Smoke Entrainment by Air Jet

Figure 1. Smoke Entrainment by Air Jet Final Image.

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Team Third Report

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Introduction

The Smoke Entrainment by Air Jet image was captured as part of the third and final team project in a flow visualization class. The photography and setup of this video was done with the help of my teammates, Beck Hermann and Domenic Decaro. The scientific intent behind the image was to capture how smoke that is denser than air can be drawn upwards when exposed to a jet velocity of air that induces pressure gradients and inertial forces. The artistic intent of the image was to capture striking images of wispy white smoke against a pitch black background. The final image is a striking image with excellent contrast between the smoke and background, and accurately depicts how pressure gradients near the jet flow overcome the gravity forces acting on the smoke to draw the smoke out of the glass.

Setup

The flow apparatus consisted of a pint glass, incense smoke, and an electric compressed-air blower. A diagram of the image setup can be seen below.

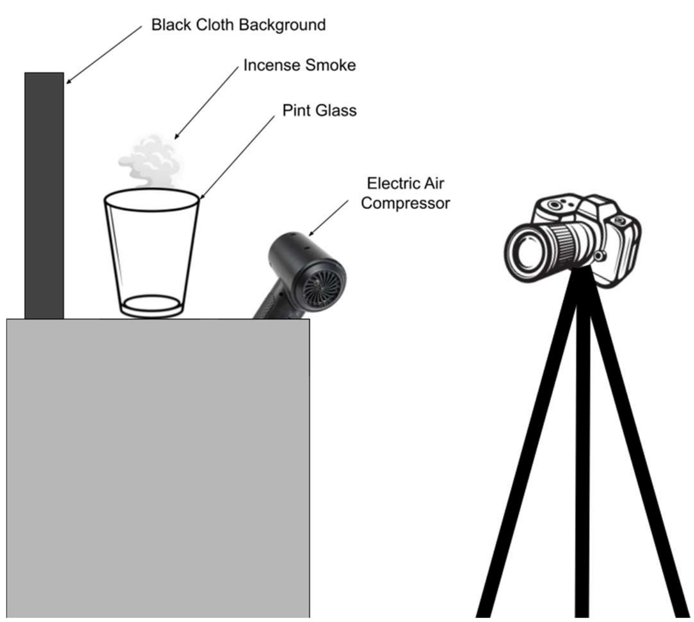

Figure 2. Smoke Entrainment by Air Jet image setup.

The setup started with hanging a piece of black cloth behind the subject. This background allows for contrast with white smoke. Next, a tripod was setup, so the camera was level with the pint glass. The incense was then lit with a butane lighter and suspended over the glass for several minutes to let the incense smoke fall and accumulate in the bottom of the clear pint glass. Once a sufficient amount of smoke had accumulated in the glass, a Newhouse Electronic Air Duster was turned on the lowest setting and pointed upwards and diagonally towards the glass. The standard default nozzle was used when blowing the electric air compressor.

Flow Physics

The flow physics in this experiment can be seen with opaque smoke. While the smoke is denser than the surrounding air, buoyancy forces do not dominate hear. Instead, the smoke is affected by the jet's momentum and the low pressure region near the air jet's high-speed flow. The jet produces a pressure gradient and shear in the ambient air that draws the surrounding entrained smoke particles into the flow. The denser smoke is quickly brought upwards out of the glass primarily by this pressure gradient. Once entrained in the jet, momentum transfer from the jet becomes greater than the negative buoyant forces, so the smoke flows in the direction of the jet. The same entrainment idea can be applied to turbulent jets and plumes in fluids literature.[1]

First we can compare the dynamic pressure of the jet to the buoyant pressure force that resists entrainment in the jet. When air speeds up in the jet, it has a higher dynamic pressure (moving fluids pressure) and lower static pressure (stationary air nearby). Before quantifying the flow, parameters, measurements can be taken to get approximate length scales of the flow.

