Post Combustion Exhaust Flame

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Team First Report

MCEN 5151: Flow Visualization

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Introduction

The Post Combustion Exhaust Flame image was captured as part of the first team project in a flow visualization class. The photography and setup of this image was done with the help of my teammates, Beck Hermann and Domenic Decaro. The goal of the image was to capture flame coloration, turbulence, and the development of fingering patterns. The blue coloring of the flame is due to oxygen-rich combustion that is occurring after the combustion chamber in the engine. The flame exits the exhaust pipe as laminar flow and as it extends outwards, it develops into turbulent flow. The transition between laminar and turbulent flow captured shows the effects of viscosity, momentum, and thermal gradients in the flame. The scientific intent of the photo was to capture the transition from laminar to turbulent flow and the capture a reacting flow. The artistic intent of the photo was to capture vibrant flame colors that contrast against the dark background.

Setup

The setup of this image included a stationary 2011 Yamaha FZ8 bike with an exhaust pipe attachment. The bike had an 800cc 4-stroke gasoline power motor. The shooting of this image was all done at night, in order to illuminate the flame as best as possible. First the engine needed to be warmed up before producing exhaust flames.

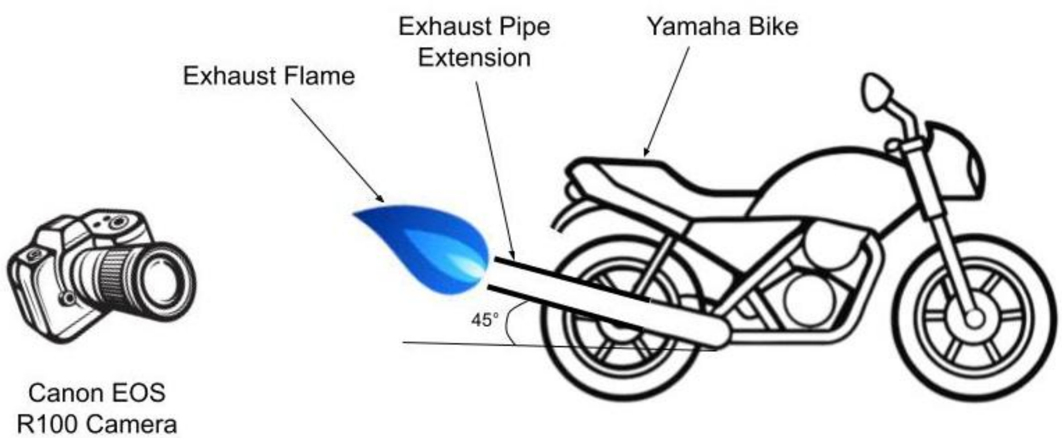

Figure 1. Flow apparatus setup diagram

Once the engine was sufficiently warm, the bike was parked in a dark area away from any light sources. For a sense of scale, the diameter of the exhaust extension outlet is approximately 3 inches (7.62 cm). The angle of the exhaust pipe is about 45 degrees from horizontal, although it does not appear at this angle in the final image. Once the bike is stationary and the cameras were ready, the motor was revved in order to produce exhaust flames in a stationary setting. All safety precautions were followed during this flame experiment. The experiment was conducted outside with proper ventilation, and all team members were several feet away from the exhaust pipe exit. The timing of this experiment is extremely important. Once the engine has been warmed up, the flames exiting the flame ignite and are extinguished extremely quickly. Post processing analysis done shows that most exhaust flames lasted only 0.07 seconds. Since the exhaust flame ignited at unpredictable times, in order to capture the flow physics in the flame we took videos of the flame instead of still images.

Flow Physics

The flow observed exiting the motorcycle exhaust is a visualization of a reacting jet transitioning from laminar to turbulent flow. At the outlet of the exhaust, there are less forces acting on the flow, so it flows as a laminar jet. The laminar flow is seen in the image as the narrow, smooth, blue-colored flow closer to the outlet. As the flow develops throughout the flame, shear and viscous forces cause instabilities and introduce turbulence in the flame. The turbulent portion of the flame can be seen in the image further left, where billowing and fingering structures start to form.

In order to perform a quantitative analysis of the flow physics occurring, we will conduct a non-dimensional analysis of several fluids parameters than can characterize our flow, and confirm our assumptions we see in the image. Before this analysis, we need to understand the general scale of our flow.

