Wood Flame in a Pizza Oven

Image-Video 4
MCEN 5151-001: Flow Visualization
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1. Introduction

This report will outline the setup that enabled this image, discuss the fluid dynamics involved in this image, and describe the visualization and photographic techniques used to take this image. This image was taken for the Image-Video 4 assignment for the "Flow Visualization" course (MCEN 5151) at CU Boulder. The image shows the fire coming off a log of wood that is burning in a pizza oven. The fire had been going in the oven for a few hours at the time this image was taken, but the specific log in the image had been in the oven for around 45 minutes. The oven is a large dome with a half-circle opening that the image was taken through.

2. Experimental Setup and Procedure

The main dome of the oven has an outer diameter of 20 inches. The oven opening is a tunnel with a half-circle cross section, 8 inches in diameter and 10-12 inches deep. The walls of the oven are 5 inches thick, therefore the inner radius is 15 inches. A diagram of the experimental setup can be seen in **Figure 1**. The experiment was performed by starting a fire in the oven using quartered logs that were about 3.5 inches wide. Then, once the fire had been burning for half an hour and the oven had warmed up, the wood was pushed to the back wall. Then, several small pizzas were baked in the oven and additional logs were added as needed to keep the fire going. After this, the log in the image was placed in the oven to keep the fire going. Then after the log had been burning for about 45 minutes and the flames had begun to fade, the image was taken through the opening at the front of the oven. The image was taken at night, so the only light source other than the fire was a 60-watt equivalent lightbulb behind the camera. The light was 20 feet away from the camera and to the side, so very little of its light made it into the oven compared to the brightness of the flame.

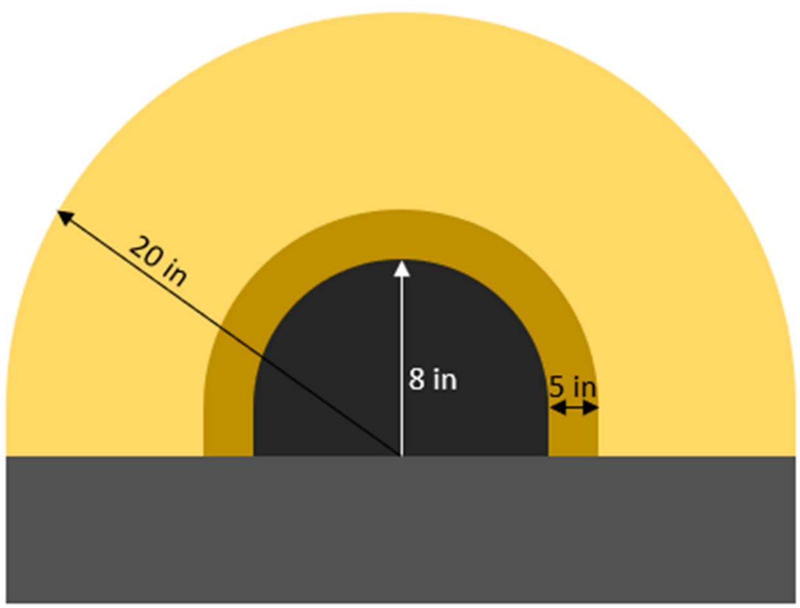

Figure 1 Diagram of the experimental setup. The fire is near the back of the inside of the dome.

3. Flow Discussion

Flames are a result of hot gasses coming off an exothermic reaction rising into the surrounding fluid. When a substance is heated, its density drops as the distance between the atoms/molecules of the substance grows. Therefore, in the case of this image, the hot gasses resulting from the combustion of the wood will be a lower density than the surrounding air and will rise due to the buoyant force on the gas. The combustion temperature of wood is around 600 degrees Celsius [1], and the kinematic viscosity (v) of air at that temperature is 9.462×10^{-5} m^2/s [3]. The flames are rising at around 1 m/s and the flame is around 0.2 m tall. Therefore, the Reynolds number of the flow is: $Re = u*L/v = 1*0.2/9.462 \times 10^{-5} \approx 2000$. A Reynolds number of around 2000 means that the flow should be mostly laminar, but there could be some parts of the flow beginning to transition to turbulence. Having a Reynolds number near this value also helps to cause the “dancing” of the flames that occur. A flow with a Reynolds number near the transition point makes disturbances in the flow grow larger and therefore cause the flickering waves that are the main features of a fire. The Reynolds number causes the instabilities to grow, but the instabilities are initially caused by the rising flow needing to push its way through the air above it. When the rising flow pushes the air out of the way, it will slow down, but it will also move to the side due to variances in the air it is moving through. This slower air now moving at a slant will then be hit by the faster rising air below it. This air below it will then move in the opposite direction of the flow it just hit because that is now the easier path for it to rise in. This causes the flow to move in a wavy motion as it rises, and these waves result in the flickering of the flames [2].

