Imagining Laminar Flow in a Microfluidic Channel

Kailey E. Shara[a,*], Hyejin Kwon[a]
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[a]*University of Colorado Boulder, 1125 18th St. Boulder, CO 80309*

1. Introduction

This report will detail the experimental setup and photographic techniques used to capture an image of laminar flow through a microfluidic channel. This image was submitted for the first assignment for the course "Flow Visualization" (ATLS 5519), with credit to Dr. Hyejin Kwon for fabricating the microfluidic channel and assistance with running the microfluidic setup. Furthermore, details about the science behind the image, particularly as it pertains to the basic concepts of microfluidics will be explored. Most importantly, when forced to travel through channels of very small dimensions, liquids tend to exhibit predominantly laminar flow. In the microfluidic setup that will be discussed here, three separate and simultaneous flows of dye-stained water converge into one larger channel. Because the concurrent flows remain laminar, mixing does not occur *via* turbulent flow, but rather via diffusion only. As such, three parallel flows of different colors are seen throughout the channel, without them appearing to mix at their boundaries. As a nod to the three primary colors used in additive color mixing (including photography), red, green, and blue dyes were selected.

2. Physics of Microfluidic Flow Phenomena

Microfluidics permits extremely fine control over transport, mixing, and segregation of fluids, and as such, is proving to be a key enabling technology within the physical sciences. Microfluidic devices are already seeing significant use in molecular biology [1], and hold promise in such varied fields as astrobiological sampling [2] and optics [3]. This experiment specifically demonstrates how, rather counterintuitively, laminar flow is the dominant flow regime within a microfluidic channel. In *laminar* flow*,* fluid particles move uniformly along a single path without strongly interacting with surrounding particle flows. If we consider such flows as separate "layers" of fluid flows, each layer will then remain separate from adjacent layers as they move past one another. Conversely, fluid particles in the *turbulent* flow regime move chaotically, resulting in the mixing of our aforementioned "fluid layers".

In fluid mechanics, such fluid flow patterns— laminar versus turbulent— are predicted by the Reynolds number [4]. In simple terms, this dimensionless number represents the ratio of a fluid's inertial to its viscous forces. At high Reynolds numbers, the inertial force is higher than viscous force, resulting in turbulent flow. In contrast, low Reynolds numbers indicate greater viscous force, resulting in laminar flow. Microfluidic channels, given their very small dimensions (including the one used in this 0.500 M experiment), tend to yield very low (even below 1.0) Reynold's numbers, correctly predicting laminar flow. See Equation 1.

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

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

3. Apparatus and Visualization Technique

The apparatus used in this experiment is a fluorescence microscope, with a microfluidic device made with polydimethylsiloxane (PDMS); see **Figure 1** and **Figure 2**.

*Corresponding author

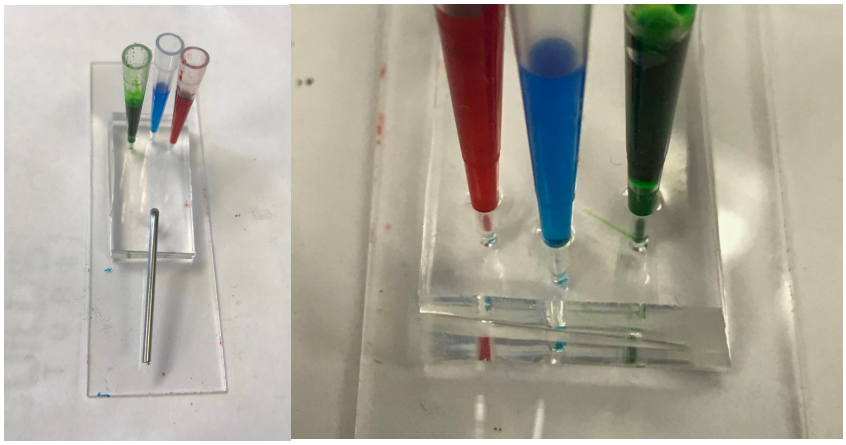
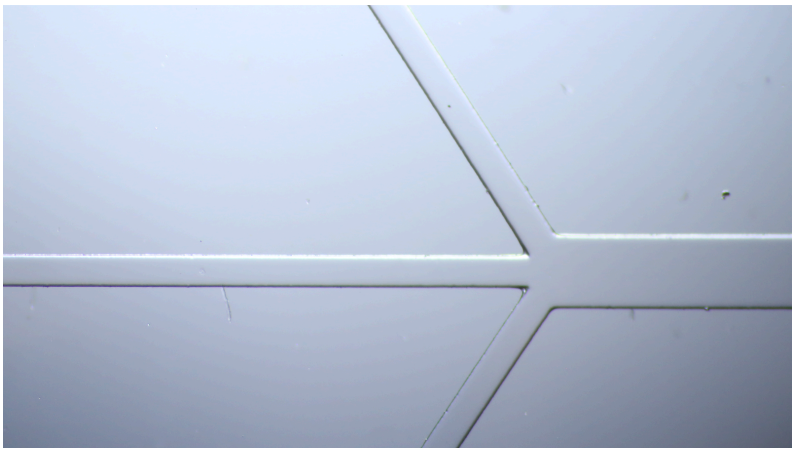