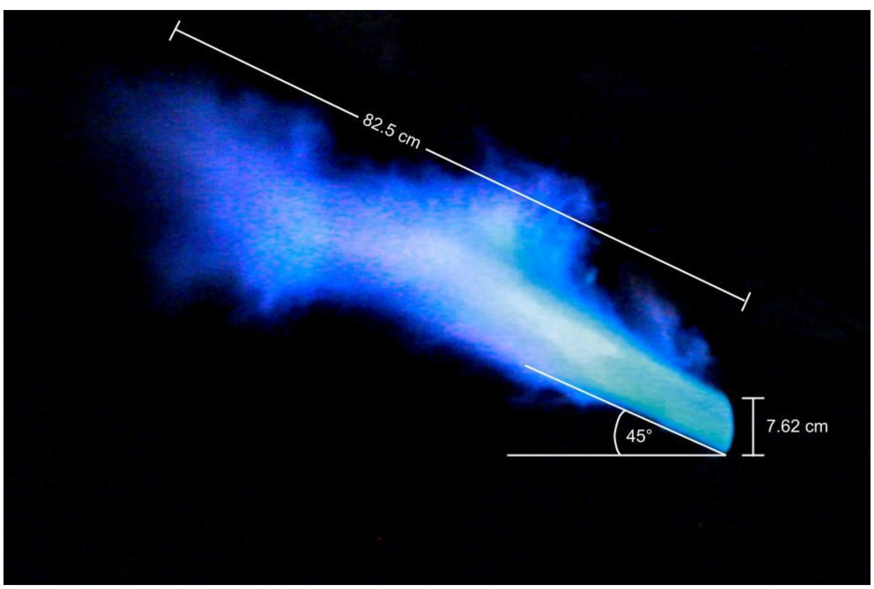

Figure 2. Reference dimensions for estimating flow physics parameters.

The first non-dimensional number we will evaluate in our flow analysis is Reynold's number. This non-dimensional number will relate the inertial forces to viscous forces present in the jet. The Reynold's number is defined as:

$$Re = \frac{\rho U L}{\mu}$$

Where ρ is the density of the gas mixtures in the flame, U is the exit velocity from the exhaust, L is the characteristic length of the flow and μ is the dynamic viscosity of the flame. We will assume the exhaust gas density is similar to that of heated air at the temperature of 1800 K, which is approximately $0.3\ \frac{kg}{m^3}$, and we will estimate the dynamic viscosity to be $\mu = 4 \cdot 10^{-5}\ \frac{Pa}{s}$. We will estimate the jet velocity to be approximately $12\ \frac{m}{s}$. This exit velocity allows the exhaust gases to reach the full 82.5 centimeter flame length within the 0.07 seconds that the flame appeared on camera. We also have measured the outlet diameter of the exhaust to give our characteristic length of $L = 7.62\ cm$. Plugging these values into the Reynold's number equation we get:

$$Re \approx \frac{\left(0.3\ \frac{kg}{m^3}\right)\left(12\ \frac{m}{s}\right)(0.0762\ m)}{\left(4 \cdot 10^{-5}\ \frac{Pa}{s}\right)} \approx 6858$$

The Reynold's number, $Re = 6858$, indicates the amount of turbulence in the flow, and also indicates the transitional regime from laminar to turbulent. Existing research shows the jet flame in the order of 10^3 to 10^4 typically exhibit this mixed transitional period in the flow.[1] The Reynolds number calculated above is in the middle of the range found in literature, which shows our flame is undergoing a transition from laminar to turbulent flow. As the flame gets farther from the exit of the exhaust pipe, the Reynold's number will increase, which means inertial forces will start to dominate compared to viscous forces.

The second non-dimensional number we will use in our analysis is the Richardson number. This parameter compares buoyancy forces acting on a flow to inertial forces. The Richardson number is defined as:

$$Ri = \frac{g \Delta\rho L}{U^2}$$

Where g is the acceleration due to gravity, and $\Delta\rho$ is difference in density between the ambient outside air, and the exhaust gases. We can estimate that the hot exhaust gases (assuming air) are approximately $0.9\ \frac{kg}{m^3}$ less dense than the cool surrounding air. Plugging our values into the Richardson number we get:

$$Ri \approx \frac{\left(9.81\ \frac{m}{s^2}\right)\left(0.9\ \frac{kg}{m^3}\right)(0.0762\ m)}{\left(12\ \frac{m}{s}\right)^2} \approx 0.00467$$

