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Team First Image Report

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Waves of Fire – Ruben's Tube Experiment

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Figure 1: Edited team first image

The image shown above in figure 1, was captured using a Ruben's tube as part of the Flow Visualization First Team Project. The goal for this photograph was to visually illustrate the effects of a standing sound wave on local pressure with respect to time. Without the addition of fire, the standing sound wave would be nearly impossible to see or produce. However, the use of propane gas which has been ignited provides the perfect medium to view the gradients in pressure. The Ruben's tube was built with materials purchased by Aaron, constructed by Byron, Robbie, Aaron and I, speakers and guitar provided by Evan and liquid propane supplied by myself. Overall, I'm very pleased with the way that the image came out, as it has a striking feel and demonstrates the troughs and peaks quite well.

The image was captured using a basic Ruben's tube setup, where we took a 5 ft long section of aluminum ducting and drilled $^{1}/_{16}{}^{th}$ inch holes at ¾ inch intervals, offset from each edge by 4 inches (to protect the speaker). The designs for our Ruben's tube were provided by JoshTheEngineer.com [1] which had detailed instructions and a helpful bill of materials. Total cost split between the team was around $70 excluding the price of the propane. In this design, we had 136 small holes for the propane to pass through, all in a straight line along the top surface of the tube. A diagram demonstrating our setup is shown on the next page in figure 2, with the camera held adjacent to the amplifier. The propane was fed into the tube using a threaded and barbed hose connection, which we sealed with ducting tape after threading it into the tube. The barbed end of the connector was pressed onto a 5 ft section of vinyl hose, which lead to a brass barb and thread connection on the other end. We then connected this hose connection to a ball valve for easy adjustment of the flow rate. From there, we threaded the valve onto a universal liquid propane regulator, which was connected to the outlet of the propane tank. All experiments were performed with the tank's valve completely open, such that the flow rate was controlled primarily by the ball valve.

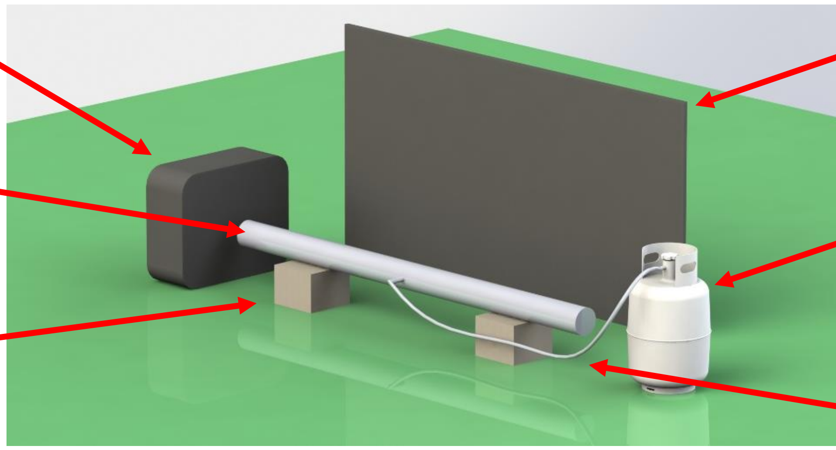

Figure 2: Diagram of experimental setup

Calculation 1:

Flow rate through each of the 136 holes – and the relationship to centerline velocity. The flames coming out of the tube for my final photograph were when the ball valve was set to 1/3 open and appeared to be equivalent to the flames coming from a standard barbeque. Using this assumption and the figures provided by [3] I can find the flow rate of liquid propane through the whole tube:

$15\ \frac{lb}{tank} \cdot 21{,}591\ \frac{BTU}{lb} = 323{,}865\ \frac{BTU}{tank}$ and with a typical burner consuming $40{,}000\ \frac{BTU}{hr}$ we can get the number of hours that a tank lasts: $323{,}865\ BTU\ /(40{,}000\ {}^{BTU}/_{hr}) = 8.09\ Hrs$

Given this time frame from full to empty, and the fact that this tank contains 15 lbs of propane, the volumetric flow rate through the whole tube can be calculated. Assuming the state after expansion through the regulator is gas at 1 atm and 65°C (similar but not exactly the conditions of the day) the density is: $1.796\ \frac{kg}{m^3}$ [4]. Therefore:

$6.8\ kg \Big/ 1.796\ \frac{kg}{m^3} \cdot 8.09\ hrs = 0.468\ \frac{m^3}{hr}$ through all of the 136 holes gives: $0.003\ \frac{m^3}{hr \cdot hole}$

Now the area of the hole can be used to find the average velocity of the flow. 1/16th of an inch is equal to $0.00159\ m$ which is the diameter of the hole. The area is: $\pi * (\frac{0.00159\ m}{2})^2 = 1.986 \cdot 10^{-6}\ m^2$

The average velocity is: $0.003\ \frac{m^3}{hr \cdot hole} / 1.986 \cdot 10^{-6}\ m^2 = 1510.6\ \frac{m}{hr} = 0.419\ \frac{m}{s}$

Calculation 2:

Reynolds number – and the relationship to laminar and turbulent flow through each of the holes

The Reynolds number is given by: $Re = \frac{\rho\, u\, L}{\mu}$ where *u* is the velocity, *L* is the characteristic length and μ is the dynamic viscosity. $\mu = 8.196 \cdot 10^{-6}\ Pa\ s$ [4], assuming a tube thickness of t: $L = \frac{Volume}{Surface\ area} = \frac{t \cdot 1.986 \cdot 10^{-6}\ m^2}{t \cdot \pi \cdot 0.00159\ m} \rightarrow L = 0.00039\ m$

$$Re = \frac{1.796\ \frac{kg}{m^3}\ 0.419\frac{m}{s}\ 0.00039\ m}{8.196 \cdot 10^{-6}\ Pa\ s} = 35.8$$

This is a very small Reynolds number, and is much less than the 2000 that would indicate transitional flow. Therefore we are well within the laminar region for the average flame. This is apparent when looking at the photograph, because we can see that all of the flames are smooth and do not appear to have any turbulence.