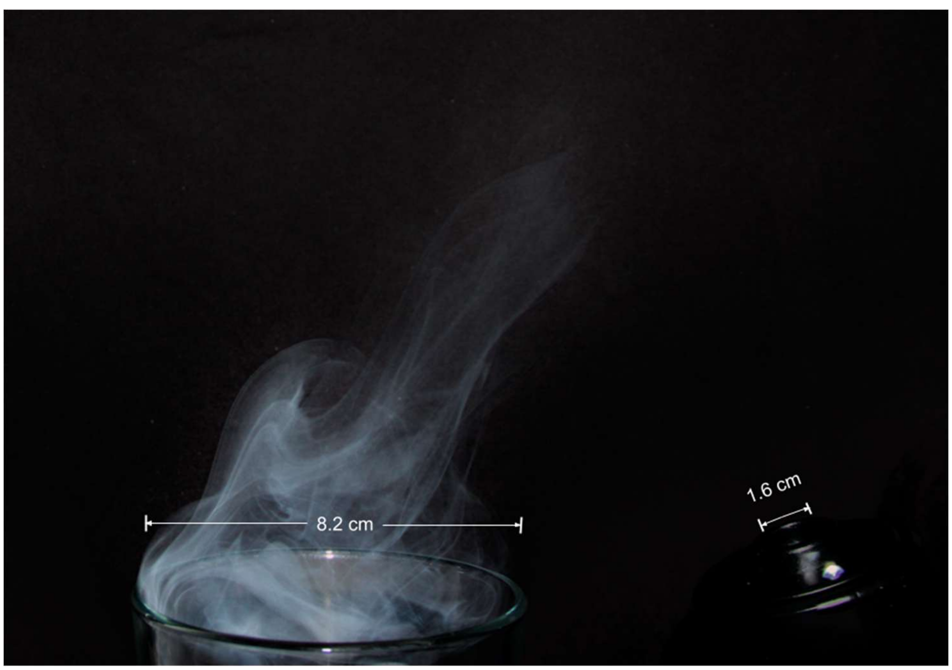

Figure 3. Approximate length scale measurements for the flow.

The dynamic pressure in the jet and the buoyant pressure scale surrounding the flow can be quantified to confirm the comparison. The dynamic pressure of the jet is defined as:

$$q = \frac{1}{2}\rho U^2$$

Where, q is the dynamic pressure of the jet, ρ is the density of the air, and U is the velocity of the jet. The density of air at room temperature is $1.2\ \frac{kg}{m^3}$ and we can approximate the air velocity out the air compressor as $15\ \frac{m}{s}$, which is typical for an electric air compressor. Plugging these values into the equation above we can estimate the dynamic pressure in the jet:

$$q = \frac{1}{2}\left(1.2\ \frac{kg}{m^3}\right)\left(15\ \frac{m}{s}\right)^2 = 135\ Pa$$

Next we can solve for the buoyant pressure that can be produced in the static air surrounding the jet. The buoyant pressure scale can be approximated as:

$$\Delta p \approx g\Delta\rho L$$

Where Δp is the pressure produced by buoyancy, g is the acceleration due to gravity, $\Delta\rho$ is the difference in densities between the fluids, and L is the characteristic length of the flow. The acceleration due to gravity is a constant $9.81\ \frac{m}{s^s}$. Assuming a density of incense smoke that is denser than air of $1.3\ \frac{kg}{m^3}$, we get a difference in density of $0.1\ \frac{kg}{m^3}$. The characteristic length L is the dimater of the pint glass where the buoyancy driven flow originates, which is measured as $8.2\ cm$. Plugging these values into the equation above, we can approximate the pressure produced by buoyant forces:

$$\Delta p \approx \left(9.81\ \frac{m}{s^s}\right)\left(0.1\ \frac{kg}{m^3}\right)(0.082\ m) \approx 0.0804\ Pa$$

Approximating both the dynamic pressure in the jet and the pressure produced from buoyant forces in the static surrounding air shows us the dynamic pressure is significantly greater than the buoyant force pressure. The dynamic pressure in the jet is about 1680 times the buoyant pressure scale. These approximations show that the jet is thousands of times stronger than the pressure buoyancy forces can generate over the length scale, which shows that the jet can easily pull in and entrain the smoke.