Figure 1. *The microfluidic device used in this experiment. At left is the entire microfluidic device (PDMS on a glass slide), with three pipette-tip reservoirs filled with the dyes and a bent metal collection tube. At right some of the green dye can be seen running through its channel.*

Figure 2. *View of the microfluidic device's channel through the microscope. The wide section at right is 400 micron wide, while the feed channels at left are 150 micron wide; all are 23 micron deep.*



The microfluidic device sits atop the stage of the fluorescence microscope, with an optical path as shown in **Figure 3**. Unlike with traditional optical microscopes, light from this microscope's 400 mW LED light source passes *through* the sample ($D_{LED\ to\ Object}$ = 600 mm) to the viewing optics, or in this case, a DSLR camera.

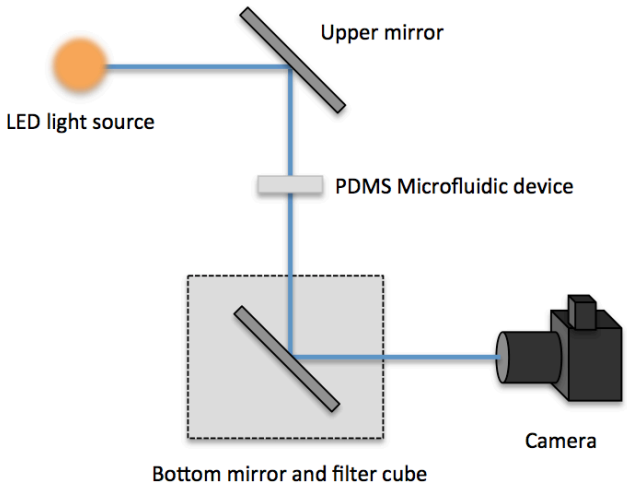


Figure 3. *Optical path and simplified setup of the fluorescence microscope, showing how light passes through the sample, rather than being reflected off of its surface.*

To balance the artistic intent of demonstrating multiple converging flows against the resulting increase in the setup complexity, a microfluidic device with three feeder channels was selected. Each of these three feeder channels was fitted with one "pipette-tip" reservoir (see **Figure 3**). One flexible air hose is attached to each pipette-tip reservoir to deliver air to each channel at ~35 kPa, yielding a flow rate of ~0.1 µL/s *out of the wide channel*. The flow rate into each of the three feeder channels is 1.3 of this value, approximately 0.033 µL/s. The dyed water is a 1:5 dilution of McCormick brand food coloring in deionized water. First prepared in plastic vials, the dyes were transferred into the pipette tip "feeder reservoirs" with the aid of a 50 µL pipette.

To ensure all the three colors of dye are injected simultaneously into their respective channels, the lab supply of compressed air was controlled by a solenoid valve, which then split off into three separate tubes. Each tube then connected to a corresponding pipette tip "reservoir". An Arduino-controlled

electronic circuit turns on the solenoid for a 2 seconds before shutting the airflow back off for 5 seconds. This enables multiple opportunities to take the photograph before the reservoirs are emptied.

The liquid simply moves within the small channels leading to the larger one, as well as within the larger channel. However, each colored liquid remains in a straight path within the larger channel and does not mix with the other two, creating three straight lines of liquid within the channel.

