Measuring Fluid Flow in a T-Junction Pipe with Colored Dye

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Changing the angle of inlets in a t-junction was found to have a weak interaction with mixing. Two buckets, one with red dye, were filled with water and hung above all other equipment such that there was no pressure difference. A tube was drawn from each bucket to a ball joint which controlled flow to a self-made clear poly-vinyl t-junction. The t-junctions tested were constructed with various angles. The flow was imaged with a standard camera and was recomposed with only a red channel. The tubing was isolated from the background, and a histogram of the color intensity was prepared. After removing the outlier, six of the seven histograms had their standard deviation measured. They were graphed on a plot of standard deviation vs. angle and found to have a weak linear regression with a slope of (15 ± 80%) which shows the weakness of this analytical method. This trend shows that as angle increase so should mixing and vice versa.

INTRODUCTION

The history of fluid mechanics is long reaching, stretching back to 250 B.C with Archimedes and his buoyancy descriptions and the invention of the Archimedes screw [1]. Since this humble start, the discipline has grown in both the scientific and engineering fields. This approach in fluid mechanics has meant that this field of learning has robust, direct applications to everyday life and a new theory is applied continuously to the lines of production regularly.

There exist two main branches of fluid mechanics - fluid dynamics and fluid statics. Fluid statics deals with fluids at rest. It deals with questions of equilibrium, such as buoyancy and pressure inside containers. It can explain many things but is not as pertinent as its partner, fluid dynamics. Fluid dynamics deals with fluids in motion and is used much more in hand with engineering. It is used to relate viscosity, density, temperature, and other qualities of fluids with each other while in motion with time and space dependence. The applications for fluid dynamics are much more numerous than fluid statics by far.

How the mixing, or lack thereof, of liquids works is still a very relevant question in fluid dynamics to this day. Navier and Stokes found the aptly named Navier-Stokes equation which is primarily used to predict the movement of liquids using a Newtonian approach theoretically. While non-turbulent problems are easy to solve by hand, many real-world problems are not so orderly. This causes many fluid dynamics problems to be only practically solvable in a computer based on this equation or with real-world tests. There is expected to be significant error from computer simulations still, about 10 %. Real-world tests should always be done before considering a real-world application.

The most significant real-world application known to the author of non-mixing flow is for the steel industry and the creation of hollow ceramic beads used to facilitate uniform casting. These beads are used in the current casting method for steel, continuous casting, and their use causes fewer defects in the steel run and thus a stronger steel. The better the bead used, the better the product. Their use in this process is shown in Fig. 1 where the beads result in higher quality steel and so a much more marketable steel[2].

During the creation of these ceramic beads, two highly reactive chemicals (where the reaction happens effectively instantly) are mixed and fed through a sprayer as shown in Fig. 2. This sprayer mixes the two chemicals into the air where the drying process causes them to form hollow capsules. It is important the mixing occurs in the air otherwise a key design - the sphere's hollowness - will not exist. This means as much of the mixing as possible needs to happen in the air; this means minimizing as much of the mixing of pipe flow as possible [2].

Pipe flow can be manipulated by the boundary conditions of the enclosing pipe. Sufficient understanding of a t-junction pipe, a pipe with two inlets and one outlet, and the effects it has on mixing might show a way to reduce pipe flow mixing. If successful, new pipe designs could be a cheap and effective way to refit current manufacturing methods of these beads. This could pass on a cheaper cost to the final consumer resulting in cheaper construction costs for large buildings, commercial ships, and more exports as American steel becomes more price competitive in world markets. This is not including tax revenue generated from exports or the cheaper purchasing of advanced steel equipment for military products [2].

THEORY

Types of Flow

In fluid dynamics, a fluid can flow in many ways, but when constrained within a circular pipe it has two forms of flow. These two forms are turbulent and laminar flow shown in Fig. 3 with their average radial velocity. Those velocities form their velocity profile.

