Report: Tanner Ladtkow
Geneva Wilkesanders
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Image: Tanner Ladtkow
Geneva Wilkesanders
Tim Read
Andrea Fabri

Vortex Frozen with Laser Sheet

Introduction

The purpose of this image is to illustrate a thin slice of a complicated flow in order to illustrate the flow phenomena more easily. The flow apparatus used creates a thin sheet of smoke that emerges from the apparatus as laminar flow but quickly transitions into turbulent flow (at high flow rates). This type of flow is called a planar jet. In this image it is easy to see that the smoke emerges as laminar flaw and then curls into a laminar vortex (figure 1). A laser sheet is used to cut (and "freeze") a thin sheet of the smoke in the planar jet. Doing this makes this thin sheet of the planar jet stand out from the remainder of the flow in the vicinity and turns a 3-D jet into a 2-D flow. The flow visualized is simply air with smoke particles intermixed to make the physics visible.

Figure 1: Final project 3 vortex image.

It would be impossible to observe this flow is such detail without the laser sheet. This image was chosen because of the detail in the vortex; this image is simple and beautiful. The flow itself isn't simple, but the almost perfect circles formed by the vortex certainly are. The artistic intent of the image was to capture a simple, yet aesthetically appealing image that illustrates a flow phenomenon. This is accomplished in part due to the contrast between the bright glow of the laser pulse, and black background. The simplicity of the circle also adds to the artistic intent of this image.

Setup

The setup for this photo is complicated; some of the equipment needed to produce this image is expensive, difficult to find, or hard to fabricate by hand. The equipment needed for this experiment is listed below (table 1).

Table 1: Equipment needed to perform experiment

Flow equipment /testing setup	**Photographic/lighting equipment**
Compressed air	Camera
Air stabilization chamber	Laser: New Wave Solo-PIV 120XT Nd: YAG Laser System
Smoke machine	
Apparatus that creates planar jet	

One of the pieces of equipment that is both expensive and hard to find is the laser sheet. The laser sheet is a powerful laser beam that is diffracted into a thin but intense sheet of light. The laser is generated by a powerful laser generator. The laser used has an energy rating of 120mJ and a pulse width of 3-5 ns (nanoseconds). This energy rating may not seem significant, however that amount of energy is packed into a very short time; this is where the safety concern originates with this laser. Safety when using this laser is first priority because one pulse of this laser in eye will cause permanent loss of vision. The laser used is also not a continuous beam. Instead, there are actually two lasers that fire one after another. The frequency of the lasers pulse can be changed using the generator to a maximum of 15 Hz. The flow apparatus used creates a thin sheet of smoke that emerges from the apparatus as a laminar flow but quickly transitions into turbulent flow at high enough flow rates.

The first step in the setup is to place the camera parallel and in line with the slit where the smoke emerges. The laser is then placed perpendicular to the flow (figure 2).

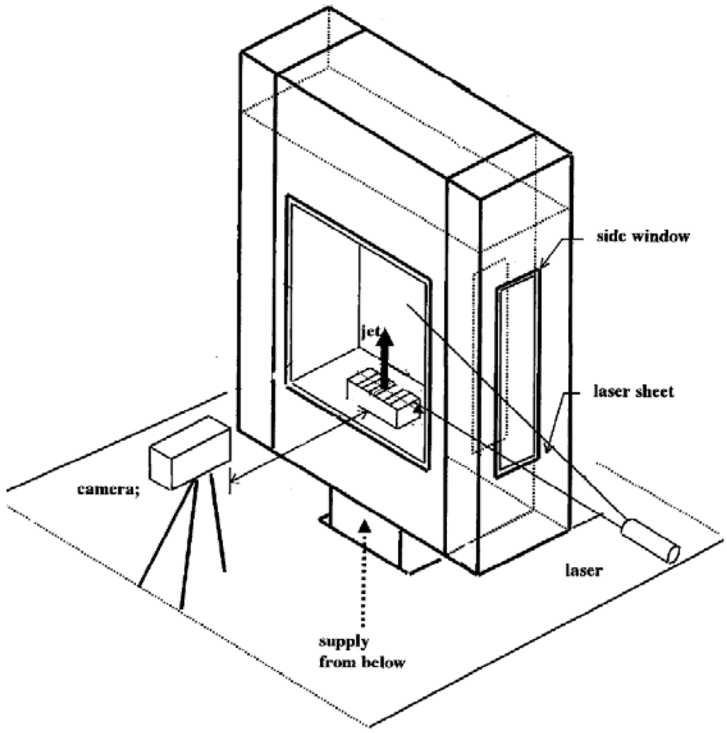

Figure 2: Experimental setup [1].

