Laminar to Turbulent Flow Transition and the Rayleigh-Taylor Instability Visualized *via* the *in Situ* Generation of Silver Nanoparticles

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1. Introduction

Mixing different fluids together results in a number of interesting flow phenomena, such as the Rayleigh-Taylor instability (RTI). The RTI occurs when a less dense fluid exerts a force upon a more dense fluid [1][2]. To demonstrate this phenomenon in a rather unique way, silver nanoparticles were employed, rather than a colored dye. To lend a more artistic flare, since this would serve as the second assignment for the course "Flow Visualization" (ATLS 5519), the silver nanoparticles were generated *in situ* with a redox chemical reaction. A small volume of 0.5 M solution of silver nitrate ($AgNO_3$) was injected into a much larger volume of 0.5 M ascorbic acid *via* a glass pipette. The resulting fluid flow included an initial laminar-to-turbulent flow transition, where the rate of silver nanoparticle generation was low and confined to the fluid boundary. Turbulent mixing then occurred as the fluid flow velocity decreased, and the rate of silver nanoparticle generation rapidly increased. This report will explore the underlying physics and chemistry of this artistically simple yet technically complex fluid flow demonstration. To capture the dynamic nature of the experiment, the final production was a video, rather than a still image. Finally, since no such demonstration is complete without a soundtrack, the author chose to set the video to a highly complementary excerpt from the second movement of Antonín Dvořák's Symphony No. 7 in D minor.

2. The Rayleigh-Taylor Instability

This fluid flow demonstration can be simplified to several discrete steps; we will explore these steps as the journey taken by a jet of silver nitrate solution, from pipette to flask. The detailed redox chemistry is out of the scope of this report, so for our purposes here it shall be simplified to the following: ascorbic acid (otherwise known as vitamin C) is a relatively potent reducing agent – an "antioxidant"– which, when in the presence of certain metal ions, will reduce said metal ions to their elemental (metallic) form. To the naked eye, silver (Ag^+) ions lend no color to a water solution, while silver metal is, as one may expect, quite opaque to light. As the silver nitrate and ascorbic acid solutions mix, these two initially colorless solutions chemically react to yield dark gray wisps of light-scattering silver metal nanoparticles.

As the silver nitrate solution is quickly injected through a glass pipette tip, its flow is laminar. Laminar flow involves particles of a fluid moving uniformly through a jet or pipe, interacting minimally with other particles of said jet or the pipe's surface. Turbulent flow, on the other hand, involves irregular movement of the fluid particles, causing them to mix with one another within the same flow, as well as with surrounding fluids. This behavior can be predicted from the Reynolds number [3]; see **Equation 1**.

$$\mathrm{Re} = \rho u L/\mu$$

Equation 1. *The Reynolds number,* Re*, is calculated from the fluid's density ( ), the fluid's velocity relative to the surroundings containing it (u), the "characteristic linear dimension" (L), and the fluid's dynamic viscosity (μ).*

With an injection velocity through a 0.8-mm tip glass pipette at approximately 12 cm/s, a density of 1.085 g/mL, and with a dynamic fluid viscosity of 1.031 cP, the 0.5 M silver nitrate jet had a Reynolds number of approximately 100. Reynolds numbers below 2300 indicate laminar flow, while those above 4000 indicate turbulent flow; Reynolds numbers in between indicate the transition region between laminar and turbulent flow. As soon as the silver nitrate solution exits the tip of the pipette, however, its "characteristic length scale" quickly increases up to ~2.5-3 cm, and flow rate increases slightly on average, to ~15 cm/s (determined from video playback). Within several millimeters of the pipette tip, the resulting new Reynolds number for the silver nitrate solution ranges from ~4000 to in excess of 4500, indicating turbulent flow. In the laminar flow regime, the silver nitrate solution jet interacts (and reacts) only at the interface between the ascorbic acid solution and itself; only a very faint grey tint to the jet is visible where silver metal nanoparticles are being formed (see **Figure 1**). However, as soon as the transition to turbulent flow occurs, with the associated rapid increase in mixing, the opportunities for collisions between silver (Ag^+) ions and ascorbic acid molecules increases dramatically, and sudden gray-brown "clouds" of silver nanoparticles appear, then ultimately sink to the bottom of the flask. This brings us to the next fluid flow phenomenon present within this experiment: the Raleigh-Taylor instability.

