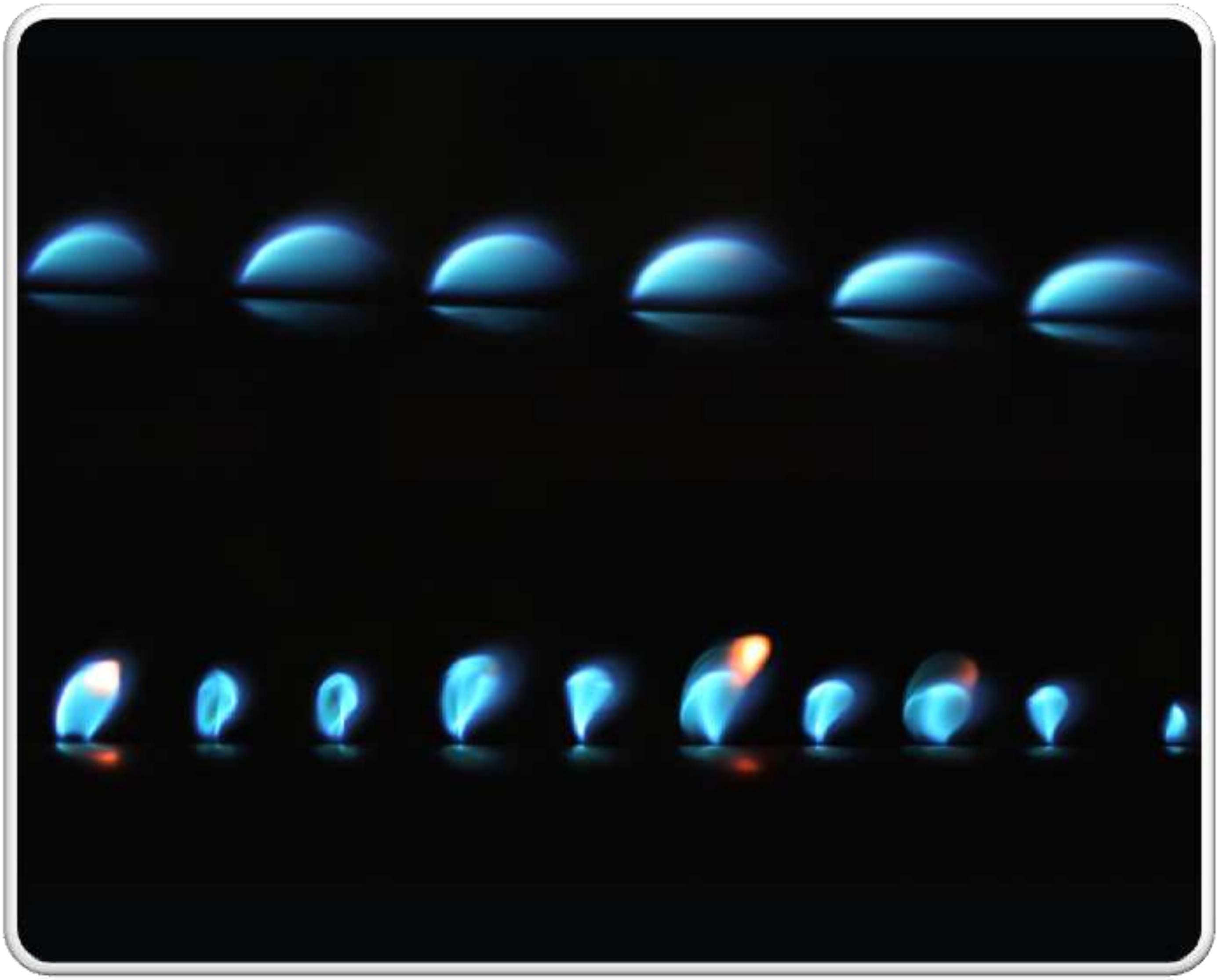
Dancing Flames



The Rubens Flame Tube

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I. Introduction

This image represents one of several shot for the Flow Visualization course Team Project 3 at the University of Colorado at Boulder with the purpose of illustrating the compressional wave nature of sound obtained and demonstrated by using a Rubens Flame Tube. The image captures the flow dynamics of sound waves represented by flame reactions to low volume sound waves created during a constant gas pressure. This report will discuss in detail the physical events that occurred in the Rubens tube, and will explain the mode at which the tube was operated when the illustrated image was captured.