The camera was placed around 50cm from the flow, and the laser was also around 50cm from the flow. The smoke created by a smoke machine is pumped into a 55 gallon drum where it is mixed with compressed air and pushed though the slit in the aluminum apparatus. The smoke is drawn out the top of the smoke (visualization) chamber though a vacuum line. It is necessary to clear the chamber periodically in order to remove excess smoke. The next step is to turn on the laser. When doing this it is important to turn away from the laser source and watch for scatted laser beams that might harm your eyes. Next the frequency was set to the desired rate and the photos were taken.

Fluid Physics

Planar jets are a fluid phenomenon that has been extensively studied. Despite this, there are still many questions regarding the physics of the fluid flow. Some such questions are regarding the heat transfer properties of the jet, and the ability to control the stability and vortex shedding of the jet.

The fluid seen in our final image (figure 1) is obviously laminar, and the Reynolds number of 330 for this flow verifies this. This Reynolds number was calculated (see calculation below) based on a volumetric flow rate of 2.83 L/min, a planar jet exit slit area of 0.001 m (400mm x 2.5mm)[1], a jet length of 10cm (at the top of the vortex), and a density and viscosity of air (at standard temperature and pressure) of 1.2 kg/m^3 and 1.82e-5 kg/m-s respectively. With the volumetric flow rate and slit area previously mentioned, the velocity of the jet can be calculated.

$$U = \frac{\dot{V}}{A} = 2.83\frac{L}{\min}\cdot 0.001\frac{m^3}{L}\cdot\frac{1}{(0.4m\cdot 0.0025m)}\cdot\frac{1}{60}\frac{\min}{\sec} = 0.05\frac{m}{s}$$

$$\mathrm{Re} = \frac{\rho U \ell}{\mu}$$

$$\mathrm{Re} = \frac{1.2\frac{kg}{m^3}\cdot 0.05\frac{m}{s}\cdot 0.1m}{1.82\cdot 10^{-5}\frac{kg}{m\cdot s}} = 330$$

Although our final image was created using a planar jet setup, the fluid physics seen is not typical of the physics generally studied in planar jet experiments. Our flow rate was much slower than typical studies, and we assume that there was some residual motion within the visualization chamber that caused the jet to rotate into a vortex. Typical studies and images are usually taken of jets with a higher flow rate, and a more turbulent profile. We did also take some of these more typical photographs, however they had less artistic appeal, and thus were not chosen for the final image. Figure 3a below is an image of a typical planar jet captured and “frozen” in our experiment using the sheet laser. Figure 3 b and c[2] show similar jets captured in a study performed by Rehm JE and Clemens NT. The Reynolds number for the jet produced in our experiment (figure 3a) was estimated to be ~1100, and thus falls slightly below that of figure 3b. This can be seen in that the jet in figure 3a appears to be undergoing slightly less mixing than that in figure 3b.

Planar jets are also a fluid flow phenomenon that is of particular interest in heat transfer. Many studies have been performed, and many articles have been written regarding the heat transfer in different areas of the planar jet and at different flow rates and forcing frequencies. They are often used for the cooling of manufacturing processes that generate a large amount of heat (i.e. planar water jets used to cool metal after hot rolling process)[3], and are also often used to cool large reactors.

