If we consider the transition range to be lower here than it would be in something like pipe flow, the Reynolds numbers calculated might also support this.

For this particular visualization technique, it might have been more useful to have a grid with less depth, as with this photographic method, the plumes in the background only make the ones in focus more difficult to distinguish. Going further, the use of a laser to illuminate only a thin cross-section of the flow would have been even better at reducing that issue, while also increasing the contrast we would have seen. The lighting, if a laser had not been used, could also have been more methodically designed: there was a lot of ambient light in the room, which illuminated the black background more than was ideal, and which gave us less control over what parts of the flow were illuminated versus those that were not.

Regarding the quality of the setup, there are several changes I would make to improve this. An apparatus more isolated from the external environment's effects would have helped significantly to ensure any turbulence we saw could be attributed only to the flow we created, and one that was more precisely designed would have made calculations far more precise. A significant amount of the numerical data here relied on pixel measurements and assumptions regarding the camera placement and field of view.

I think it would have been interesting, if possible, to see the effects of varying water particle sizes on the flow observed, with all else held equal. It would be interesting to determine whether observed plume velocities could be used to estimate the local Reynolds numbers of the flow around each particle. Stokes' law can be used to predict drag and thus settling velocities of spherical particles, under the assumption that the particles' Reynolds numbers (Re_p) are less than 1 (Ricketts). Perhaps any discrepancies between the velocities observed and those predicted by Stokes' law could indicate the domain of the Re_p values.

References:

Leishman, J. G. (2022). *Types of fluid flows*. Introduction to Aerospace Flight Vehicles. Embry-Riddle Aeronautical University.

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Ricketts, B. (2023, March 9). *Fluid flow: Stokes Law and particle settling*. Geological Digressions.

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