THE UNIVERSITY OF COLORADO

Group Image 1 Report

Multiple Internal Refraction of Laser Light in Laminar Flow

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Flow Visualization

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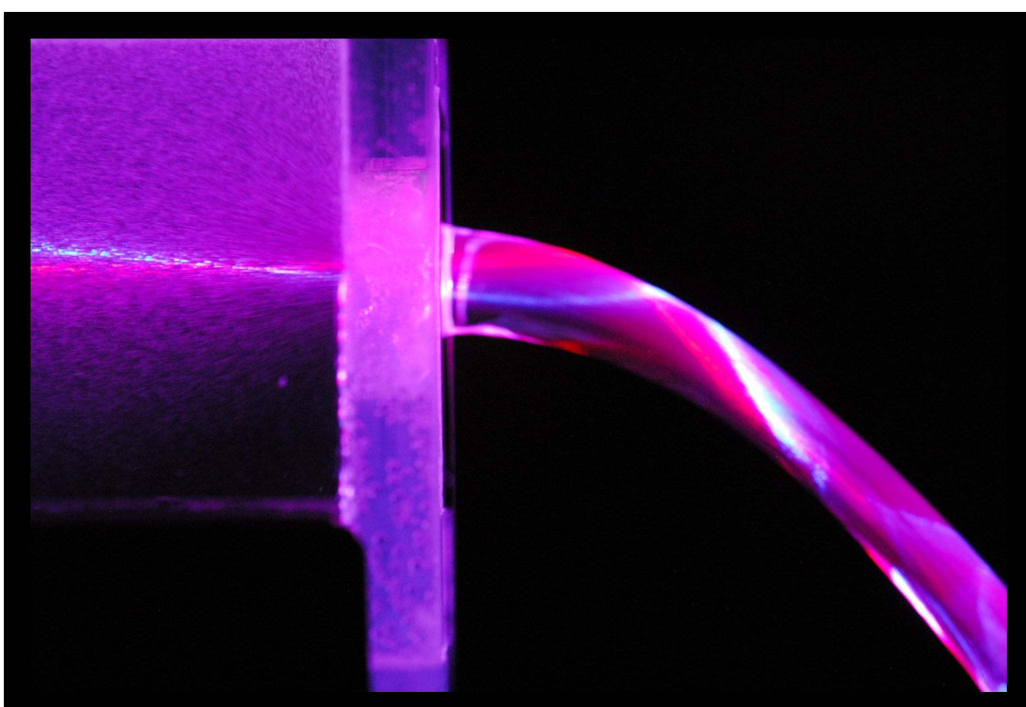

1. Purpose of Image

The image for this report was captured for the initial group assignment for The University of Colorado, Boulder's MCEN 4151: Flow Visualization course. The class is designed to encompass multiple disciplines ranging from engineers to visual arts students. For the first group assignment, students were asked to observe a fluid phenomenon of interest and document it through whatever visual medium he or she thought best represented the fluid flow. For the image taken, the fluid flow in question pertained to internal refraction of lasers. Three separate lasers (red, green, and blue) were projected at different angles into a laminar flow of water. At the onset of fluid flow, the lasers are cleanly reflected by the interior walls of the water jet. As the fluid jet becomes less laminar and more turbulent, the beams become distorted and combine to form a uniform bright, almost white color. The image nicely synthesizes fluid flows associated with laminar jets with optical refraction associated with Snells law.

2. Image Set Up and Approach

A complex setup was required for the production of the image, and was accomplished with help from employees of the physics department (Michael Thomason), who provided the space and equipment for the experiment. The fluid tank was mounted on a stand approximately one foot above the surface of the table. The tank itself was approximately two and a half inches deep, eighteen inches tall, and twelve inches long. Located on the bottom end of the narrow face of the tank (nearest the closed side), was a 0.5 inch diameter orifice. At this part of the wall, the thickness had been tapered and eventually removed, and had been replaced by an approximately 0.1 inch thick piece of aluminum. This thin wall allowed for flow effects around the orifice to be minimized. This helped ensure a laminar flow of water out of the opening. A rubber plug filled this hole in order to control when fluid flow occurred.

Each laser was mounted on a separate vertical stand in line with the tank orifice and fluid jet. The lasers were individually turned on, and manually adjusted so that the beam of each laser impinged onto the same point on the orifice plug. Although each laser impacts the same point on the plane of the plug, due to the differences in incoming angle, each beam impacted a different surface of the fluid jet. The result was that the lasers seemed to spiral around one another.

