Testing the Success in Creating Laminar Flow Using a Couette Cell Apparatus

Emma Brinton
Physics Department, The College of Wooster, Wooster, Ohio 44691, USA
(Dated: May 4, 2017)

The couette cell apparatus can be used to rotate lines of colored fluid and then return them to their original positions. This is due to laminar flow, which occurs when fluid moves in distinct layers which do not mix. This experiment tests how successful the couette cell apparatus is at creating laminar flow. Before and after pictures of color bands of corn syrup that were injected into clear corn syrup and then rotated and returned to their initial position were used to analyze the success of laminar flow creation in the apparatus. This was done through the calculation of the ratio of final and initial band widths at specific heights below the surface of the liquid which was then analysis of this ratio as a function of depth below the surface or the angular velocity of the rotation. Quantitative results showed that there is a linear relationship between laminar flow behavior and how far below the surface the fluid the color is located. This relationship is direct, meaning that the apparatus is more successful at creating laminar flow at greater depths below the surface. The slope of the trial showing the ratio as a function of depth where the fluid rotated at an angular velocity of 0.18 revolutions per second was $-29 \pm 2\frac{1}{m}$. Qualitative results showed that there is a relationship between the velocity at which the fluid moves and laminar flow behavior. This relationship is inverse, meaning that the apparatus is less successful at creating laminar flow at greater angular velocities.

I. INTRODUCTION

When thinking about fluid motion, there are two big picture ideas about how layers within the fluid can move. These ideas are summarized as laminar flow and turbulent flow. During turbulent flow, the layers of fluid will mix together. While laminar flow occurs, the layers of fluid will remain isolated and not mix together. These two states of flow occur at varying Reynolds numbers. At low Reynolds numbers, laminar flow will occur. In this experiment, the couette cell apparatus was used to observe this phenomena.

In 1890, Maurice Couette discovered the idea of the couette cell. He proposed a design of two concentric cylinders in order to observe fluid motion[1]. From initial observations of using the couette cell to induce laminar flow, it was clear that at lower angular velocities and deeper depths, laminar flow occurred. This experiment was used to verify that such relationships can be found.

II. THEORY

Laminar flow only occurs at low Reynolds numbers. The value for Reynolds number can be calculated as

$$Re = \frac{\rho v d}{\eta}[2] \tag{1}$$

where ρ is the density measured in kilograms per meters cubed ($\frac{kg}{m^3}$), v is the velocity measured in meters per second ($\frac{m}{s}$), d is the characteristic length of the body measured in meters (m), and η is the viscosity of the fluid measured in kilograms per meters-seconds ($\frac{kg}{ms}$).

Since laminar flow occurs at low Reynolds numbers, Eq. 1 shows that laminar flow will occur when the viscosity of the liquid is high and/or when the velocity (or angular velocity) of the liquid is low. In order to fulfill the high viscosity requirement for observing laminar flow, corn syrup is used in the apparatus.

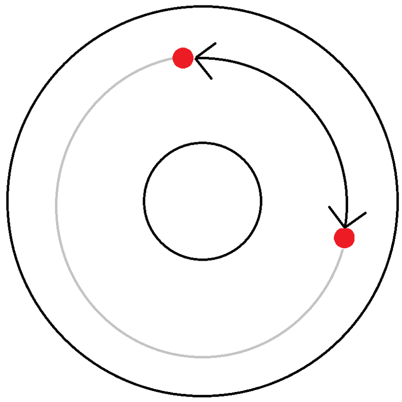

FIG. 1: This is a top view of an fluid moving in a circular motion due to laminar flow. A vertical layer goes down into the picture, perpendicular the the surface. In any given vertical layer of fluid, an line could be drawn from a point at the surface of the liquid to the bottom. This line will ideally travel parallel to the rotation of the inner rotating cylinder and then can be rotated back to the original location if it stays in the vertical layer of fluid. This is shown by the dark line of motion of a red vertical line in the grey vertical layer.

When laminar flow occurs, liquids will ideally travel in layers parallel to the motion which will not mix as shown in Fig. 1. This means, that any one spot within the layer can be rotated and then brought back to the original position once the liquid is in the opposite direction. This phenomena can be mathematically analyzed by comparing the before and after width of a color band as it is moved due to laminar flow (An example of a color band is shown in Fig. 2).

