# Schliern Z-Type Flow Visualization System – Visualization of Negatively Buoyant Plumes in Water

Nicholas Travers

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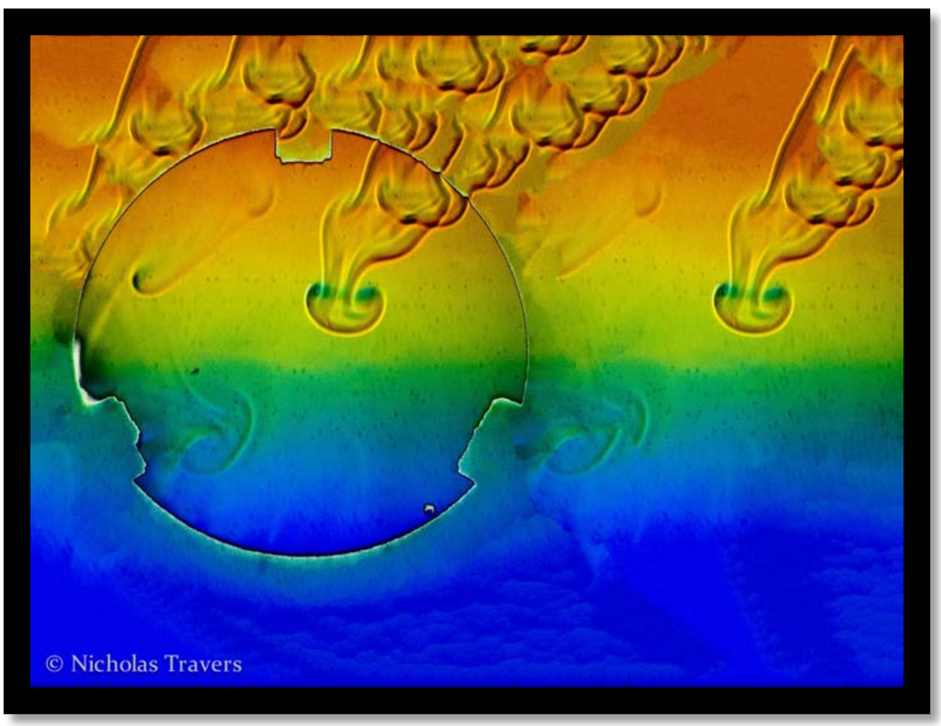
Team3 Assignment – Flow Visualization 2012

University of Colorado at Boulder



For the fifth assignment, titled *team3 assignment*, of the mechanical engineering course Flow Visualization[1] at the University of Colorado at Boulder students are encouraged to design and setup an experiment to investigate a fluid phenomenon, and use an imaging technique to demonstrate the phenomenon in an artistic and visually pleasing manner. The primary goal of the investigation done for this assignment was to setup and use a schlieren system, which are used to visualize normally invisible flow phenomena. A z-type schlieren system with a color filter was used and is described. This system was used to observe plumes of cold water falling from ice. The physics and fluid principles involved, based on the insight provided by the schlieren imaging system, are discussed. Particulars of the photographic technique are also discussed.

**Schlieren Setup**

Using schlieren systems subtle changes in transparent media can be visualized. Specifically schlieren systems are sensitive to variations in the media's refractive index, which can provide insight into temperature and density gradients. As light passes through regions with varying refractive index the light gets bent, and deviates from its normal path. This bending is called a schliere, from the German for smear. Schliere cause an effect similar to shadows on the bottom of a pool, or the shimmering mirage of heat in the desert. Using a knife-edge or filter in a schlieren system subtle temperature or density changes in a media located in the test section can be maid clearly visible.

The schlieren setup used in this investigation is a Z-type system similar to that in Figure 1. A bright light source is directed at mirror 1 and is located one focal length from the mirror. The first mirror collimates the light, which produces parallel rays of light in the test region. A second mirror then focuses the collimated light towards the camera and filter (knife-edge in figure). When a ray of light passes through the test region it is bent by changing indices of refraction and causes a schliere (Settles, 2001).