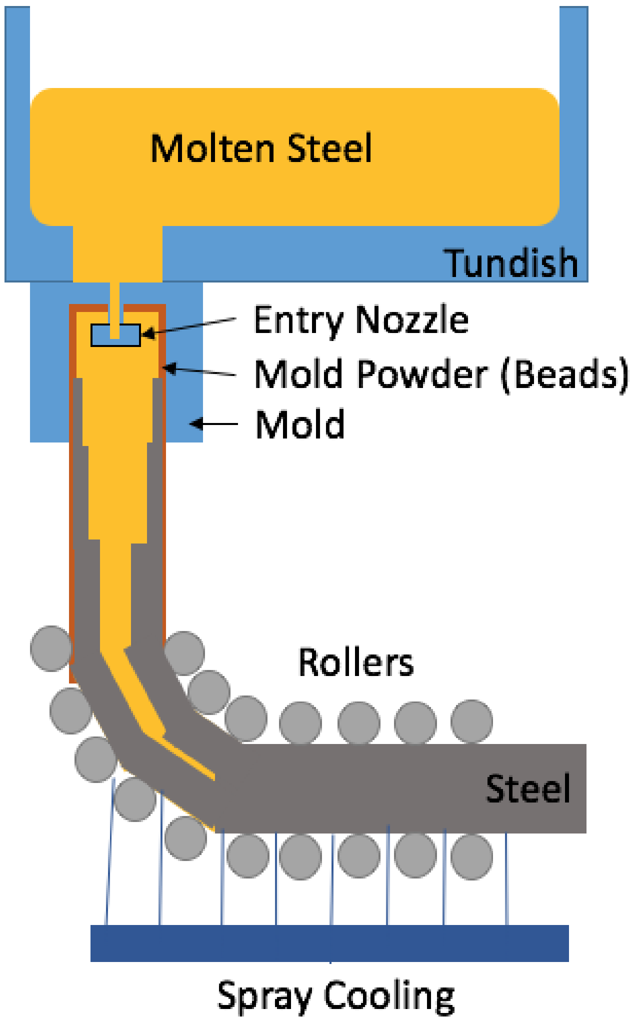

FIG. 1: The process of steelmaking starts with the tundish, a large reservoir, which is filled with the molten steel. This tundish always is filled with molten steel and fills a hanging mold. Mold powder is used to keep the steel uniform and without defects.

Turbulent flow is used to describe pipe flow when there exists eddy currents, nonuniform currents of varying velocity. This form of flow, as expected, is the harder of the two to model as it interacts with itself more. To analyze these types of flow, a person would use statistical mechanics to find common trends as the system tends to be chaotic and ever-changing.

Laminar flow is much more uniform. All of its velocity vectors point in the same direction. This makes it preferable to work within precision applications. The problem is that laminar flow can only occur at lower speeds in smaller pipe inner diameters (IDs). For this experiment, we will focus on the laminar case as it is more predictable.

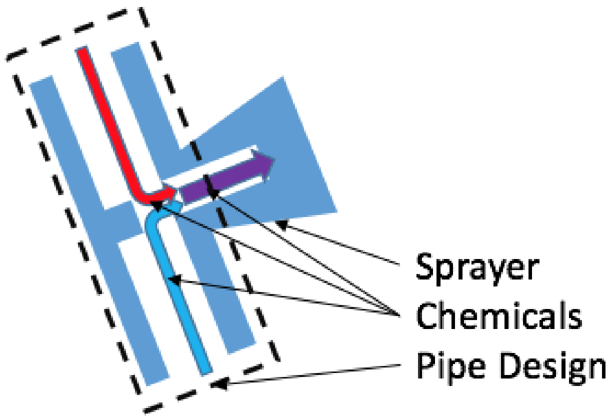

FIG. 2: The sprayer is used as a way to mix liquids right before they enter they air. The sprayer turns high pressure flow into a fine mist.

Reynolds Number and Determining Flow Regime [3]

To determine which kind of flow is in a pipe flow we can look at the flow's Reynolds number. The Reynolds number is simply the ratio of inertial forces to viscous forces. The viscous force is directly related to the kinematic viscosity of the fluid ν, but the inertial forces are derived to be related to the average velocity V_{avg} and the Hydraulic diameter D_h seen to be

$$Re = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{V_{avg} D_h}{\nu}. \tag{1}$$