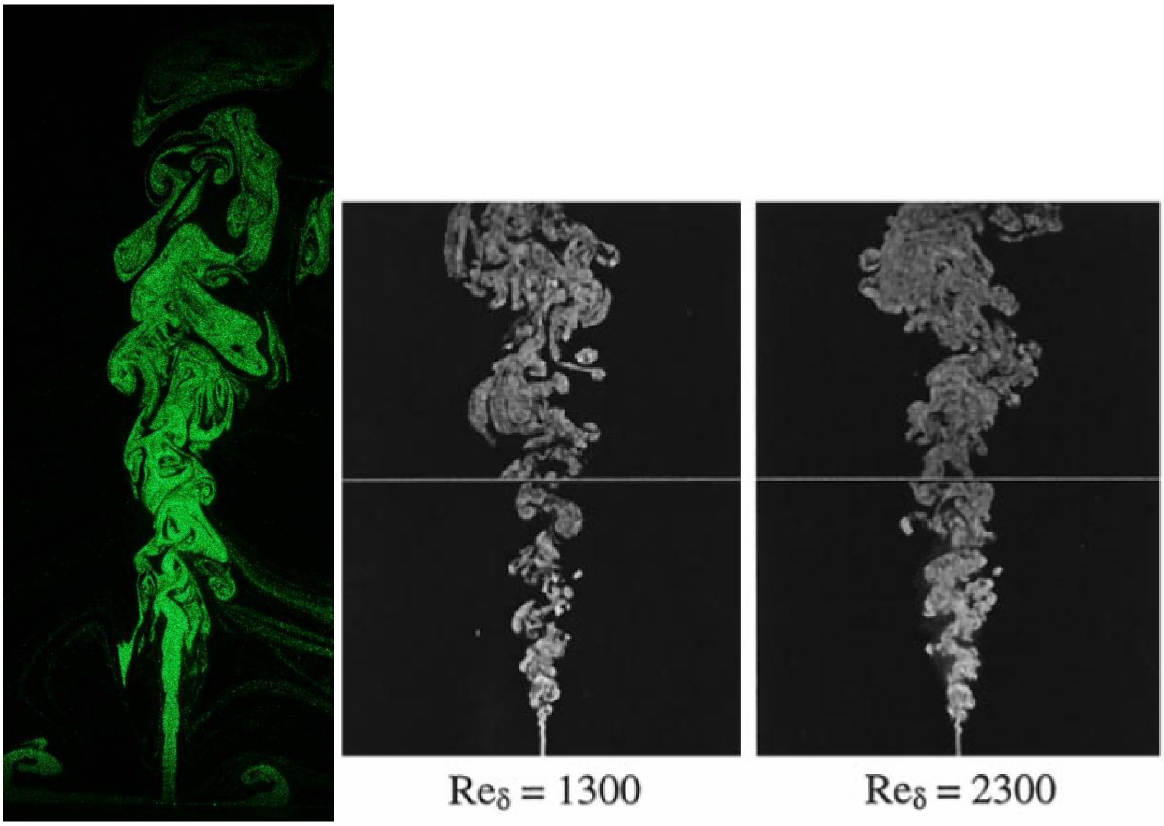

Figure 3a-c: Typical images of planar jets captured at various Reynolds numbers.

Photographic Technique

The basic photographic techniques that were used in this photograph are listed in the figure below (table 2). In addition to these, Photoshop was also used to crop and sharpen this image. There was a small amount of excess smoke that was removed from the image using Photoshop. The spatial resolution for this photograph found from the field of view and pixilation (table 2) was 11.5 pixels/mm. The flow does look a little grainy but this is actually just a feature of the flow. The graininess is the light reflecting off the individual smoke particles; the orientation of the particle changes how the light is reflected. This gives the image a grainy look.

Table 2: Information regarding the photograph technique use for this photo

Photographic technique	**Value used**
Field of View	(30cm wide x 20 cm tall) 600 cm^2
Pixilation	3456 x 2304 pixels
Distance from object to lens	50cm
Lens focal length	55 mm
Type of camera	Canon EOS DIGITAL REBEL XT
-Aperture	f/25
-Shutter speed	1/20
-Film speed	ISO 400

For this image, the shutter speed on the camera was set long so that the laser pulse would freeze the flow while the shutter was open. The duration of the laser pulse is 3-5 ns, and the frequency of the laser pulsing was set at the highest speed with both lasers firing. The idea was to catch just one laser pulse per shutter opening. The camera was also set to take 5 photos in rapidly in sequence. With the laser pulse width previously mentioned (used to freeze the flow), and an estimated flow speed of 0.1 m/s, the smoke will not blur across any pixels in the photograph. Some of the pictures didn't turn out well; some captured two laser pulses in one image, some were cut in half (we believe the camera timing was malfunctioning and photographing the shutter half-open), while others were just black (no laser pulse while the shutter was open). Despite these few poor pictures, most came very well with the laser pulse freezing the flow in one shutter opening. No other light source was present, and the flash did not fire.

This image shows the development of a vortex in a planar jet. While vortices are generally thought to be turbulent, and a source of turbulent mixing, this vortex remains very laminar. The flow material simply consists of air with smoke particles intermixed. The laser sheet is used to cut a cross-section of the flow in order to visualize what is happening within the flow. This type of image would be impossible to capture without the use of a laser sheet. The only flaw with this image is the graininess of the flow. Overall we were very happy with this image and we especially like how simple the image is with the almost perfect spiral of the bright florescent vortex on a black background.

References

[1] Peacock T, et al. Forcing a planar jet flow using MEMS. Experiments in Fluids 37 (2004) 22–28. March 2004.

[2] Rehm JE, Clemens NT. The large-scale turbulent structure of nonpremixed planar jet flames. Combustion and Flame 116 (4): 615-626. March 1999.

[3] Zumbrunnen DA. Convective heat and mass transfer in the stagnation region of a laminar planar jet impinging on a moving surface. Journal of Heat Transfer 113 (1): 563-570. August 1991.