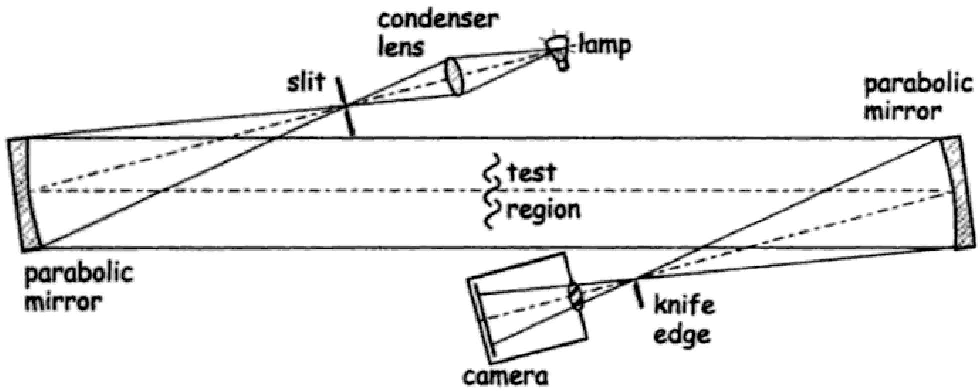



**Figure 1 - A z-type schlieren system (Settles, 2001). The system used in this investigation had twp 6" diameter mirrors with 48" focal lengths placed approximately 77" apart. A color filter was used in place of a knife edge.**

[1] The flow visualization course website can be found at: http://www.colorado.edu/MCEN/flowvis/

A point light source is important for creating a homogenous collimated beam of light, and facilitates filtering the light at the knife or filter (Settles, 2001). For a light source a LED headlamp was placed behind a vertical slit cut in opaque acrylic using the laser cutter of the ITLL. The slit is approximately 2 mm wide and 10mm tall. The slit was useful because it approximated a point light source in one direction, which created good high contrast, and also provided bright illumination due to its length. Several additional light sources were used during the investigation. The PG&E lamp that comes with the setup, which is partially blocked by a shade with a circular cut out, performed well but was dim and images were less sharp. A 7000mcandle LED was also filed down and covered with aluminium tape to create a point light source (Ian, 2011). Unfortunately the power circuit, which included a timer to send short duration light pulses, appeared to limit the LEDs brightness and was not useable. Using aluminium tape to cover a LED headlamp also produced a good point light source which was bright and easy to adjust.

When the collimated beam is focused by the second mirror ideally a point is formed by the collimated light. The schliere however cause the light to be deflected somewhat so that it does not pass exactly through the focal point. A filter or knife at the focal point is used to filter the disturbed light. In the case of a knife-edge (Figure 2, (1)) some of the light is blocked such that the schliere produces a light or dark area in the image (Settles, 2001). When a filter is used none of the light is blocked and instead the schliere shifts the ray of light so that it passes through a particular color of the filter (Figure 2, (2)). The bullseye target filter used has a purple center followed by light purple, blue, light blue, green, yellow, orange, and is surrounded in red. Bull's eye filters are used to indicate how rapidly the refractive index is changing (Settles, 2001); red would indicate a rapid change and blue a small change.