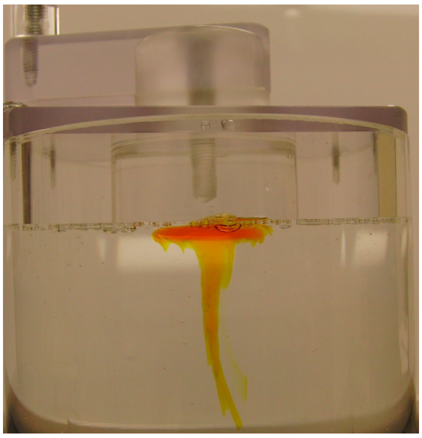

FIG. 2: Initial color band for experimental procedure.

Recording the initial color band width at some height and then comparing it with the color band width at the same height after rotating the fluid allows for a ratio value to be calculated as

$$R_h = \frac{W_f}{W_i}, \tag{2}$$

where R_h is the ratio between band widths at some height h pixels below the surface and W_i and W_f are the initial and final width respectively, both measured in pixels (one pixel is approximately 5.43×10^{-5}m).

This band width is measured by drawing horizontal reference lines across the color band at specific depths and then determining the width in number of pixels. This is shown in Fig. 3.

Under conditions where laminar flow occurs, this ratio should be equivalent to 1. From initial test runs with the apparatus, it is clear that this is not always the case. The color band stretches horizontally after being rotated. Initial observations showed that the color band would stretch more towards the surface of the liquid than areas which were deeper under the surface as seen in Fig. 4. Graphing R_h vs. depth at some constant angular velocity and being able to fit a curve to the graph would mathematically verify this trend.

Another trend which can be verified is the relationship between angular velocity and laminar flow. Testing R_h at

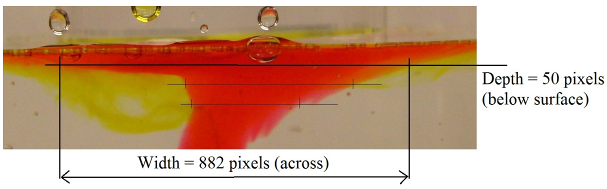

FIG. 3: Demo measurement of the band width 50 pixels below the surface of e_3 with horizontal reference line.

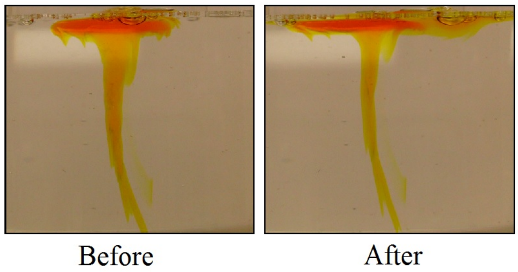

FIG. 4: Initial observations from rotating a color band at some unknown angular velocity. At the top, the band width increases after the rotation. It appears as if the width stretched more towards the top of the band than at the bottom of the band.

a specific height while the angular velocity of a complete rotation cycle of the corn syrup is varied allows for the verification of this relationship. Once R_h is graphed in relation to the angular velocity, the results will confirm this verification or may be inconclusive.

III. EXPERIMENTAL PROCEDURE

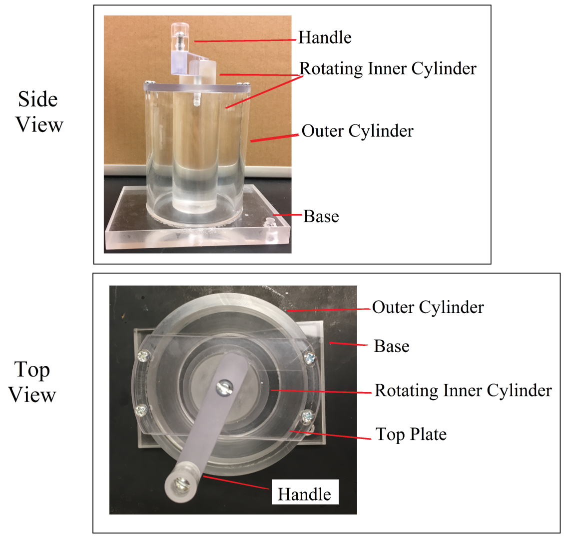

FIG. 5: This figure shows the side view and top view of the apparatus used in the experiment. Each picture shows the base with an two cylinders mounted onto it, the rotating inner cylinder, the stationary outer cylinder, and the handle used to rotate the inner cylinder. The top view also shows the top plate which holds the inner cylinder in place [3].