4. Visualization Technique

The fluid flow was visualized using the black body radiation emitted by the hot soot particles in the rising flow above the burning log. Particles are always emitting black body radiation, but most objects we see mostly emit in infrared wavelengths. The soot particles can be seen because they are hot enough to emit light in the visible spectrum and therefore our eyes can detect the emitted light. The log had mostly burned by the time the image was taken, so the amount of soot coming off it had greatly decreased from its maximum [1]. This caused the flame to be less bright than when it initially started burning. This meant that most of the interior of the dome was not bright enough to be seen relative to the flame and the image received a plane black background. The logs were “European Split White Birch” logs that were split into quarters about 3.5 inches wide (therefore the original logs were around 7 inches in diameter). The oven was already built at the house when my parents moved in, so it is made of an unknown material.

The experiment was illuminated by the light emitted by the flames. The image was taken at night, so there was no sunlight coming into the dome from behind the camera. However, there was a single porch light near the oven. The light is a 60-watt equivalent light bulb with a semi clear cover to diffuse the light. This light likely did not affect the image, as it was around 20 feet away from the oven, mostly to the side of the opening, and I was behind the camera blocking most of its light from reaching the opening of the oven. Therefore, the flames are the only significant light source in the image.

5. Photographic Technique

The camera used could not adjust the aperture or the focal length, so only the exposure time and ISO could be adjusted. The exposure time determines the amount of motion blur, which was the main problem in taking the image, so it was dialed in first. The exposure time was picked by decreasing it until the motion blur was small enough to not be noticeable. This kept the motion blur out of the image while keeping as much light available as possible. Once the exposure time was set, the ISO was chosen so that the flames were not overexposed and the background remained a solid consistent black. The camera was held about 2 feet from the flame, and the camera setting that the image was taken with were:

Camera:	Samsung SM-G960U (Galaxy S9)
Aperture:	f/1.5
Exposure:	1/500 s
Focal Length:	4 mm
ISO:	50
Width:	1128 pixels
Height:	907 pixels

The image was edited using Darktable and the built-in photo adjustments from the phone's camera app. I originally tried to edit the raw image only using Darktable, but I could not get the colors and detail to look as good as the image modified by the phone's built in image processing. Therefore, I used the image that the phone modified instead of the raw image. I then used Darktable to crop the image to the final shape. The unedited image can be seen in Figure 2 in the appendix.

6. Image Commentary

This image allows for a common everyday flow phenomenon to be seen and investigated. Looking into these everyday phenomena is one of my favorite types of experiments because it shows just how much we look over when we go about our days. All these beautiful details are waiting to be seen if someone takes the time to stop and look into the finer details.

This image turned out quite well. The dimmer flame from letting the log burn for a while has a smaller dynamic range than the larger flames from when the log started to burn. This lower dynamic range allows for the details of the flames to stand out more. If I were to perform this experiment again, I would try one of two things. One would be to have the flames move in a controlled pattern, such as a vortex. The other would be to have the flames flow around an object to see how the flames behave when there is something that might be taking away the heat of the flames faster than if they were just flowing through the air.

References

[1] Chris Lautenberger, Carlos Fernandez-Pello, A model for the oxidative pyrolysis of wood, Combustion and Flame, Volume 156, Issue 8, 2009, Pages 1503-1513, ISSN 0010-2180, https://doi.org/10.1016/j.combustflame.2009.04.001

[2] Xiangyang Zhou, Watit Pakdee and Shankar Mahalingam, Assessment of a flame surface density-based subgrid turbulent combustion model for nonpremixed flames of wood pyrolysis gas, Physics of Fluids 16, 3795 (2004); https://doi.org/10.1063/1.1778371

[3] Engineering Toolbox, Air – Dynamic and Kinematic Viscosity, https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html

Appendix

Figure 2 Unedited image of the flow