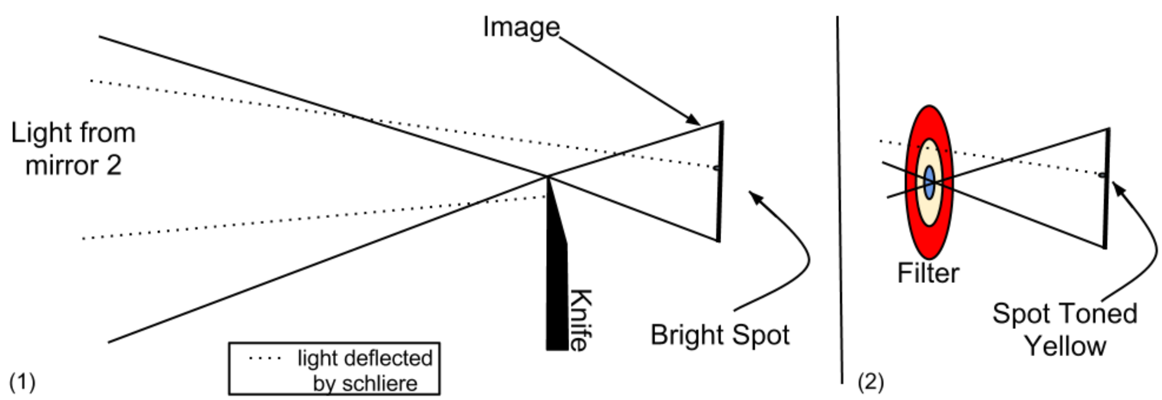



**Figure 2 – Schliere deflects light (1) past the knife edge to form a bright area in the image, or (2) through a color of the bullseye target which forms a colored area in the image, here yellow.**

For imaging the camera is placed just after the knife or filter. A long focal length lens is needed (~250mm for a 35mm camera) so that the second mirror, and the schlieren image, fills the view. It was interesting to observe that the aperture of the camera could be used as a knife edge.

**Flow Description**

To make use of the schlieren system a sheet of ice was set in a fish tank to produce the plume of cold dense water imaged. A fish tank filled with water was placed in the test region of the schlieren system so that the collimated beam of light passed through the plume of cold water beneath the ice sheet (Figure 3).

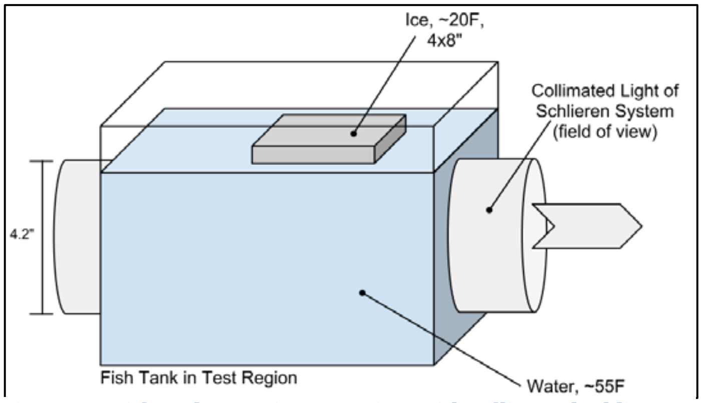



**Figure 3 – Fish tank setup in test region, with collimated schlieren system light passing through, contains a sheet of ice in ~55°F water.**

Several size ice sheets were made, including some round discs. The image presented is from an ice sheet approximately 4x8 inches in size and ¼ inch thick. The ice was oriented parallel to the collimated light such that multiple plumes are likely superimposed in the image. As the ice is melted by the warmer water on which it is floating, whose temperature is approximately 55°F, a layer of cold water forms on the underside of the ice sheet. The cold water tends to collect due to roughness of the ice surface and perturbations in the water. The collecting cold water is denser than the water below it, which is un unstable arrangement leading to formation of the Rayleigh-Taylor instability visualized (Sharp, 1984).