A non-dimensional analysis can also be performed in order to check flow characteristics. The first non-dimensional parameter we will consider is the Grashof number. This parameter indicates if the difference in densities in the flow alone could induce convection. The Grashof number indicates the scale of natural convection is given by:

$$Gr = \frac{g\left({}^{\Delta\rho}/_{\rho}\right)L^3}{v^2}$$

Where Gr is the non-dimensional parameter, g is the acceleration due to gravity, ${}^{\Delta\rho}/_{\rho}$ is the different in densities between fluids over the density of the fluid flowing, L is the characteristic length of the flow, and v is the kinematic viscosity of air. We will use the same values as above for the variables g and L, and assume the kinematic viscosity of air is $1.5 \cdot 10^{-5}\ \frac{m^2}{s}$. We will use The density ratio term can be given by dividing the difference in density between the incense smoke and air by the density of air. Plugging in these values we get the non-dimensional Grashof number:

$$Gr = \frac{\left(9.81\ \frac{m}{s^s}\right)\left(\left(0.1\ \frac{kg}{m^3}\right) \Big/ \left(1.2\ \frac{kg}{m^3}\right)\right)(0.082\ m)^3}{\left(1.5 \cdot 10^{-5}\ \frac{m^2}{s}\right)^2} = 2 \cdot 10^6$$

The extremely large Grashof number calculated above shows that if buoyancy acted alone in this flow, it would lead to significant natural convection of the smoke. The next step of the non-dimensional analysis shows why even this significant force will not be the force that dominates the flow.

The second non-dimensional number we can use to confirm the flow physics observed is the Richardson number. The Richardson number compares the buoyant forces to the inertial forces in a flow. The Richardson number is given by:

$$Ri = \frac{g\left({}^{\Delta\rho}/_{\rho}\right)L}{U^2}$$

Where Ri is the non-dimensional parameter, g is the acceleration due to gravity, ${}^{\Delta\rho}/_{\rho}$ is the different in densities between fluids over the density of the fluid flowing, L is the characteristic length of the flow, and U is the flow velocity. We will use the same values as above for the variables g, ${}^{\Delta\rho}/_{\rho}$, L, and U. Plugging in these values we get:

$$Ri = \frac{\left(9.81\ \frac{m}{s^s}\right)\left(\left(0.1\ \frac{kg}{m^3}\right) \Big/ \left(1.2\ \frac{kg}{m^3}\right)\right)(0.082\ m)}{\left(15\ \frac{m}{s}\right)^2} = 2.979 \cdot 10^{-4}$$

The numerator of the Richardson number represents the buoyant forces in the flow, and the denominator represents the inertial forces. Given that the Richardson number calculated is extremely small, it shows that the denominator is large and that inertial forces dominate the forces in the flow. In general, when $Ri \ll 1$, inertial forces in the flow dominate.

The pressure gradient calculations and the non-dimensional analysis both indicate the entrainment of the incense smoke in the jet of air. Previous fluids studies similar to this experiment show similar results. One study determines that entrainment arises naturally from turbulent shear layers, where ambient fluid is continuously drawn into a jet due to large scale eddies generated at the jet boundary.[2]

The dynamic pressure of the jet is estimated to be significantly greater than the buoyant pressure scale, which shows the jet can easily pull the smoke in due to this pressure gradient. The Grashof number indicates that buoyancy forces air present due to the difference in density, however the Richardson number shows that internal forces from the jet dominate over these buoyant forces. The inertial forces dominating explains why the jet is able to carry the denser smoke out of the glass towards the fast moving air.

Visualization

The visualization of the fluid physics described above was done through using opaque smoke and proper lighting techniques. Incense is optimal for visualizing these flow physics because it produces fine, continuous particles that move smoothly with surrounding air. The smoke also allows for high visual contrast so that subtle flow structures can be seen against a dark background. Another benefit of the incense smoke used was its density being greater than that of air. This allowed for proper accumulation, accumulation, and manipulation of the smoke in order to visualize the flow physics.

The lighting used to visualize the rising smoke was solely from the flash of the digital camera being used to take the image. All other lighting near the experiment was turned off, so that the experiment area was completely dark and only illuminated by the camera flash.

Photography and Post-Processing

The video was captured using a Canon EOS digital camera. The camera was held approximately 20 centimeters away from the subject. The field of view of the photo was approximately 50 centimeters wide by 30 centimeters tall. Flash on the camera was also used to capture the flow in this image. The flash mode is outlined in Table 1.