The hydraulic diameter is defined to be

$$D_h = \frac{4A_c}{p},$$

where A_c is the cross-sectional area of the pipe, and p is the wetted perimeter or the perimeter of the boundary which holds the water (typically a pipes ID). For circular pipes of diameter D we see

$$D_h = \frac{4\left(\frac{\pi D^2}{4}\right)}{\pi D} = D$$

Shown in Table I is how the Reynolds Number relates to which flow is present. These values are experimentally determined for a uniform circular pipe in normal conditions. There is something to note however in the table, and that is the presence of a transition zone. The transition zone is the Reynolds Number where the fluid flow randomly switches between laminar flow and turbulent flow. The point between the transition zone and the laminar zone is the critical Reynolds number. Under normal conditions in an average room, the number

TABLE I: The typical industry standard for application of Reynolds number for a circular pipe. [3]

Laminar	Re <2300
Transition	2300 <Re <4000
Turbulent	4000 <Re

is near 2300, but this can change based on a multitude of factors including pipe roughness, pipe vibrations, and fluctuations in flow. These can be presently controlled in lab settings to move the critical Reynolds number from 2,300 to near 100,000.

Velocity Profiles[3]

Both types of flow, laminar and turbulent, have a velocity profile, the curve generated from the average velocity in a section of pipe. Both flows differ in these but share one main characteristic in their velocity profiles, the boundary condition. According to the established theory, the velocity flow through the pipe is continuous from the internal shear stress of the flow meaning that since the wall has a velocity of zero the immediate flow against the wall is also zero. This is called the no-slip condition. The velocity increases until the center of the pipe (uniform circular pipe) where it reaches its maximum. Obviously between zero and the maximum velocity exists an average velocity.

The velocity profile differs between laminar flow and turbulent flow, however. While the no-slip condition still holds true for both of them as it always does, turbulent flow has eddy currents within its flow. These currents can flow radially in the pipe from the center. This confers momentum throughout the flow, so the maximum isn't as large. The end effect is a squished look for turbulent flow velocity profiles when compared to their laminar flow counterparts as seen in Fig. 3.

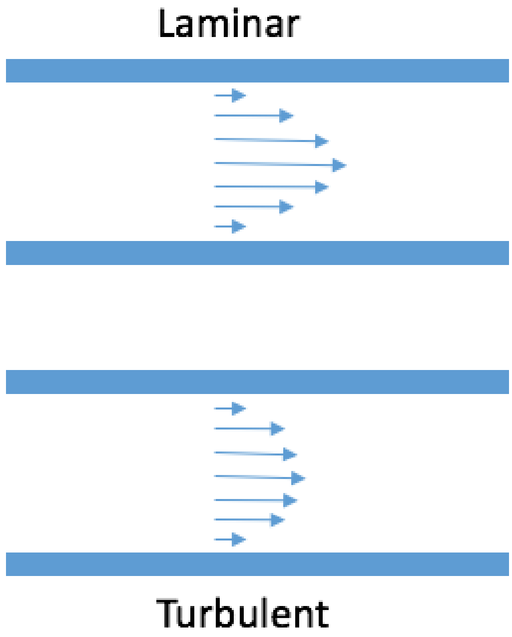

FIG. 3: This shows the two types of flow and their velocity profiles inside a uniform pipe.

Entry Lengths[3]

When flow enters a pipe for the first time, the no-slip condition takes effect. This causes the fluid in contact with the wetted perimeter to stop and causes a further frictional force on the next layer of fluid radially. This is what eventually leads to a fully developed velocity profile, but until then we have only a partially developed velocity profile. We characterize this portion as the entry length as shown in Fig. 4 where the steps to the final velocity profile are shown.

The size of the entry length for laminar flow $L_{h,laminar}$ is approximately.

$$L_{h,laminar} = 0.05DRe. \tag{2}$$

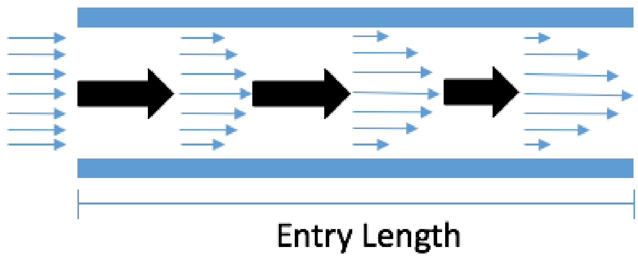

FIG. 4: The steps of forming a velocity profile inside a pipe. Starting on the left with an equal flow to the right with an established laminar flow, you see the effects the no-slip conditions has on forming the velocity profile.