II. Setup

This experiment consisted of building a Rubens tube to demonstrate a dramatic and visual representation of sound waves creating standing waves inside a tube. The buildup of this apparatus consisted of a 4 inch diameter copper tube of 60 inches in length. The tube was tightly closed at one end by a thin silicon membrane, and in the other end it was connected to a propane inlet plug allowing no leakage of gas other than into the tube. Furthermore, a row of $^1/_{16}$ inch holes was drilled along one side of the tube (these where ½ inch of length apart, giving us a total count of ~100 holes). A 4 inch speaker was connected to a frequency generator and then adapted to connect to a sound card and was sealed directly on top of the silicon membrane at the end of the tube. The speaker acted as the sound input source, sending sound waves of different frequencies down the length of the tube (see Figure 1 for setup schematic).

Before the speaker was used, the tube was filled with propane, and then the row of small holes was ignited with the use of a match. After all the holes were ignited, the speaker was put to use generating waves of different frequencies and disturbing the flames according to the differences in pressure obtained with the variety of standing waves formed in the tube. The Rubens Fire Tube was situated outside, and the "Combustion Experiment Guidelines"[1] set for the course were carefully followed. The images were taken after dusk and in a darker space to fully capture the details of the flames created by the disruption of various frequency waves. The camera was hand held and was positioned at different angles and distances from the Ruben Flame Tube. These images, in particular, were taken looking down the length of the tube at a distance of roughly 10 cm from the tube.

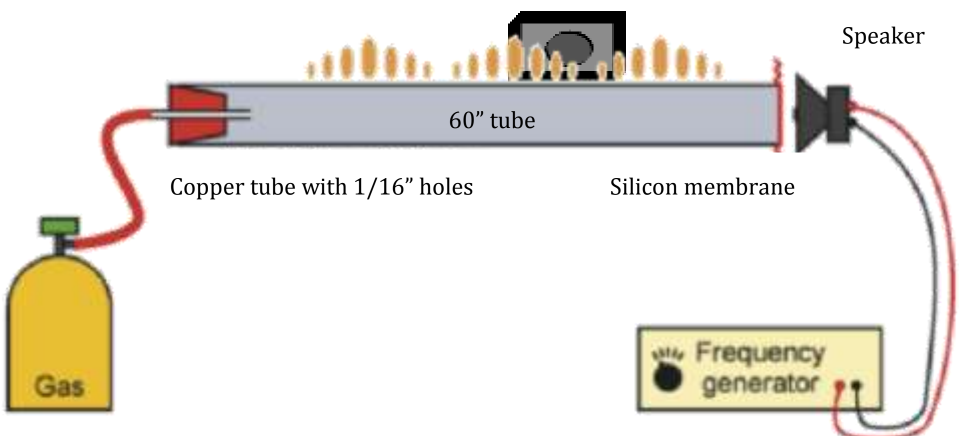


Figure 1: Setup Schematic

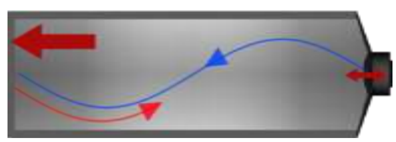
III. Photography

The photograph of the two-image sequence captured using the Rubens Flame tube was collected using a Canon EOS Rebel XS, digital SLR. The camera was set to manual operation to appropriately adjust the exposure, shutter speed and aperture according to what was appropriate for the image. The lens focal length used was 55 mm for the first image and 32 mm for the second to focus on the desired details of the flames, respectively. The image was exposed with an aperture value of f/5, a shutter speed of 1/13 sec and an ISO speed rating of 1600 without having the flash fired to prevent over exposure. The original image was exposed enough that no lighting adjustments were made. However, the contrast and saturation of each image in the sequence were slightly adjusted independently from the original image to highlight the outlines and colors of the flames as best as possible. The cropping tool was utilized to remove unnecessary space from both images and to focus primarily on the flames. After the two images were manipulated to obtain the best results, they were then merged to create the final sequence with a final image resolution of pixel dimension [X: 4207, Y: 3346]. All of these adjustments were made using Photoshop.

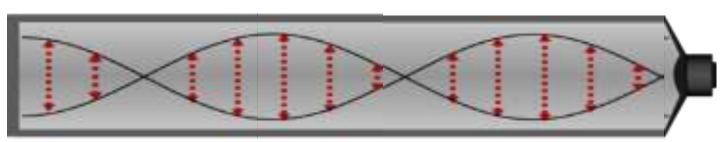
IV. Analysis

German physicist Heinrich Rubens created the first Rubens tube in 1904. Through this invention, Rubens demonstrated a dramatic and visual representation of sound waves creating standing waves in a pipe. Sound waves consist of alternating regions of high and low pressure. The speaker emits the sound waves into the pipe, and they travel back and forth along the tube. As the waves travel inside the tube, they reflect back and forth from each end of the tube creating standing waves. Constructive and destructive interference of the sound start to take place, and as a result, the pressure differential of the reflected waves is mirrored by the ignited row of flames on the tube surface.