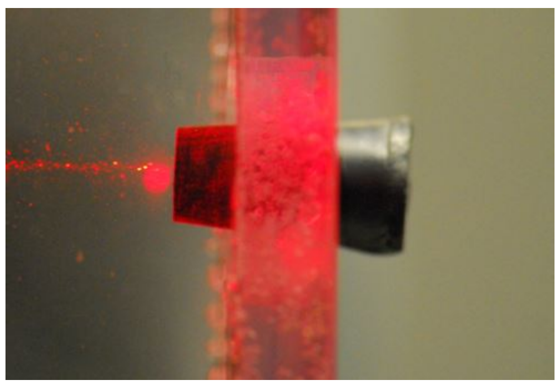

Figure 1: Red laser contacting the rubber plug

The fluid tank was then filled to the brim with water. Approximately a 1/8 cup of pine sol was then added to the water. The pine sol – a small colloidal particle – gave each laser a medium to be visualized on. If plain water was used, the path of the laser would be invisible to the naked eye, and only the final point of the path would be visible. As a laser beam encounters a small colloidal particle (in this case the pine sol solution) a small portion of the light is scattered. This allows the beam to become visible. Immediately after adding and stirring the pine sol in the water, the solution contains a large amount of bubbles. To obtain the best image, these bubbles were allowed to settle, leaving a clear fluid

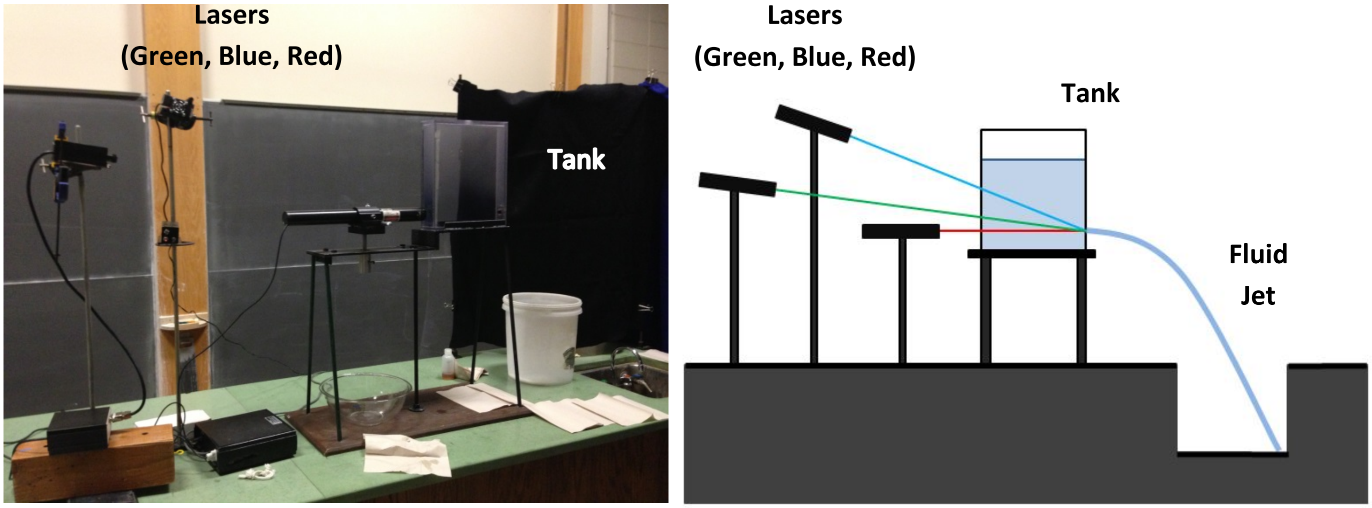

Figure 2: Actual Set-Up (Left), Set-Up Schematic (Right)

solution. However, in the chosen image, this process had not been allowed to reach a steady state or equilibrated point, and small bubbles were still present in the fluid. While these particles adversely affect the sharpness and resolution of the image, they also allow the fluid dynamics to be better visualized. As the fluid in the tank exited the tank, the surrounding bubbles are pulled along with it. In the image, this creates motion blur due to the long exposure time required to correctly visualize the laser beams. The closer a particle is to the exit orifice, the more motion blur it induces in the image (fluid velocity is greatest surrounding the exit hole).