Calculation 3:

Standing wave resonance calculation. According to a journal article investigating flame tube resonances, the predicted resonances and the measured resonances tended to differ by some slight amount [5]. The prediction of this is that the holes drilled into the tube have a noticeable effect on the development of the standing waves. However, I don't have the resources to model these effects. The standing wave seen in the photograph developed at middle C, which is 261.6 Hz. In a closed tube, the allowed wavelengths for a standing tube are as follows: $\lambda_n = \frac{4L}{n}$ for $n = 1, 3, 5 \ldots$

Given the relationship between frequency and wavelength: $v = \lambda * f$ and the speed of sound in propane as: $v = 258\frac{m}{s}$ [6] Therefore, wavelength can be found for middle C in propane: $\lambda = \frac{v}{f} \rightarrow$

$\lambda = \frac{258\frac{m}{s}}{261.6\ Hz} = 0.986\ \mathrm{m}$ this can then be put into the previous equation to find which resonance this is: $\lambda_n = \frac{4L}{n} \rightarrow 0.986m = \frac{4 \cdot 1.54\ m}{n} \rightarrow n \approx 6$. Which diverges from theory slightly as predicted by [5]. This is an interesting case that could have been impacted by our construction or other factors that were not accounted for such as the effect of our lower pressure.

The flow visualization technique used in the creation of this photo is seeded boundary. This refers to the fact that the flow can only be seen from the heat generated by the soot in the smoke and that no individual particles can be resolved. All materials were purchased at Home Depot and modifications were made by the team. The fuel was liquid propane that was fed into the Ruben's tube from a standard 15 lb (5 gal) propane tank used for gas barbeques. Combustion was started with a kitchen lighter and only occurred outside the tube because we flushed out the air by running the propane for a few seconds before ignition. The lighting for this photo was diffuse sunlight right before sunset. This lighting provided the opportunity to focus in on the flames, because any earlier in the day and we may have had difficulties capturing the flames well.

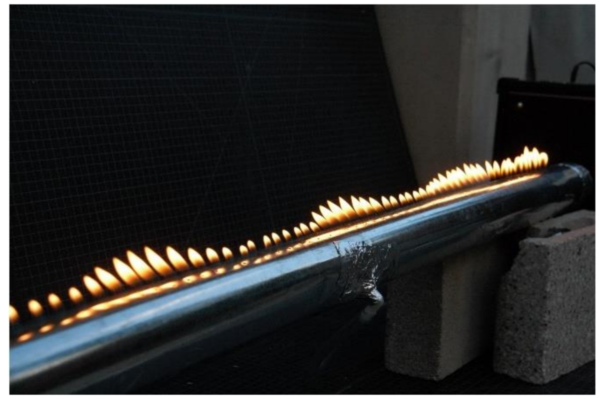

Figure 3: RAW image from camera

The image was taken using an old Cannon Rebel XTi on the full manual mode. The field of view in the final image covers a 4 foot section of the Ruben's tube, and the camera was held next to the end of the tube at about 12 inches away. As I intended, the center of the image is most sharply in focus and the areas near the edges are less sharp. Using basic trigonometry I can tell that the camera was 2 feet and 4 inches away from the center of the image. For this image I was using a wide angle (18 – 55) lens, which I had zoomed to a focal length of 40 mm. This zoom helped me cut out the cinder blocks on the sides without much cropping, and kept my depth of field fairly short. The original RAW image is shown to the right, and it has a height of 2592 pixels and a width of 3888 pixels. The two main goals for this image was to drop out the dark background, and eliminate any motion blur in the flame. Therefore, I opted for a fast shutter speed to reduce the amount of light coming in and get rid of any blur. My settings were as follows: ISO-1600, f/6.3, shutter speed 1/640 seconds. The editing was fairly limited on this photo and was performed in Gimp. I cropped out the far end of the tube, where the flame stops, while maintaining the aspect ratio. Next, I increased contrast using the s-curve in Gimp, and finally, I used the paint brush and then the healing brush feature to remove the nozzle and ducting tape from the image (can be seen towards the lower center of Figure 3). The post processing really helped bring this image to life, because I was able to bring more focus onto the flow and remove distracting elements.

To me, this image reveals the careful balance of flow in the Ruben's tube. Although the flow appears as peaceful as I intended it to be, it was tricky to get the flow to workout like this. In reality the flow was often too violent for the standing wave to be apparent or so low that the flames would go out. What I really like about this image is how well the flow is demonstrated, the whole point of the Ruben's tube is to view the effects of standing auditory waves on local pressure, and therefore flow rates from each hole. I still wonder if I should have gone for a larger depth of field to get more than just the central portion of the flames in focus. If I were to push this project further, the only changes that I would make is with the depth of field. However, I really like the final product both in a visual sense as well as how it captures the fluid mechanics.

References

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