Since the Richardson number approximation , $Ri \approx 0.00467 \ll 1.0$, the above calculation shows that inertial forces dominate near the outlet of the exhaust. In contrast, as the hot gases flow away from the nozzle into the atmosphere, they slow, which causes the Richardson number to increase. A larger Richardson number further away from the exhaust shows that towards the end of the flame, Buoyancy forces do affect the shape of the flame, do to the less dense exhaust gases flowing through the denser cool air. The Buoyancy forces can be seen starting about halfway through the flame, where it slightly bends upwards away from its original trajectory. The bending of flames due to Buoyancy is a known existing phenomenon that has been previously researched in jet flames transitioning from laminar to turbulent.[2]

The final non-dimensional number we will consider in the analysis is the Damköhler number. This parameter compares the flow timescale to the chemical timescale. In the case of this image, the chemical reaction occurring is the combustion time for the exhaust flame. The Damköhler number is defined as:

$$Da = \frac{\tau_{flow}}{\tau_{chem}}$$

Where τ_{flow} is the time scale of the exhaust gas flow, and τ_{chem} is the time scale of the chemical reaction. In the exhaust flame image, τ_{flow} can be calculated dividing the characteristic length of the flame (exhaust outlet diameter) by the exit velocity of the exhaust gases.

$$\tau_{flow} = \frac{L}{U} \approx \frac{0.0762\ m}{12\ \frac{m}{s}} \approx 0.00635\ s$$

In order to estimate the time scale of the combustion occurring, we can reference existing literature. Given a hydrocarbon fuel burning at atmospheric pressure, we can approximate that the time scale of combustion is approximately on the scale of 10^{-3} seconds.[3] Plugging in our time scale values to the Damköhler number equation:

$$Da \approx \frac{0.00635\ s}{10^{-3}\ s} \approx 6.35$$

This Damköhler number shows that the timescales of the flow and the combustion reactions occurring are on the same order of magnitude, and therefor are relatively close to $Da = 1$. The time scales on the same order of magnitude indicate that neither the chemical kinetics nor flow dynamics are dominating, so they are coupled. This coupling leads to a more sensitive flame structure and local disturbances in the flame. Since the chemistry time scale is similar to the flow timescale, these disturbances can be seen directly in the flame as wrinkling, fingering, and tip-splitting instabilities.[4]

These three nondimensional numbers quantitively confirm the flow physics we are observing in the image. The Reynold's number, $Re \approx 6858$, is in the transitional range of Reynold's numbers, in the order of 10^3 to 10^4, which confirms the flame is transitioning from laminar flow at the outlet, to turbulence later in the flame. The Richardson number, $Ri \approx 0.00467$, is significantly less than one, which indicates that inertial forces dominate the flow over buoyancy. The

Richardson number also shows how buoyancy forces start to affect the flame later in the flow as gas velocity decreases, which can be seen in the image with the slight bending upwards of the flame. The Damköhler number shows that the timescales of the flow and the combustion reactions occurring are on the same order of magnitude, which influences the disturbances structures in the turbulent portions of the flow.

Visualization

In order to visualize the fluid physics and instabilities described above, specific lighting was needed to enhance the exhaust flame color and geometries. No dyes or tracers were needed to visualize the flow. The experiment was done at night when it was completely dark outside. The dark background was necessary to see details in the flame that could not be seen in excess of light during the daytime. The experiment was performed away from any streetlamps to minimize unwanted light. There was one unavoidable light source, which was the taillight of the motorcycle as seen on the left in Figure 3, but this proved to not affect the visualization of the flame. The absence of lighting allowed the flame to be extremely distinguished in the black background.

Photography and Post-Processing

The image was captured using a Canon EOS Rebel T3i digital camera. In order to capture the extremely quick exhaust flames, a continuous video was taken to capture several exhaust flame instances. These flames lasted for approximately 0.07 seconds. Using a video processing code, my teammate was able to extract images when the flame appeared on camera. From there the best images were selected for post-processing. The field of view of the image was approximately 165 by 93 centimeters. The camera was positioned about 50 centimeters from exhaust pipe, held horizontally to the ground using a tripod. Before the flames started the camera was focused on the end of the exhaust pipe to get an initial focus for the image.