This partially developed region that exists before this distance has elapsed has some downsides which experiments want to avoid. The biggest one is the lack of theory for these sections. Pipe flow deals almost exclusively with developed velocity profiles which only occur after the entry length.

Determining Reynolds Number[3]

To determine Reynolds Number we must use the known relation of Poiseuilles law [4]

$$V_{avg} = -\frac{\sin(\theta)\,\pi D^2}{32\nu}$$

where ν is the viscosity of the liquid and θ is the angle of inclination. Our buckets weren't directly overhead our head so an approximation will be made of a constant sloping angle. The buckets were located a 0.25 m away from the t-junction at a height of 0.75 m, for an angle of declination around 72°.

This value into our equation with the diameter of a quarter inch converted to meters gives a average velocity of 0.0132 $\frac{m}{s}$ with a viscosity of water of 8.9 10^{-3} Pa s. Using this with Eq. (1) we get a *Re* value of 0.009. This is a case of a very laminar flow.

Using this with Eq. (2) we calculate the required entry length to establish a laminar flow velocity profile is 0.0003 cm. This means that the entry length is mostly negligible and that entry effects resolve themselves almost instantly.

PROCEDURE

Overview

All construction was done in-house by the experimenter. The setup consisted of a flow source (raised buckets) and quarter inch ID tubing into a half inch ID ball joint to a custom t-junction. The connections basic overview seen in Fig. 5.

T-junction Construction

The tubing used for the t-junction is a clear poly-vinyl tube. An angle was drawn on a wood plank and a section of tube was cut whose one side matched that angle. This was done twice per angle as drawn, with seven angles for a total of 14 cut sections of the tube. The seven angles drawn were supposed to be in 10-degree increments, but the final products were remeasured for accuracy. Most angles did not result in the ideally desired output but were remeasured and was determined they had enough of a range of angles to be used.

The 14 cut sections of tubing were matched into seven pairs with another section of the same angle cut. These pairs were bonded together at the angle cut with clear PVC cement. This cement works by breaking down the top layer of tubing which causes a reaction where the tube swells. The PVC cement also has a liquid PVC resin. This resin hardens into clear PVC over an extended amount of time (approximately one hour) and finishes curing soon after (approximately one day).

This liquid is tacky to the touch but not strong enough to hold the tubing together while it cures. This problem required some creative joining at angles and not at a flat surface. It is important to note that since no internal removable material filled the joint while the PVC resin cured, some could have leaked through into the seam and the tubing's ID.