By interpreting the colors in the schlieren image, in comparison to the gradual tone fluctuations expected, information about the temperature and corresponding density changes in the flume can be made. For this image the bullseye target filter was aligned so that horizontal bands of color appear in the image, red above transitioning to blue below, with less variation in the horizontal direction. Examining the images in Figure 4 the predominant color shift is a red band on the lower edges of the plume. Red indicates that the light was bent up to pass through the red band of the filter, and indicates increasing density in the vertical direction. Also interesting is the

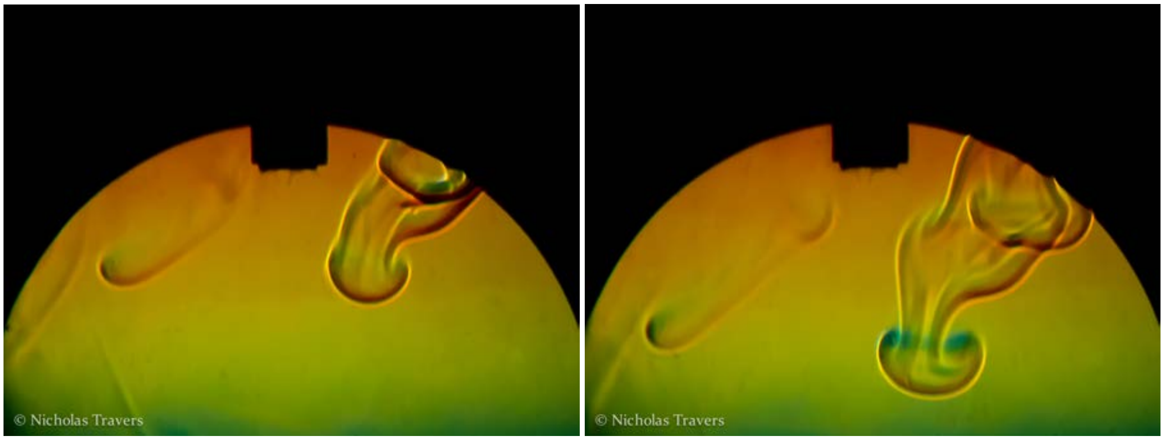



**Figure 4 - Crops of schlieren images showing development of the negatively buoyant plume.**

blue-green color shift that adds definition to a mushroom shape at the bottom of the plume. The blue color results from light being bent down by the schliere and indicates decreasing density (Settles, 2001). This indicates that the plume formed as a single column with a blunt head which then curled back on itself; in mixing with the surrounding fluid the plume warmed, and the density decreased. The plume is experiencing a second instability, the Kelvin-Helmholtz instability, due to shear forces between the cool water and the warm water. The formation of vortices of this type on the sides of plumes is not uncommon (Sharp, 1984), and a second smaller Kelvin-Helmholtz instability is faintly visible left middle of the plume.

To determine the Reynolds number of the flow the speed was extrapolated from images of the plume taken in a burst series. The images in Figure 4 were taken less than 1 second apart, in which time the plume descended approximately 0.66 inches (300 pixels at 450 pixels per inch). The Reynolds number is defined as the ratio of inertial forces to viscous forces and is estimated to be:

$$\mathrm{Re} = \frac{Ud}{\upsilon} = \frac{0.665\,in/\sec \times 0.31in}{0.0027\,in^2/\sec} = 75 \qquad \text{Equation 1}$$

where the kinematic viscosity is estimated as that of water at 32°F. This indicates that the flow is laminar, and indeed the flow appears well ordered.

**Photographic Technique**

The flow was visualized using the schlieren setup detailed above. To Photograph the image a NIKON Coolpix P7100 located behind the filter was used. The camera has a 6.0-42.6mm, f2.8 lens with image stabilizer. The aperture was left wide open to capture available light, and because when closed down the aperture would cut off some of the image. To provide clarity an ISO setting of 400 or less was desired. The light source used with the schlieren system (see above) required an ISO of 400, which allowed a moderate shutter speed of 200. At this shutter speed there appears to be vertical motion blue in the image from camera and mirror vibrations. The bottom portion of the plume is thicker than the sides by 3 pixels which is probably due to image shake as the temporal resolution of the exposure will freeze fluid flows slower than 0.8 in/sec in two pixels. The camera settings used are summarized in Table 1.