For the original video, a focal length of 29 mm was used, and the exposure setting was set to automatic, so the aperture of the video varied from F4.5 to F6.3. The ISO setting on the video was also set to automatic. The video was shot in Full High Definition at 29.97 frames per second. With this frame rate, and the fluid velocity of 12 $\frac{m}{s}$, the flow moves approximately 40 centimeters during the frame, which is significant relative to the image scale. The significant movement of the flame during the frame causes blur in the image. If this experiment was to be repeated, a video shot at 60 frames per second may be about to reduce blur in the final image. The original image pulled from the video was 1920 by 1080 pixels in size. No flash was used, as low light conditions were needed to capture the colors and fluid physics in the flame.

Post-processing and editing of the image were aimed at emphasizing the vibrant colors of the flame and the fluid physics described above. All image editing was done in Dark Table.

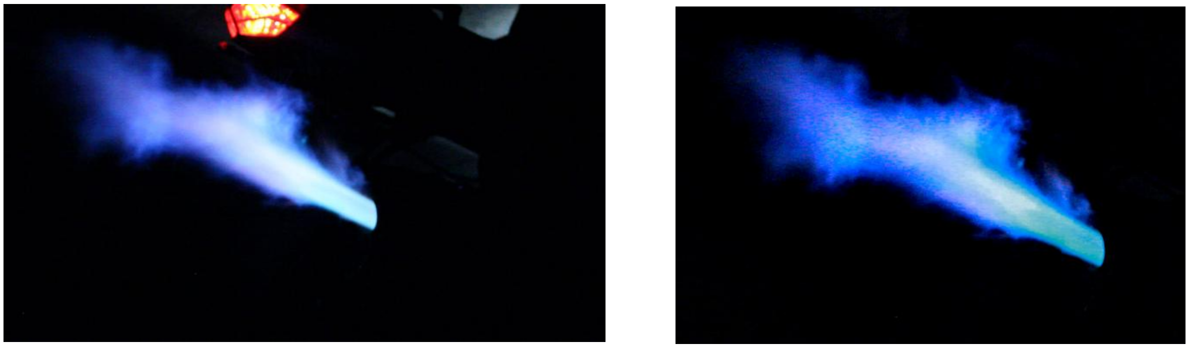

Figure 3. Side by side images of unedited image (left), and final image (right)

First the lighted portions of the image including the taillight and reflections on the bike were removed and made black to blend in with the rest of the background. This correction was done using the retouch tool, performing a clone using black areas elsewhere in the image. A crop was then made to center the flame in the image and minimize black space. The image size after cropping was 1300 by 861 pixels. Next, the blues and purples in the image were increased in saturation using the color zones tool. These coloring edits increase the contrast between the flame and the dark background, enhancing the flow physics and colors seen in the flame.

Conclusion

The final image reveals a laminar-turbulent transition state flame that is amazingly brought out by the blue colors due to lean combustion. The image clearly shows a transition from laminar to turbulent flow while showing inertial versus buoyant forces, and instabilities due to chemical kinetic timescales. One thing I really enjoy about this image is the contrast distinct shape of the circular exhaust outlet seen in the right side of the image. The way the laminar flow starts from complete darkness is fascinating to look at. One aspect about the image that I would like to improve is to have the flame in focus, rather than the exhaust outlet. The flow near the exhaust appears much sharper since it is closer to exhaust pipe where the focus was set. The image fully satisfied my intent, as it properly shows the fluid physics of a transitioning turbulent flame. In future experiments, it would be interesting to see how different chemicals introduced in the exhaust pipe could affect the coloration in the flame.

References

[1] Chen, J.-Y., & Driscoll, J. F. (1988). The role of turbulence in the stabilization of lifted turbulent jet flames. Combustion and Flame, 73(3), 283–301.
[2] Huang, Y., & Yang, V. (2009). Dynamics and stability of lean-premixed swirl-stabilized combustion. Progress in Energy and Combustion Science, 35(4), 293–364.
[3] Smith, G. P., Crosley, D. R., Golden, D. M., & Frenklach, M. (1985). Flame structure and detailed chemical kinetics: An experimental and modeling study. Symposium (International) on Combustion, 20(1), 887–901.
[4] Driscoll, J. F. (2008). Turbulent premixed combustion: Flamelet structure and its effect on turbulent burning velocities. Progress in Energy and Combustion Science, 34(1), 91–134.