3. The Physics behind the Flow

The bulk of the fluid flow properties for this image are determined by the velocity of the 'free jet' of water exiting the tank. Through rearranging Bernoulli's equation for a large, open reservoir exiting into the atmosphere, one can derive the 'free jet equation.' This equation is shown below, and will be used to calculate the velocity of the stream, which will help determine the Reynolds number of the flow.

$$Free\ Jet: V = \sqrt{2gh}\ [4]$$

Where the above variables are defined as:

$$V = Fluid\ Jet\ Velocity, Unkown$$

$$g = Acceleration\ due\ to\ Gravity = 32.2\ \frac{ft}{s^2}$$

$$h = Head\ Height\ of\ Fluid\ Tank = 0.5\ ft\ (Approx.height\ of\ fluid\ at\ image\ capture)$$

The free jet velocity is then calculated to be:

$$V = \sqrt{2gh} = \sqrt{2\left(32.2\ \frac{ft}{s^2}\right)(.5\ ft)} = 5.683\ \frac{ft}{s}$$

To minimize any potential vena contracta effects – decrease in the area of the jet with respect to the exit orifice – caused by a sharp corner at the exit location, the tank was constructed so that the acrylic walls smoothly taper down to the exit hole. At this location, a square of the acrylic wall was removed and replaced by a very thin piece of aluminum with the appropriate sized hole. This thin material ensures that the fluid flow has much less of a 90° turn to make as it exits the tank, and reduces the amount of vena contracta that is present (ie $C_c \approx 1.0$) [4].

The free jet velocity found above can then be used to calculate the Reynolds number (a dimensionless ratio of the fluid inertial forces to the fluid viscous forces)of the fluid flow. In order to properly internally refract the laser beams, the fluid flow must be laminar in nature (ie low Reynolds number).

$$Re = \frac{VD}{\nu} \text{ [4]}$$

Where the above variables are defined as:

$$V = Average\ Velocity = 5.683 \frac{ft}{s} (Calculated\ from\ Free\ Jet\ Equation)$$

$$D = Diameter\ of\ Free\ Jet = 0.0416\ ft$$

$$\nu = Kinematic\ Viscosity = 1.664E-5 \frac{ft^2}{s}\ (Water, At\ Room\ Temperature\ 40°C, [3])$$

Reynolds number is then calculated to be:

$$Re = \frac{VD}{\nu} = \frac{\left(5.683\ \frac{ft}{s}\right)(0.0416\ ft)}{1.664E-5\frac{ft^2}{s}} \approx \mathbf{14207.5}$$

The critical Reynolds number allowed for laminar flow is 2300. Since this number is much greater than that value (~4x), the fluid is mathematically classified as behaving in a turbulent manner. However, the empirical evidence and nature of the experiment were that the free jet flow was laminar in nature. Somewhere within the calculation of either the free jet velocity or the Reynolds number lays an inconsistency which is generating this incorrect mathematical result. It is difficult to identify directly as there are few independent variables within the equations, and all are known to a relatively high level of confidence. In order to achieve a fluid flow on the boundary of being turbulent, either a head height of 0.15 inches, or an orifice size of 0.08 inches in diameter. Neither of these criteria are feasible, so that calculation was left as is.

4. Visualization Technique

To visualize the flow, small bubbles were employed to act as particle markers. Each bubble was small enough that it did not over power or degrade the image, but large enough that the generated motion blur was enough to demonstrate the fluid flow. The lasers nicely illuminated the set-up, with the combination of the red and blue lasers providing a nice purple hue within the image. Unfortunately, some aspects of the image are out of focus – such as the acrylic tank. The intended focal point of the image was the refracted laser path on the right hand side of the image, so the tank became less defined. A fair amount of motion blur also exists in two places: on the left hand side in the form of particle motion, and on the right in the form of free jet fluid flow. Both of these areas of motion blur provided a sense of speed and motion to the image, which aid the overall effect.

5. Photographic Technique

The camera used to capture this image was a Nikon D2x. The camera lens was a 60mm Macro-Nikkor F28 lens. The camera itself was fixed to the extended boom of a three-leg tripod. The image was captured as a RAW file and was post processed as a .tif. The camera settings were an ISO 1600, a focal length of 105 mm, an aperture size of f/4.5, and a shutter speed of 1/20sec. The field of view is approximately 10 square inches. No post processing occurred. The original image is shown below.