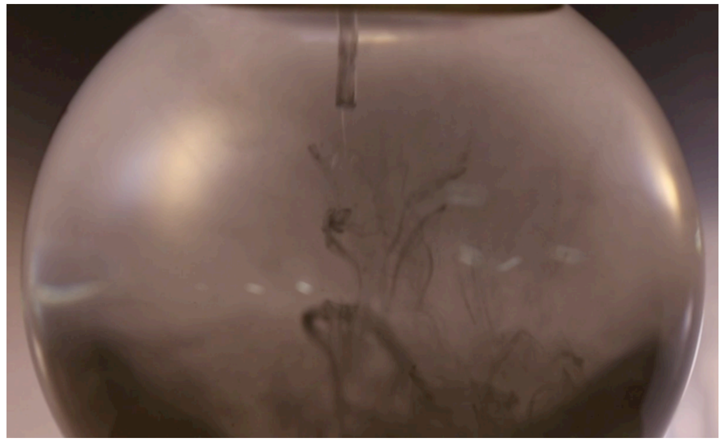

Figure 1. *Visualizing the laminar to turbulent flow transition.*

The mixing of two fluids of different densities often results in the RTI, as well as vortex rings. In the case of fluids with two different densities, the lighter fluid pushes upward against the heavier fluid, causing parts of the heavier liquid to move upward in a "mushroom cap" shape. This is particularly visible near the beginning of the video, when the least silver is present within the flask (see **Figure 2**, right image). Vortex rings are circular flow regions wherein a fluid moves in a circular path around an axis perpendicular to its original flow vector. This circular flow creates a closed ring: a vortex. Such vortex rings are frequently invisible unless some form of dye or particle tracker is added to the fluid; in this case, the latter is employed. Some trails of silver nanoparticles temporarily enable one to see vortex rings before sinking to the bottom of the flask (see **Figure 2**). In a further complication, the densities of these two interacting fluids is not constant; the original silver nitrate solution's silver ion concentration continuously drops as it reacts with the surrounding ascorbic acid solution. Therefore, one can expect that the RTI may become more pronounced the further the silver nitrate jet descends away from the pipette tip.

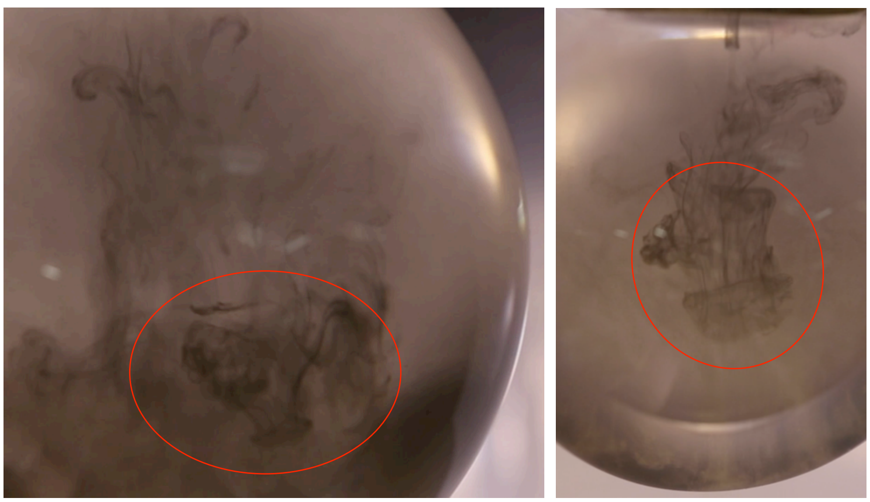

Figure 2. *Vortex rings result from the Rayleigh-Taylor instability.*

3. Apparatus and Visualization Technique

The apparatus used in this experiment (see **Figure 3**) is comprised of a 100 mL round bottom flask "overfilled" with 110 mL of a 0.5 M solution of ascorbic acid. This "overfilling" ensured that even the neck of the flask would be partly filled, such that no distracting "water line" would be visible. The flask was clamped to a ring stand, and surrounded by pieces of white reflective cardboard to create a neutral background. Preparation of the ascorbic acid solution involved the following: first dissolving 9.70

g of ascorbic acid in 75 mL of deionized water, then topping up the final volume to 110 mL with a graduated cylinder. This solution was then poured directly into the round bottom flask.