As the speaker begins to vibrate, it sends a series of continuous waves of air, at the sound of speed, that are reflected at the opposite end of the tube, producing two identical sound waves traveling in opposite direction. Characteristics of the sound waves come from the back and forth vibration of the particles of the medium (in this case propane gas) through which the sound wave is moving. The sound is continuously produced by the speaker. Therefore, sound traveling in one direction along the tube encounters sound traveling in the opposite direction causing the waves to interfere with each other. In places where two high-pressure regions overlap, constructive interference (antinodes) occurs, and the wave amplitude increases. Where high pressure encounters low pressure, destructive interference (nodes) occurs, and the wave amplitude may drop to zero. The left to right motion of this sound wave displaces gas particles both toward the right and left as the energy of the wave passes through making the sound wave a longitudinal wave. This sequence of events is represented in Figure 2 as standing waves of sound[2].



The speaker vibrates creating compression in the gas (sound waves) that travel down the Ruben Flame Tube. The initial wave sent along the length of the tube is reflected back when it collapses with the other end of the tube. Thus, two waves are created and move in opposite directions.



Pressure variations are represented by the red doted lines

If the wave length is in accordance with the length of the tube (or the length of the tube is an odd multiple of a quarter of the wavelength), the two waves will add together to form a standing wave. This standing wave contains areas where the pressure varies significantly (antinodes) and others where it is constant (nodes)

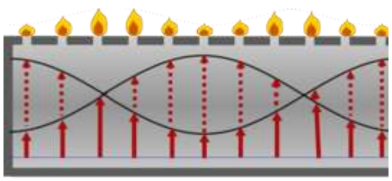
Figure 2: Sequence of events and description of standing wave formation upon constructive and disruptive interference.

In the Rubens Flame Tube, the holes act as a damping, broadening the resonance and allowing it to form patterns even when the wavelength is not completely accurate. Usually a resonance will occur in the pipe when the length of the tube is an odd multiple of a quarter of the wavelength (see equation 1). The average pressure at all points of the tube is the same. However, the reactions of the flames depend on the local, time-dependant pressure changes due to the sound wave interference or any changes in the gas pressure itself. Rubens actually discovered that his creation behaved in two completely opposite ways, or that it was possible to achieve two different modes of operation by varying the main factors (the pressure of sound waves or gas)[3]. For a constant sound intensity, the flames will typically be highest at the anti-node of the standing wave (the oscillating pressure node). If the gas pressure is reduced, the flames at the nodes will be the highest. On the other hand, for a constant gas pressure, a high sound volume results in high flames at the nodes and vice versa at low sound volumes[4].

$$\lambda = 4L/n, \text{ where } (n = 1, 3, 5\ldots)$$
$$\lambda = \text{wavelength}$$
$$L = \text{length of tube}$$

In this report, only the constant gas pressure mode at high volumes is discussed in detail, which was the mode at which the portrayed image was captured. With the assumption that conditions such as temperature, the length of the tube and gas pressure were kept constant, the following physical dynamics occurred in the Ruben Flame Tube.

For reasonably small pressure differences, the flow of gas though the holes is described by the Bernoulli's principle that states that, "The gas flow is proportional to the square root of the pressure difference between the inside and the outside of the tube." The qualitative behavior that is usually labeled with the term "Bernoulli effect" is the lowering of fluid pressure in regions where the flow velocity is increased[5]. This relationship in the Rubens Flame Tube, at the mode being described, means that the time average of the flow is reduced at the points with oscillating pressure and thus flames are lower at these locations (antinodes), whereas the flow at the nodes is increased creating larger flames. [2]. See sketch below and Figure 3 for a visual understanding.



The areas with oscillating pressure (high sound volume parts of the tube) produce shorter flames due to the reduction of gas flow within those areas (represented by solid red arrows), whereas the areas with the smaller changes in pressure (low sound volume parts of the tube) produce longer flames due to the increment of gas flow within those areas.