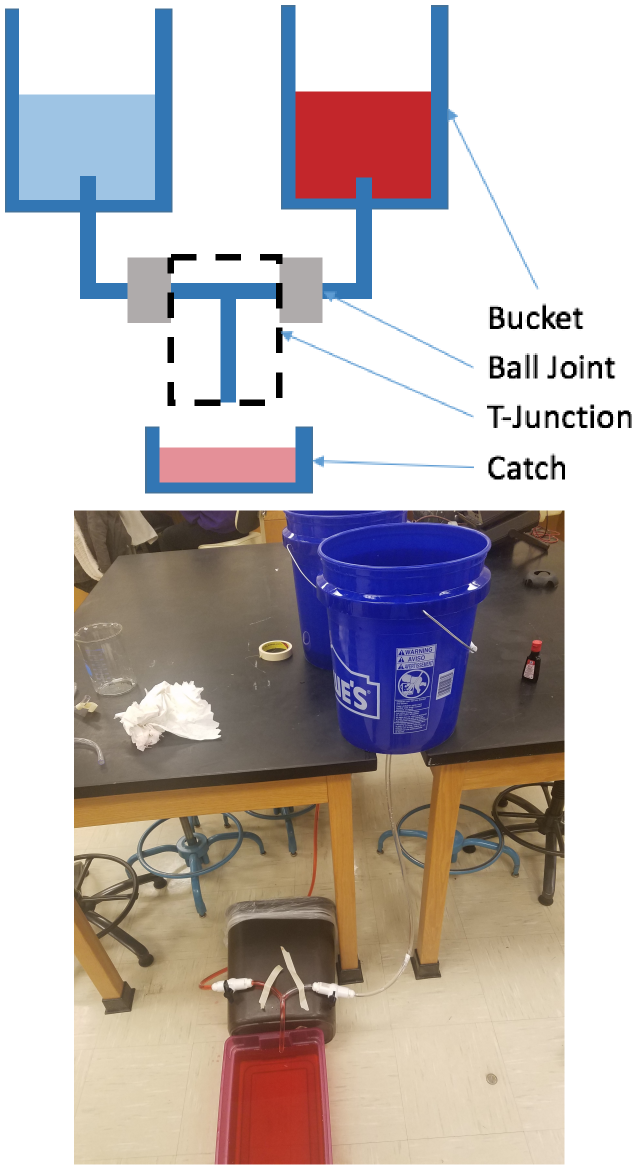

FIG. 5: The setup is very simple which helps with rapidly testing t-junctions. Each test took only around 30 minutes. Not pictured here is the camera used to photograph the dashed area during tests.

After the seven joints were cured, a cut was made into them. This was large enough to fit a new tube section which would serve as the outlet. This outlet was joined following the same procedures as for the first round of joining and so also had the same problems. All other parts were standard prefabrication parts.

Setup

After the t-junctions were made, the two inlets of a t-junction were fit into two ball joints respectively which each controlled the flow from one of two raised buckets. The buckets were filled with water with one of the bucket's water dyed red for data analysis. A catch tub was placed at the outlet of the t-junction to catch the outflow from the pipes shown in Fig. 5.

The two ball joints were opened, and water flowed into the t-junction, mixed at the joint and flowed out of the outlet. Multiple pictures were taken for analysis using a standard camera phone from a distance of between 5 and 10 cm. The joint was then photographed for analysis where the angle to be measured is the angle between the two inlets. The ball joints were closed, t-junction was removed, and replaced. The catch was drained, and the buckets' water level was checked and filled if necessary. The steps were repeated until all seven t-junctions were tested.

RESULTS & ANALYSIS

Measuring Mixing

From the dyed photos we were able to extrapolate mixing data. Since the dye used into the tube was red, and the background that the tube was on was black, all the red in the photo inside the region occupied by the clear tube was from the dye. When the concentrated dyed water meets clear water they mix, causing a dilution of the dye. Since the dye is diluted into a large solution, its concentration goes down.

Beer's law states that the absorbance of a solute in a solution is directly related to its concentration. This was extrapolated to say that if the dye is concentrated the redder it will appear in both our eyes and the camera. Since concentration changes as the solutions are mixed, the more mixing, the more concentrations and so the more different reds. The more reds that appear in solution can create a statistical distribution whose standard deviation from a mean relates the total amount of spread and so mixing between photos. It is important to note this will only work near the mixing location. If measured too far away, after significant mixing, the concentrations will reduce as the dye is slowly mixed equally thought-out solution. Defining near and far would obviously change as the speed and type of flow changed, but for this experiment all pictures were taken less than 5 cm down the flow. For joint 2 however, it seemed this was too far away as we only get a picture at the end of the mixing process.

A standard consumer camera measures three values per point measured on a scale from 0 (least intense) to 255 (Most intense). This scale is the RGB scale and stands for red, blue, and green. While any of these will work for our applications since our dye isn't perfectly red, it is so much redder then it is blue and green it makes more sense to look at only the red values.

To isolate the red from the image a color decomposition is done on the image. This separates the red, blue, and green channels into three layers. We then need to recompose the color layers while masking the blue and green channels at zero. This leaves a final image whose pixels have no blue or green component. We then crop the image and make the rest of the now white background transparent, so the only visible element is the tubing to be measured, this is shown in Fig. 6 where you see the change the process took on the photo[5].