For the two hypothesis tests completed during this lab, the apparatus in Fig. 5 was used. This apparatus consists of two concentric circles mounted on a base. Corn syrup is poured in the space between the two layers and then the inner cylinder can be rotated using the handle at the top to induce laminar flow.

For each set of trials, the apparatus was initially set up so that one clear line of colored corn syrup was injected in one vertical plane as seen in Fig. 2. The inner cylinder was then rotated in one direction for three revolutions and then back. Pictures were taken of the initial set up and after each series of rotations. Each set of data was also video recorded in order to allow for the calculation of the average angular velocity for each trial.

IV. DATA & ANALYSIS

For each set of trials, the series of pictures was labeled as a_1, a_2, a_3, ..., a_n until the nth picture. (Each data set was labeled with a letter and then the pictures were labeled in series so that the varying angular velocities between pictures could be recorded). The pictures were then used to determine the width of the color band at specific depths below the surface. Trials were then compared so that the ratio of the widths between trials was calculated using Eq. 2. This gave the ratio of band width between some trial a_n compared to the previous trial a_{n-1} at a determinable angular velocity.

Each set of trials was used to look for a relationship between laminar flow and liquid depth and/or a relationship between laminar flow and the fluid angular velocity. This was done by graphing the ratio as a function of depth or angular velocity.

A. Laminar Flow in Relation to Liquid Depth

To compare laminar flow success at various depths, the ratio of the change in color band width was graphed as a function of depth below the surface of the liquid in units of pixels. The graph in Fig. 6 shows the result found from comparing trial e_2 to trial e_1. This trend shows that there is a direct relationship between the ratio of band width when compared with the depth of below the surface.

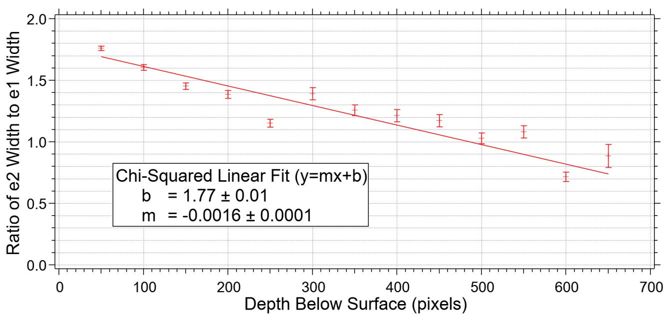

FIG. 6: The ratio of the initial width to the resultant width as a function of depth with the inner cylinder rotating at a constant angular velocity of 0.18 revolutions per second. The ratio is unitless and the depth is measured in pixels with 0 pixels being the surface of the corn syrup.

B. Laminar Flow in Relation to Angular Velocity

Qualitative data shows that at greater angular velocities, flow is not completely laminar. This was apparent from watching as bands of color would stretch more when rotated at a larger angular velocity. The pictures in Fig. 7 show the change in bands at two different angular velocities. This figure shows the before and after pictures for color bands at two different angular velocities. For the d_1 to d_2 transition, the angular velocity was 0.11 rev/s and not much stretch was observed. For the $b1$ to $b2$ transition, the angular velocity was 0.33 $\pm$0.01 rev/s and more stretch was observed than in d_1 to d_2 transition.