| Table 1: Camera's Image Capture Settings | |
|---|---|
| Original and final Image Size | 3648x2736 pixels |
| Resolution | 240 pixels/inch |
| Shutter Speed | 1/200 |
| Aperture | f/6.3 |
| ISO Speed Rating | 400 |
| Focal Length | 42.6 mm |
| Lens | 6.0-42.6 mm f2.8 |
| Camera | NIKON P7100 |

The image is 3648 x 2736 pixels in size and shows the original 4.2 inch circular section of the flow (reflected by the second mirror). The fill tool in Adobe Photoshop CS5 was used to interpret and pattern the imaged flow onto the surrounding negative space. The resulting image is reminiscent of a flag and I found the image more dynamic and engaging than a simple crop (such as those in Figure 4). The color and contrast of the image was adjusted some to achieve more attractive tones. The noise from using a 400 ISO setting was reduced using the luminance and detail recovery functions. The bubbles on the tank were left in the final image for their added texture. However, they were removed using the spot healing tool in Adobe Lightroom 3 for the images presented in Figure 4. The final and unedited images are appended for comparison.

**Concluding Remarks**

Setting up and using the schlieren system has been challenging but awe-inspiring, and simply inspiring, as well. This investigation explored the basics of schlieren imaging and revealed a world of possibilities to explore and refine a schlieren imaging technique. Attempts were made to improve the light source, including the construction of a timed LED light system (appended, Figure 5) which could be improved in the future. Refining the system so that quantitative measurements could be made is desired. However there is plenty to be done qualitatively to take advantage of the numerous unique styles of schlieren imaging. An experimental verification of density plots of three dimensional plumes created using computer simulations (He, Zhang, Shiyi, & Doolen, 1999) would be a challenging but rewarding and beautiful application of schlieren imaging. The schlieren systems available form the mechanical engineering department of the University of Colorado at Boulder are a wonderful resource to have and I am sure they will continue to be used to perform vital and engaging flow visualizations.

**References**

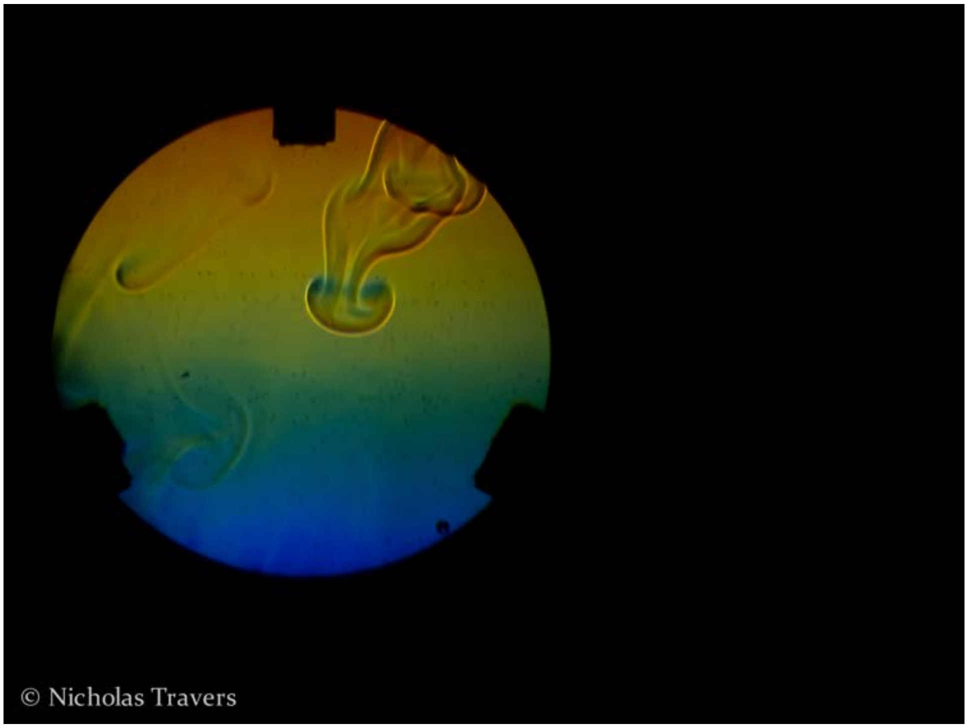
He, X., Zhang, R., Shiyi, C., & Doolen, G. D. (1999). On the three-dimensional Rayleigh – Taylor instability. *Physics of Fluids , 11* (5), 1143-1152.