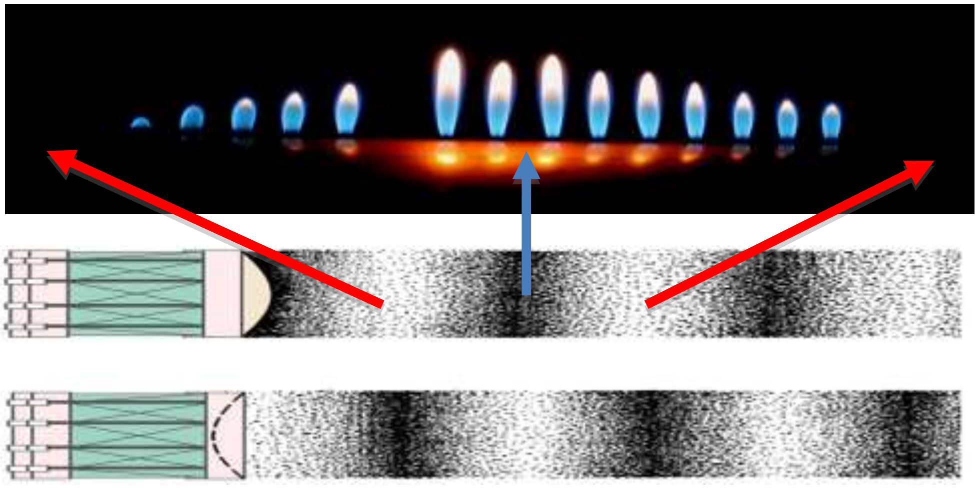


Figure 3: Drawing of a pressure wave where the darker areas represent (in this specific case) a higher gas molecule concentration and thus a higher gas flow (nodes), and similarly the lighter areas signify lower gas flows (antinodes).

Another reaction that occurred in the Rubens Flame Tube that was captured in this image is the combustion of a mixture of propane gas and air illustrated by the color of the flame. This image was captured while the tube was still being filled with propane gas, thus there was enough concentration of air in the tube to produce an oxygenated mixture of propane and create a nearly pure blue in color flame. With increasing oxygen supply, less blackbody-radiating soot was produced due to a more complete combustion and the reaction created enough energy to excite and ionize gas molecules in the flame, leading to a blue appearance (see Figure 4 for example)[6]. The amount of air in the tube as it filled with propane was enough to initially create an oxygenated mixture of propane making the combustion “cleaner” and forming the blue flames seen in the image.

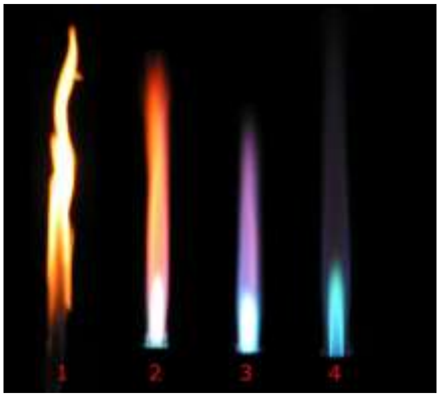


Figure 4: Example of different flame types of a Bunsen burner dependent on oxygen supply. On the left, a rich fuel with no premixed oxygen produces a yellow sooty diffusion flame; on the right, a lean fully oxygen premixed flame produces no soot and the flame color is produced by molecular radicals, especially CH and C2 band emission[6].

V. Conclusion

There was a collection of almost 400 images captured while performing this experiment. The collection covered images from standing flame waves representations (as seen in Figure 3), snapshots of shooting flames due to the high volumes the tube was subjected to and close-ups of nodes and antinodes captured at different frequency settings and different types of tunes. The sequence chosen to represent the physics of these dynamics was taken while the tube was operated at constant gas pressure and high volumes, as previously described, and focused on the nodes reaction (the larger flame section of flames at this mode). These were two snapshots taken at different settings of this mode’s timeframe: (1) with no sound application to the tube, and (2) after the speakers were producing sound. The mixture of air concentration in the tube was still present because both of these images were taken as the tube was still being filled with propane. The flames are blue due to the formation of an oxygenated mixture of propane in the tube creating a cleaner combustion.

The standing bubbles, captured when the gas flow was constant and still lower in concentration (the tube was still filling), depict such a calm and peaceful environment. The flames look like floating drops of water that create a feeling of touch, cold rather than hot. The second snapshot was captured after sound was being played through the speakers. This image of dancing flames was captured at a high volume but with calm tunes playing through the speaker. Dancing flames were only seen at the nodes during the setting of lower concentration of gas. Calm and peaceful again, with more gas concentration in the tube, since the yellow flame began to appear, these flames depict small dancing ballerinas. The power this Ruben Flame Tube possesses to exemplify the physics of sound waves through fire is shocking. To see the reaction of sound and gas pressure differentials depicted in flames is an amazing visualization.

[1] J. Hertzberg, Flow Visualization Course (2010) <www.colorado.edu/MCEN/flowvis/course/CombustionGuidlines.html>

[2] D. Ansell, The Naked Scientists (2010-2011) <http://www.thenakedscientists.com/>

[3] FYSIKBasen.dk, The Ruben Flame Tube (2008) < http://www.fysikbasen.dk>

[4] G.W. Ficken and F.C. Stephenson, The Physics Teacher, 17 306 (1979).

[5] C.R. Nave, Hyperphysics (2010) < http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html>

[6] Wikipedia, Flames, (2011) < http://en.wikipedia.org/wiki/Flame#cite_note-7>