Exhaust Back Fire

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FlowVis MCEN 4151

Team First

Domenic DeCaro

Beck Hermann

Duncan Laird

Introduction

This image was captured for the team first project in Flow Visualization. The project involved capturing the visual and physical character of a flame formed during post-combustion from the exhaust of my 2011 Yamaha FZ8 motorcycle. We tried to capture the fluid flow dynamics involved, focusing on the regime of laminar-to-turbulent flow and the vivid colors resulting from high-temperature oxidation. Duncan and Beck focused on photographing and video recording the flow, while I controlled the motorcycle's throttle to produce the backfire flames. The intent of my photo was to isolate the form of the flame, emphasizing the color and movement of the fluid and eliminating background clutter.

Flow Setup and Physics

My 2011 Yamaha FZ8 motorcycle, powered by an 800cc, 4-stroke gas engine, comprised the flow apparatus. The engine was first taken up to operating temperature by running it first in order to get high enough exhaust temperatures for combustion. The shot was taken at night to ensure that the flame would be visible and not washed out by other light sources. The exhaust port is roughly 3 inches (7.62 cm) in diameter and is angled roughly 45 degrees upward. Flames were achieved by revving at high RPM, then residual fuel in the exhaust gases would ignite when exposed to oxygen-rich air.

The observed flame is due to a phenomenon referred to as post-flame oxidation. If the exhaust system is holding unburned hydrocarbons and is exposed to residual combustion heat (up to approximately 1000 K), those hydrocarbons will combust when in contact with fresh air (Vera 2011). The exhaust is jet of reacting flow, which is initially laminar when leaving the exhaust tip but quickly turns into turbulent flow since instabilities develop due to velocity and temperature gradients. A Reynolds number calculation can be utilized to approximate this behavior. The exhaust exit velocity is approximately 12 m/s (this is a guess), exhaust diameter is 0.0762 m, density of hot exhaust gases is around 0.3 kg/m^3, and dynamic viscosity is around 4×10^{-5} Pa·s.

Plugging these in: $Re = (\rho UL)/\mu = (0.3\ kg/m^3 \times 12\ m/s \times 0.0762\ m) / (4\times10^{-5}\ Pa\cdot s) \approx 6850$.

This Reynolds number places the flow in the regime of transitional flow from laminar to turbulent flow. The flame begins as a thin, smooth region near the exhaust outlet but quickly develops shear-layer instabilities that result in billowing and fingering structures downstream. These are characteristic of turbulent combustion and are a function of the interaction of viscous, buoyant, and inertial forces.
In addition to inertial and viscous effects, buoyancy contributes slightly to the motion of the flame as hot gases are displaced upward by surrounding cooler air. The intense blue color in the photo results from oxygen-rich combustion, which burns hydrocarbon fuel to its fullest extent and emits shorter, more energetic light wavelengths (Gao 2022).

Visualization Technique

The experiment was done outdoors in the black, open area for safety reasons and to eliminate external light sources. There were no additives or dyes used—the light of the flame provided all of the colors seen. The black background and lack of illumination in the surrounding environment made the blue flame especially prominent. Safety precautions were taken at all times; all personnel remained at a safe distance from the exhaust, and the motorcycle was operated in a well-ventilated area.

Photographic Technique

The picture was captured using a Canon EOS Rebel T3i digital camera.
The camera was positioned around 0.5 meters away from the exhaust tip on a tripod.
Focal Length: 29mm
Exposure setting: F4.5 to F6.3
Automatic ISO
Quality: HD (1920x1080)
FPS: 29.97

Frames were extracted from the video using code to detect any frames with blue pixels. From around 50 photos I picked the one I thought captured the flow best. I lowered contrast slightly, increased highlights to emphasize the structure in the flame, and turned up the saturation in order to bring out the blue, orange, and purple coloring. The image was then cropped such that the flame would be centered and clipped from the surroundings. Finally, I used a magic eraser tool to remove the red taillight and other visible parts of the motorcycle and surroundings, leaving the flame well suspended in black space.

Discussion and Conclusion

The final photograph realistically captures the inception of laminar-to-turbulent flow in an exhaust-gas reacting jet. Smooth upstream area near the exhaust outlet progresses to a billowing, complex flame front showing the unsteady character of the flow. Aesthetically, I am satisfied with the colorfulness and isolation of the flame against the crisp black background. The editing choices were effective in bringing out the depth and color contrast without burning the highlights. The blues are especially vibrant and give the image a clean, dynamic feel. Scientifically, the image illustrates the transitional flow regime of the exhaust jet and the turbulence due to shear instabilities.

If I were to optimize the image further, I would use higher frame-rate video or reduced exposure time in order to reduce motion blur and have the turbulent features better defined. Additionally, filming several occurrences of backfire in rapid succession may permit interesting comparisons of the structure of flame under closely related conditions, put I would need a highspeed camera for that. Overall, the image succeeds in my objective of depicting both the physics and beauty of combustion flow.

References

Vera, J., & Ghandhi, J. (2011). Investigation of Post-Flame Oxidation of Unburned Hydrocarbons in Small Engines. *SAE International Journal of Engines*, 4(1), 67–81. https://doi.org/10.4271/2011-01-0141

Gao, J., Wang, X., Song, P., Tian, G., & Ma, C. (2022). Review of the Backfire Occurrences and Control Strategies for Port Hydrogen Injection Internal Combustion Engines. *Fuel*, 307, 121553. https://doi.org/10.1016/j.fuel.2021.121553

Unedited photo