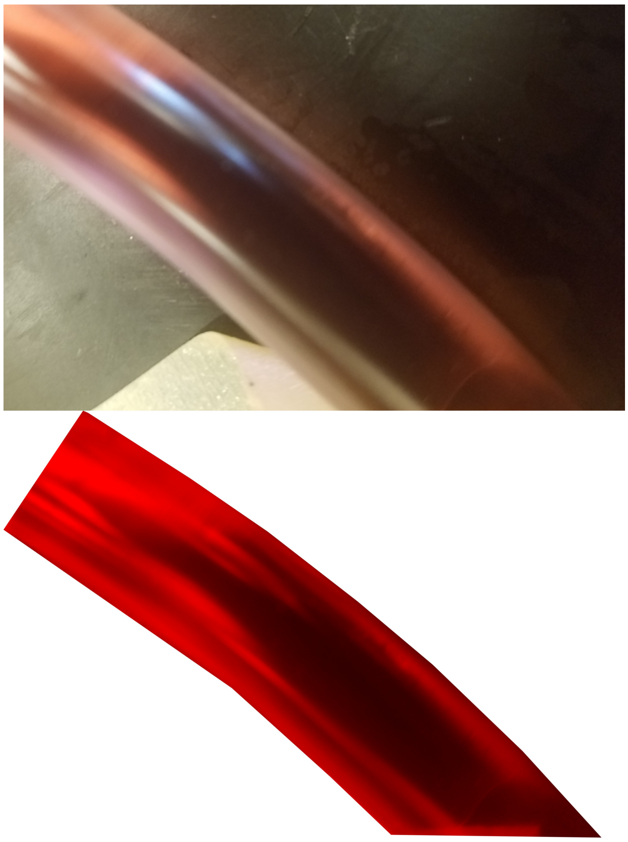

FIG. 6: An isolated pipe, Joint 3, is shown before photo manipulation and after with only its red channel. The bright spots are of high concentration and so less mixing, while the darker spots are well mixed lower concentration areas. The flows start from the top left and goes to the bottom right. Make special note of the bright areas near the no-slip condition walls in the lower right. This will be discussed in a later section.

A histogram was generated of the discrete values from 0 to 255 to plot the number of pixels vs. the intensity. This is an automated process as the pictures used contained millions of pixels. This graph had its standard deviation measured to see how big the spread is of intensities of the red dye.

The histogram is important also as a visual way to see what step in the mixing process the solution is. When the unmixed dye solution is made the peak for a histogram if measured would be a spike as the dye is equally distributed throughout the solution. As the solution has new not dyed water added, the spike begins to shift left, and a slope is formed. Eventually, a new spike farther left will form the same shape as the first but shifted left. These shapes weren't extensively studied in this paper but could be categorized to see what action is happening on a macro mixing scale.

Results

Looking at the histograms of the seven t-junctions in Fig. 7 measured we see that the photos were taken with multiple stages of mixing. Some almost done and some were starting. We can tell how far along they are by the development of the lower peak. This could explain some of the outliers on the graph. Although not the intended purpose of the experiment, this way of investigate flow through these kinds of histograms is a powerful tool.

A plot was created using the standard deviations of each histogram and plotting it against the joining angle and is shown in Fig. 8. This plot when first created had an outlier measured near an angle of 150 degrees. This caused a reinspection of the photo used to measure its value. It had a purple reflection from the plastic catch on it, which undoubtedly altered the results. This raises a valuable question about the validity of all the other points. The smooth poly-vinyl tubing was slightly shiny and could hold a reflection. This could as this data point shows, throw off measurements. If testing is redone, a matte clear tube should be used to avoid this issue. While this was left on the plot to show its value, it was not counted when doing a linear regression. Following the line we see that the most mixing happens at large angles of 180 degrees which is to be expected as the flows are opposing each other, at smaller angles the flows oppose each other less and so the mixing is less.

The line produced by linear regression is shown on Fig 8. This line has large error bounds on the slope of (15 $\pm$ 80%). This is from two data points, while nothing is wrong enough with two points from a data collection side to rule them out, they do have unique histograms. One of the two (histogram 3) has two sharp peaks, and the other (histogram 2) has one large peak with a trailing end. Histogram 2 suggests that the flow in the pipe has already been well mixed and is so far so that it has nothing of the first peak but the trailing. Histogram 3 is personally the most exciting of the two as it has two distinct peaks suggesting two zones within it of dye concentrations. These two zones do not mix much otherwise this histogram would have a large reading between the two peaks.