5. Photographic Technique

Since this image was captured through a microscope's optics, some typical camera metadata is not available for this image. Still, the key specifications are:

Camera and Image: Canon EOS 6D (digital), Original (w x h) = 5472 x 3648 pixels, final (w x h) = 3342 x 1848 pixels

Microscope: Nikon Eclipse TE300 Fluorescent Microscope

Effective focal length: approximately 90 mm

Distance from object to camera sensor: 549.5 mm

Angle and field of view: approximately 13.2°, approximately 2.89 mm respectively

Exposure settings. ISO 4000, shutter speed 1/160 sec, f-number of approximately 20.

The raw image, before editing, can be seen below in **Figure 4**. The edited image appears on the following page as **Figure 5**. The key edits made were increasing saturation by 20%, reducing only the background's exposure by 30%, erasing specks of dust, and cropping out a much smaller section of the image.

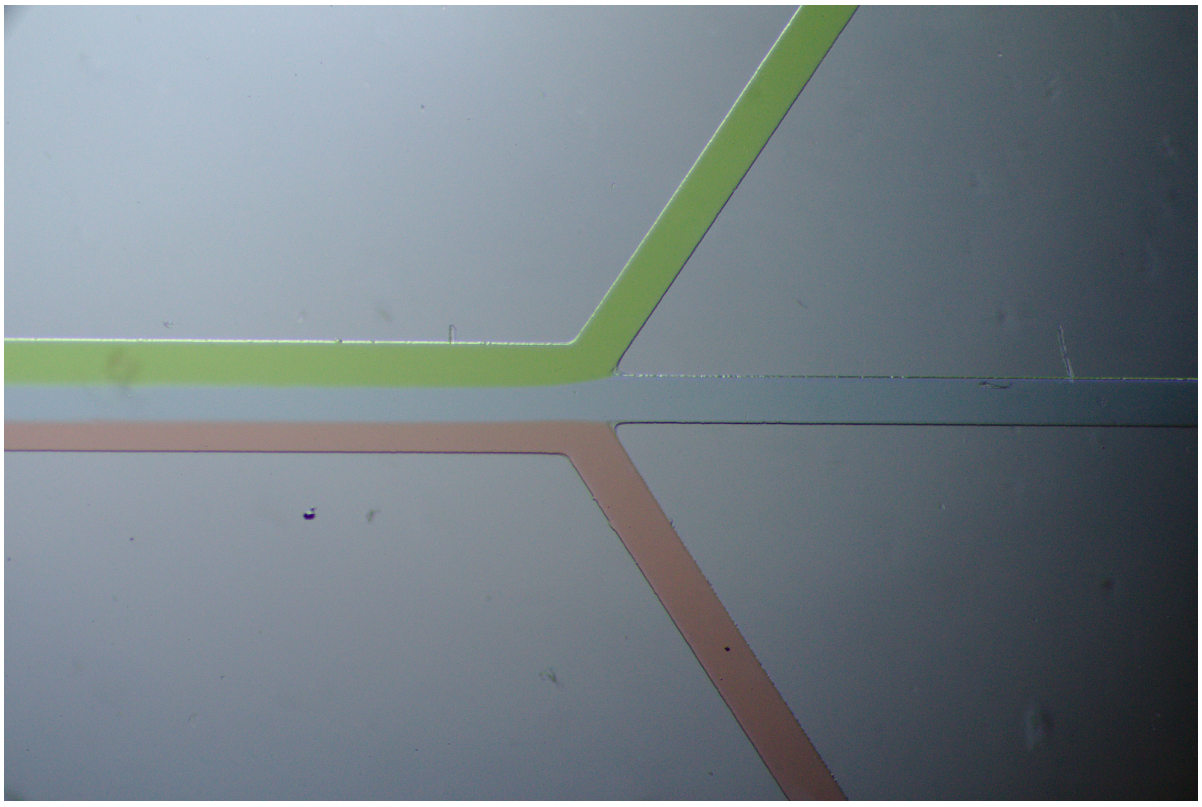


Figure 4. *The original raw, unedited image. Below: the final processed image.*

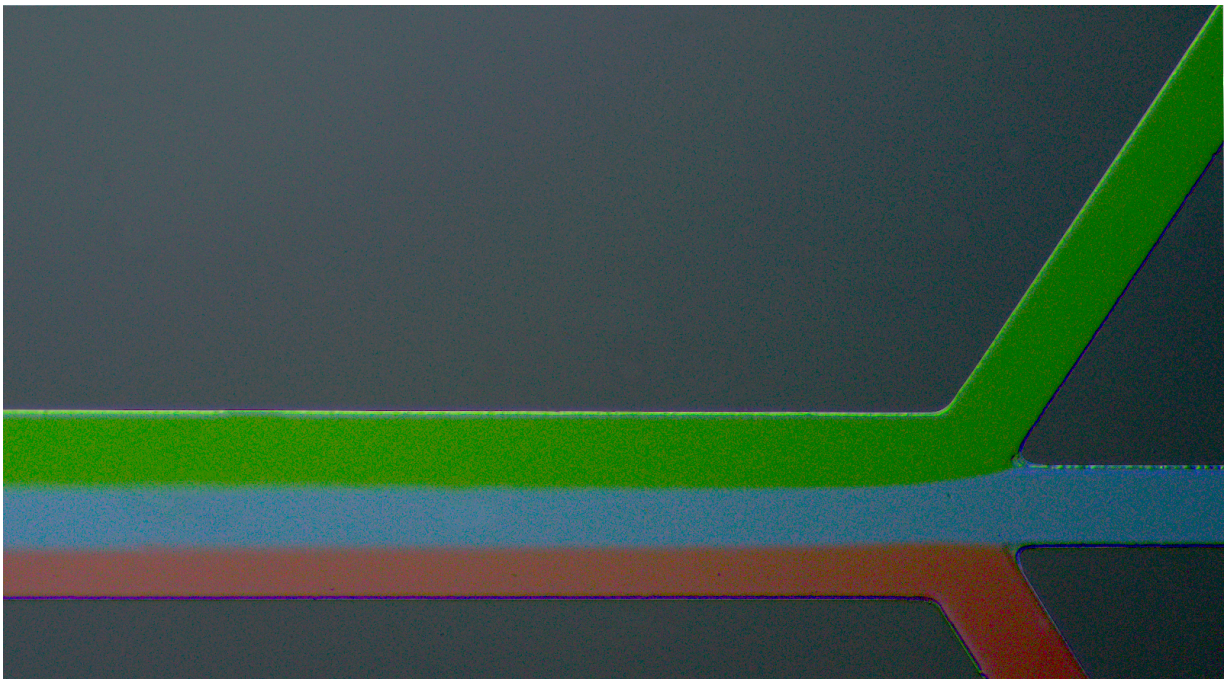


Figure 5. *The final processed image.*

6. Image Commentary

Overall, the image reveals the intriguing nature of fluid flow at very small dimensions. Although one may expect the convergence of these three liquid channels to result in an irreversible mix, the result is instead three distinct parallel fluid flows. Only the fine haziness at the boundaries between colors betrays that some mixing is occurring due to diffusion. Compared to the original image, the cropped final image helps focus the viewer's eye more toward the point of flow convergence. I would have preferred if the blue dye were slightly more concentrated to yield a slightly more intense blue hue in the middle channel. At such small liquid volumes, the dye must be present at high concentrations for the fluid flow to appear intensely colored. Even still, I quite like how the final colors, particularly the red and green hues, stand out from the charcoal gray background. Light reflections off the green channel's top edge provide some depth, when the channel is otherwise only 23 μm thick. Capturing images through a microscope can be challenging, with little control over the lighting, but I find the light-to-dark gradient from the image's upper left to lower right corner more interesting than if the microfluidic channel were to be uniformly lit.

Although more complex to fabricate, a microfluidic channel can be designed [5] to intentionally disturb laminar flow (by combining meandering channels and projections within the channel), yielding a turbulent "mixing region". An image showing this laminar-to-turbulent transition, with separately colored channels gradually converging into one could make for an interesting follow-up experiment.

References

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[5] You, J. B., et al. PDMS-Based Turbulent Microfluidic Mixer. *Lab Chip* 2015, *15* (7), 1727–1735. https://doi.org/10.1039/c5lc00070j.