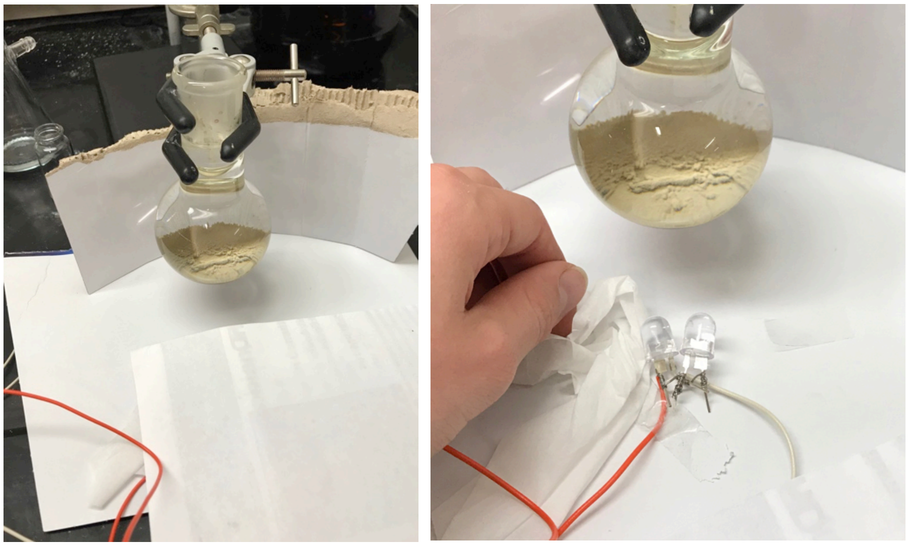

Figure 4. *Experimental setup for the silver nitrate experiment. These photos were taken several hours after the experiment had been performed, with the resulting silver particles having settled to the bottom of the round bottom flask.*

Lighting was provided by two 150 mW LEDs, wired manually by the author; one LED provided a "cool" white, while the other provided a "warm" white. These two LEDs were taped to the bottom reflective white cardboard, and covered with a piece of tissue paper to act as a diffuser. The solution of silver nitrate ($AgNO_3$) was prepared separately by dissolving 255 mg of silver nitrate in 1 mL of deionized water, then topping up the volume to 3.0 mL in a graduated cylinder. The resulting solution was then aspirated into the glass pipette immediately before filming. Actually performing the experiment was very simple: the pipette's latex bulb was slowly squeezed with the pipette tip immersed in the ascorbic acid solution.

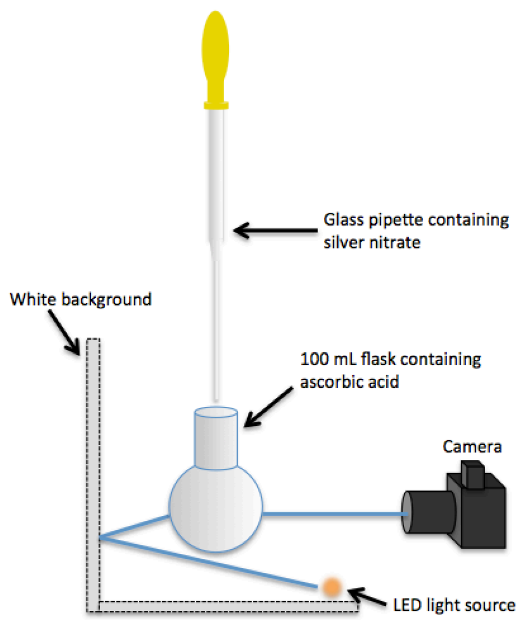

Figure 3. *Simplified diagram of the photographic setup, showing how illumination is provided by bouncing light from the LEDs off of the white reflective background.*

5. Photographic Technique

The following camera settings were used to record the video:

Camera and Image: Canon EOS 6D (digital), original and final version 1920 x 1080 pixels

Focal length: 100 mm

Distance from object to camera: 200 mm

Angle and field of view: 12.7°, approximately 44.4 mm respectively

Exposure settings. ISO 100, shutter speed 1/50 sec, f-number of 4.

No changes to color or contrast were made in editing; only cropping and frame rate adjustments were made. Significant effort was made in camera positioning, focus, aperture settings, ISO and lighting, including several test shots, before the final video was shot. Additionally, the entire video was originally recorded on a lower-resolution camera at 240 fps, but it was quickly determined that this experiment was actually best viewed in real time, not in slow motion as was originally envisioned.