Ian. (2011). *Point Light Source Examples.* Retrieved 04 15, 2012, from Schlieren Photography - Seeing Air: http://www.ian.org/Schlieren/PointLightSource.html

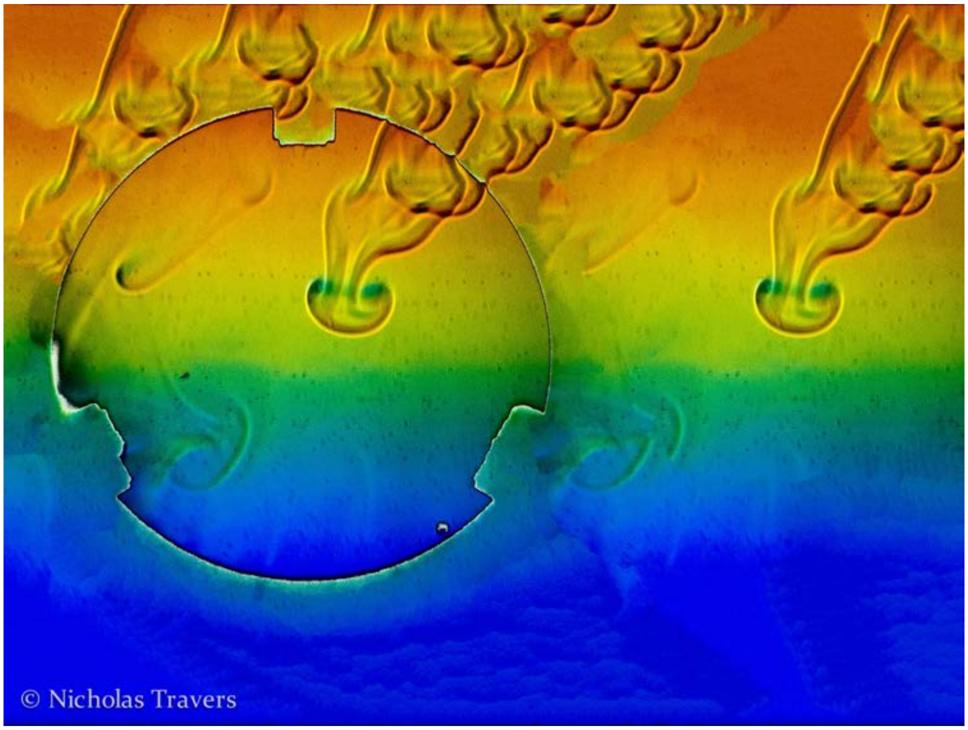
Pedrotti, L. S. (n.d.). *Basic Geometrical Optics.* Retrieved May 09, 2012, from International Society for Optics and Photonics: http://spie.org/Documents/Publications/00%20STEP%20Module%2003.pdf

Settles, G. S. (2001). *Schlieren and Shadowgraph Techniques: visualizing phenomena in transparent media.* New York: Springer-Verlag.

Sharp, D. H. (1984). An Overview of Rayleigh-Taylor Instability. *Physica D* , 3-18.




Original, as shot, schlieren image of a negatively buoyant plume of cold water descending from a melting ice sheet,




Edited Image:

Pattern – black background removed and filled in using smart, content aware, fill tool in Adobe Photoshop CS5. Tone adjustments - exposure increased; contrast increased; brightness increased; clarity and vibrance increased. Some noise reduction.