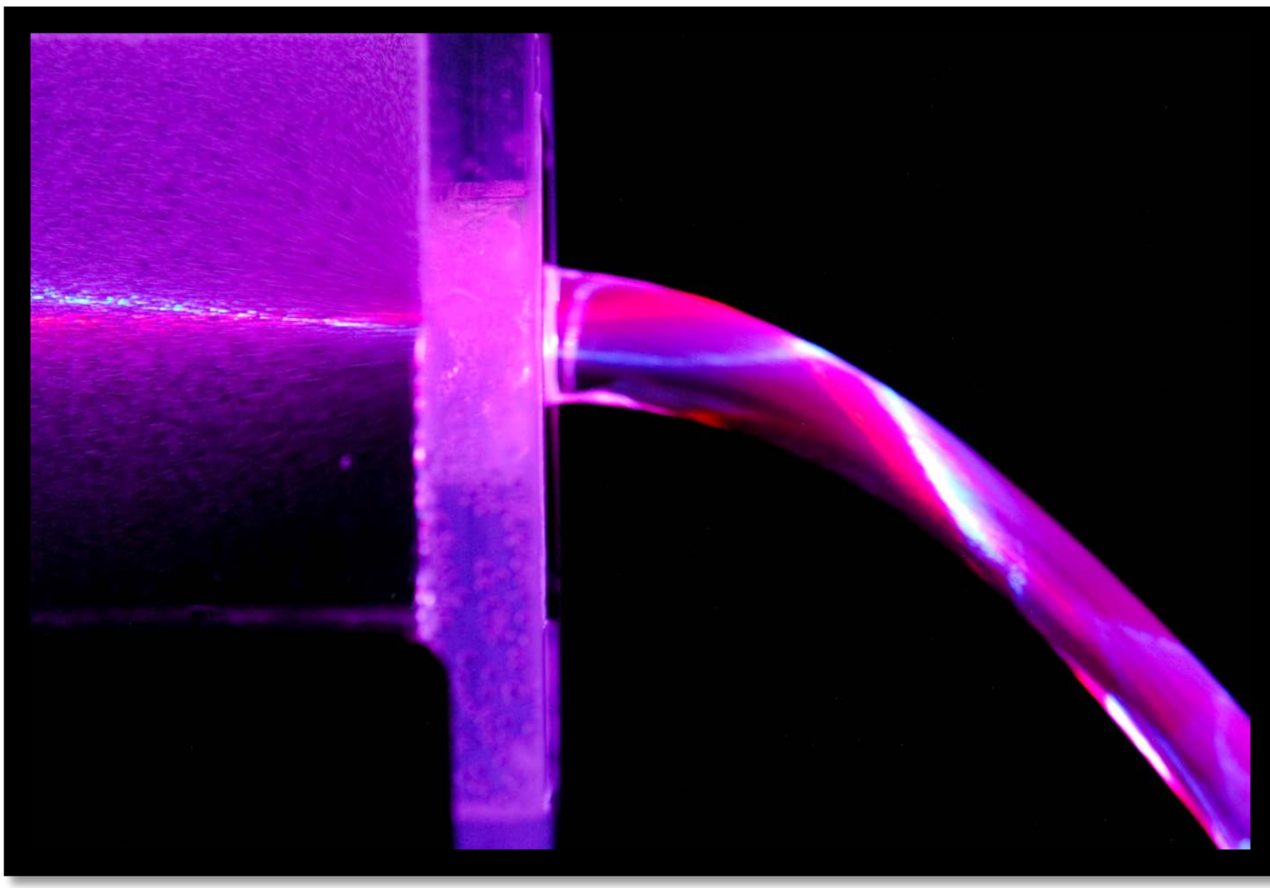

Figure 3: Unedited Image

6. Conclusion

This image is a unique example of fluid phenomena – internal refraction of light. Additionally, the small bubbles that exist in the image help build a sense of flow as the image progresses left to right. The depth of color is fairly rich, with a color palate which is nicely contrasted by the black backdrop. The way in which the two beams of light twist around each other is also telling of the beauty that gets created as the light is refracted by the internal walls of the fluid flow. While the image could ideally be a little sharper in some areas (such as the walls of the container), it should be taken into consideration that a fair amount of motion blur exists within both halves of the image (particle and free jet flow). Overall, the image nicely represents fluid dynamics.

Works Cited

[1] http://eet.cecs.pdx.edu/expt/tankdrain/pdf/tankDrainingLabExercise_Fall09.pdf

[2] http://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html

[3] http://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html

[4] Young. , Munson, , Okiishi, , & Huebsch, (2007). *A brief introduction to fluid mechanics*. (4th ed.). Hoboken, NJ: Wiley.

[5] http://en.wikipedia.org/wiki/Reynolds_number