Photo Spec	Value
Camera	Canon EOS 600D
Camera Type	Digital
Focal Length	18 mm
Aperture	f/5
Shutter Speed	1/200 s
ISO Setting	400
Flash Mode	Flash, compulsory

Table 1. Camera settings for the Venturi Effect image

In order to calculate the time resolution of the flow within the shutter speed, we will assume that the smoke ends up moving continuously with the air jet at approximately $15\ \frac{m}{s}$. With this shutter speed, and the assumed fluid velocity the flow moves approximately 7.5 centimeters during the frame, which is about the diameter of the pint glass. This is a significant overestimate of the time resolution, since the smoke in the image does not fully enter the air jet and move at this velocity, however it is important to consider for higher speed flows in future experiments.

A significant amount of post-processing was performed to enhance the flow physics in the image and limit distracting elements. All post-processing steps were performed in Dark table. First, a crop was performed to focus on both the smoke exiting the pint glass and the electric air compressor nozzle, which was the catalyst for the flow observed. Before the crop, the original image size was 5202 by 3464 pixels. The final image size is 1298 by 900 pixels.

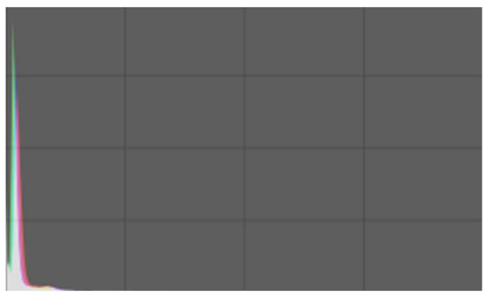

Figure 4. Image histogram after post processing

The next post-processing steps were performed in order to make the background fully black, and increase the contrast with the white smoke. First the overall exposure was lowered to -1.250 EV, and the black level correction was increased to +0.0246. This made the black background overall darker. Next the tone equalizer was adjusted at certain light levels: -5 EV to +0.25 EV, -4 EV to +2.00 EV, -3 EV to +0.23 EV, -2 EV to +0.16 EV. Adjusting these specific exposure levels allowed for targeted darkening of certain light levels and made the background a uniform black color. Finally, I adjusted the RGB monotonic curve to better bring out the white smoke without lightening the background. The final image histogram can be seen in Figure 4. The histogram shows the distribution of brightness and color values in the image, with the horizontal axis representing pixel brightness levels, where black is on the left and white is on the right.

Figure 5. Side by side of unedited image (left), and final image (right)

The final edited image clearly depicts the desired flow phenomenon and fulfills the artistic intent of the image. The post-processing performed enhances the contrast between the white smoke and black background, while keeping all aspects of the flow characteristics true to the original image.

Conclusion

The final image successfully reveals the flow of the physics of entrainment of dense smoke into a shear layer of the nearby compressed air jet. The curved path of the smoke clearly shows how the pressure gradient near the jet draws in the smoke and overcomes the gravity pulling down on the denser smoke. In the fluid physics analysis, the dynamic pressure of the jet is estimated to be significantly greater than the buoyant pressure scale, which shows the jet can easily pull the smoke in due to this pressure gradient. The non-dimensional analysis of this flow determined that buoyant forces would be prevalent in the flow due to the differing densities, however, the very small Richardson number shows that inertial forces from the air jet dominate over these buoyant forces. One aspect of the image I really enjoy is how the image draws your eye to certain feature in the image. At first my eye is drawn to the bright white smoke, which then indicates it is being acted on by some external force. Then, your eye is drawn to the air compressor outlet in the bottom left, which shows that there is interaction between these two elements in the image. Another aspect I like about this experiment is the counter intuitive nature of the flow. One would expect that the compressed air would blow the smoke away from the jet, but the smoke is attracted to the jet instead. One improvement I would like to make to this image would be to have a dark, uniform black background. This would reduce post-processing steps that could take away from the flow characteristics. Future iterations of this experiment could include varying the air jet strength or performing the same experiment with a liquid jet in a tank.

References

[1]Morton, B. R., G. I. Taylor, and J. S. Turner. 1956. “Turbulent Gravitational Convection from Maintained and Instantaneous Sources.” *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 234, no. 1196: 1–23.
[2] Turner, J. S. “Turbulent Entrainment: The Development of the Entrainment Assumption, and Its Application to Geophysical Flows.” *Annual Review of Fluid Mechanics* 18 (1986): 31–64.