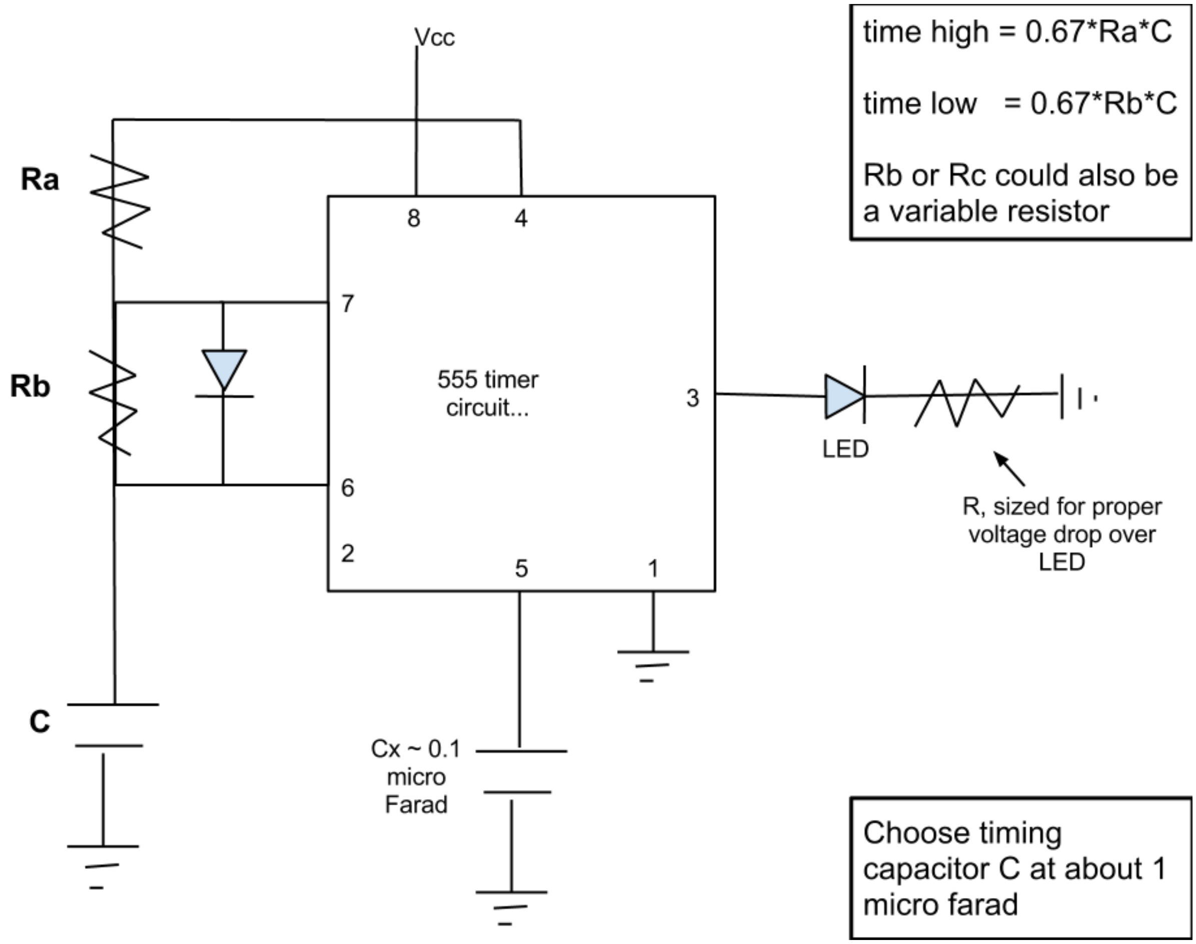



**Figure 5 - Flashing LED light source constructed, materials available with schlieren system for future improvement.**