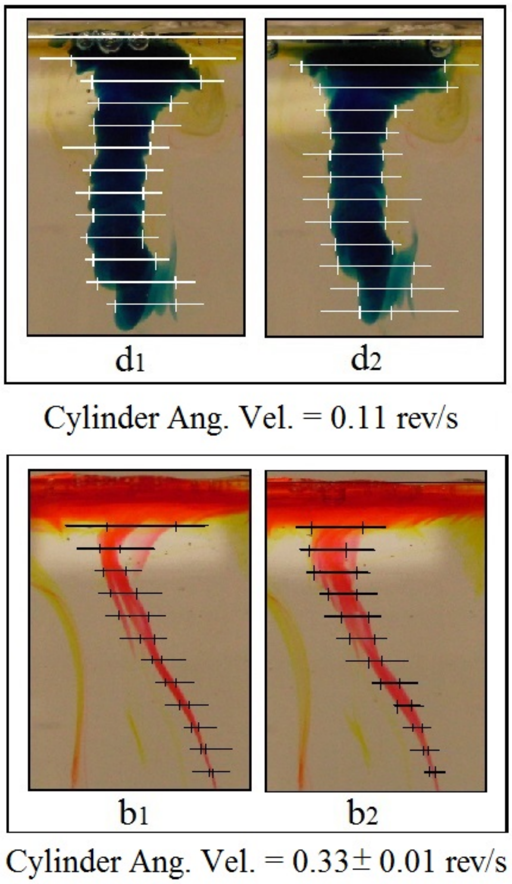

FIG. 7: Pictures to compare trials at different angular velocities to show the relationship between band width ratio and angular velocity. The set of pictures on the top shows the change in band width at an angular velocity of 0.11 rev/s and the set of pictures on the bottom shows the change in band width at an angular velocity of 0.33 rev/s. Looking at the horizontal reference lines right below the surface, it is clear that the band widths grow in both cases. It is also noticeable that the change in band width is greater for the bottom set of pictures than for the top set.

V. CONCLUSIONS

From this experiment, it became apparent that there is a definite relationship between color band behavior due to laminar flow and how deep the color is below the surface. This trend is linear and shows a direct relationship between the two variables. The apparatus is more successful at creating laminar flow at greater depths.

Qualitative data also verified that there is a relationship between the angular velocity of the fluid and color band behavior due to laminar flow. Observation showed that at higher angular velocities, the color band width will stretch more than at lower angular velocities. This means that the two properties of angular velocity and laminar flow behavior are inversely related to each other. The apparatus is less successful at creating laminar flow at greater angular velocities. The exact relationship is indeterminable from this data.

Overall, the couette cell apparatus can create laminar flow with the most success at greater depths and while the angular velocity is kept low. As the angular velocity is increased or closer to the surface, laminar flow can still be observed, just less successfully.

VI. FUTURE WORK

For the future, change can be made to the apparatus to improve the results of the experiment. Ideally, each trial would be taken with color band with a uniform width which was rotated and then removed before the next trial. Due to time constraints and financial means, this experiment was done by using a series of rotations and then comparing the before and after pictures for each rotation period. A more mechanical method for color band injection would also help with the creation of the uniform width which would allow for trend to be seen more clearly.

Another adjustment which could be done to this experiment would be to add another layer of testing to the process. This would be to test various fluids that have varying viscosities to see the relationship between the viscosity of the liquid and the success of laminar flow. Theory predicts that at higher viscosities, laminar flow will occur more successfully than at lower viscosities. Due to a time limitations, multiple fluids were not tested in this experiment.

VII. ACKNOWLEDGMENTS

I would like to thank Dr. Leary for advising me through the process of completing this experiment. I would also like to thank Timothy Siegenthaler for constructing my apparatus. A thanks to Dr. Feierabend for supplying me with syringes to allow for a more reliable method of syrup injection. To Dr. Lindner and Jack Mershon I would like to say thanks for giving me inspiration to study laminar flow for my Junior I.S. project. Finally, I would like to thank the College of Wooster Physics Department for helping to fund my research and providing the space and resources for me to complete my project.

[1] RJ Donnelly, *Taylor-Couette Flow - The Early Days.*. Physics Today. 44:32-39, 1991. `http://yb7zk3sd3g.scholar.serialssolutions.com/?sid=google\&auinit=RJ\&aulast=Donnelly\&atitle=Taylor\%E2\%80\%90Couette+Flow:+The+Early+Days\&id=doi:10.1063/1.881296&title=Physics+today\&volume=44\&issue=11\&date=1991\&spage=32\&issn=0031-9228`. Accessed: 29.03.2017.

[2] *Laminar Flow.* University of New Mexico. `http://physics.unm.edu/flash/viscosity.phtml`.. Accessed: 29.03.2017

[3] *Couette Cell for Demonstrating Laminar Flow.* LLC Wellspring Worldwide. `http://www.flintbox.com/public/project/6027/`. Accessed: 29.03.2017