6. Video Commentary

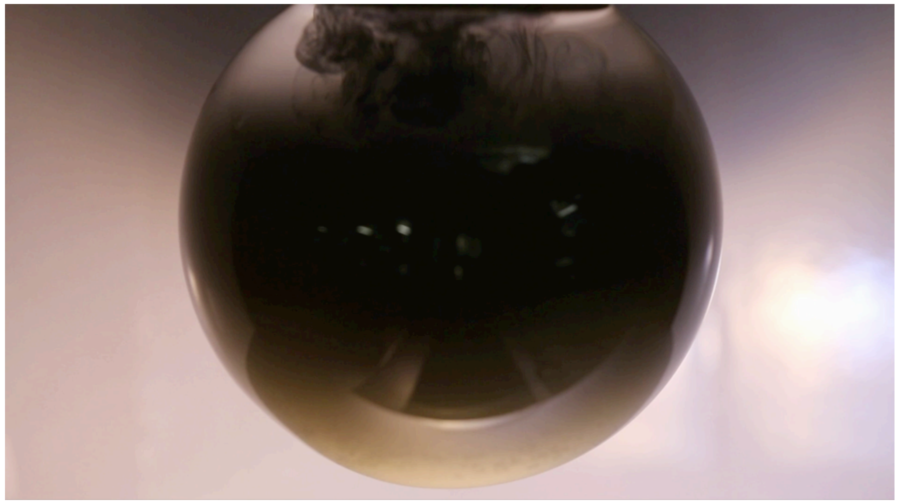

Figure 5. *A still from the final cropped video.*

The final video provides an intriguing glimpse into the various fluid dynamics at play during this chemical reaction. At first, the mixing of the two solutions is nearly invisible; once the chemical reaction takes place, however, the *in situ* generated silver nanoparticles act as particles for tracking the fluid flow. Additionally, the appearance of vortex rings at the approximate midpoint of the video heralds a nearly complete transition from laminar to turbulent fluid flow. At this point, the silver nitrate solution fills the majority of the round bottom flask.

Visually, I like how the clouds of silver nanoparticles stand out in stark contrast to the light background. Positioning the light to reflect off the background provides a relatively soft light to uniformly illuminate the flask, and avoid glare. The subdued, warm color palette is meant to complement the choice of classical music; electronic music may have warranted more green and/or blue hues. Additionally, before shooting, the focus was set to optimally focus on the pipette tip being held in the very middle of the flask. In order to create an increased sense of depth, the f-number was set on the lower end, such that silver nanoparticles close to the back or front would be less in focus. This also has the effect of drawing the viewer's eye to the jet exiting the pipette tip.

It is also worth noting that the musical selection chosen for this video fits very well with the timing of the fluid flow. Minor adjustments were made to the playback rate at the beginning of the recording, in order to time the start of the silver nitrate jet to a crescendo from the brass section. The rest of the video plays in real time. Most additions of silver nitrate solution to the ascorbic acid solution are well aligned with a change in rhythm, melodic direction and/or musical dynamics. As the mixture becomes darker toward the end (see **Figure 5**), the music gradually increases in volume and intensity. At the very moment the flask is completely dark, full of silver nanoparticles, the music also hits the end of a crescendo; the music then reverses in volume, ending on a quieter, more sinister note. In the final second, one can see the silver just beginning to settle. It is precisely this ebb and flow of musical dynamics that aims to instill emotion and personality into the fluid flow visuals.

One potential improvement would be to inject the silver nitrate solution with a syringe pump, such that the flow rate would be very accurately controlled, producing a more uniform jet. This may, however, be less interesting when set to music.

References

[1] Lord Rayleigh, Scientific Papers (Cambridge University Press, Cambridge, England, 1900) Vol. II, p. 200.

[2] G. I. Taylor, Proceedings of the Royal Society Series. A 201, 192 (1950).

[3] Sommerfeld, Arnold (1908). "Ein Beitrag zur hydrodynamischen Erkläerung der turbulenten Flüssigkeitsbewegüngen (A Contribution to Hydrodynamic Explanation of Turbulent Fluid Motions)". *International Congress of Mathematicians.* 3: 116–124.