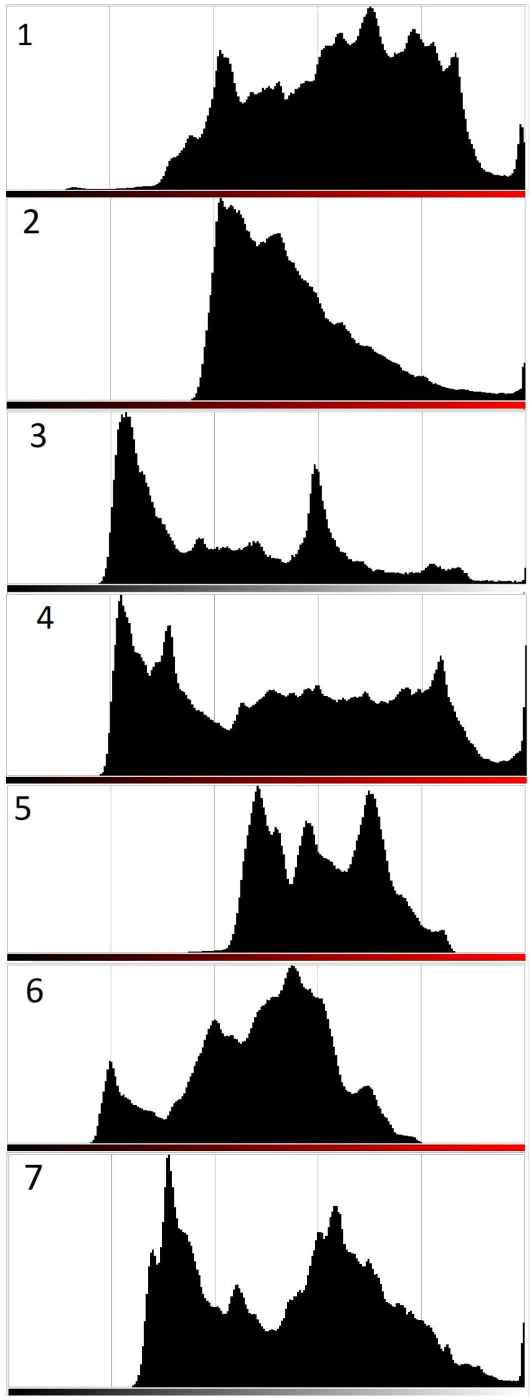

FIG. 7: All the histograms for the seven joints tested were labeled with a number and the angle they met at. The scale is from 0 to 255 on the red channel.

IMPROVEMENTS FOR FUTURE WORK

The histogram plots generated are interesting and could be very useful if taken correctly. The first main issue was the specular reflection from the shiny poly-vinyl plastic tubing that was used. New tubing would have to have a matte finish in order to stop these reflections. Not

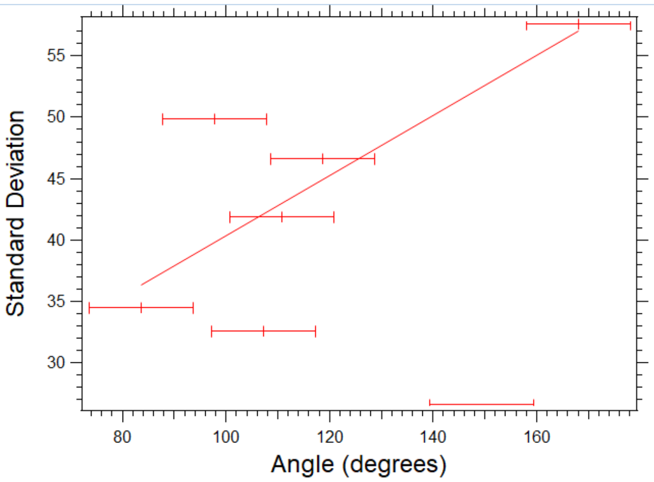

FIG. 8: The plot shows a weak linear regression model on the spread of standard deviation vs. angle. The lower right point was counted as an outlier because of a reflection on the photo taken.

only this, but the distance from the joint to the end of the photo needs to be well documented or the photo taking device mounted with a ruler in the photo so between images one has a reference point to make measurements. This is important so that one can compare how the histogram data changes as distance past a joint increases.

CONCLUSION

After this experiment, it was found that dull clear tubing is needed to minimize reflections and a constant color background for reference. Regardless of the technical difficulties from the reflections, some data was able to be collected well. The initial idea of graphing standard deviation vs. angle was not very useful with a linear regression model, because it was found that the slope of the line had large error bounds of 80%. The trend in the linear regression is still within a positive range however and so suggests an upward trend. This trend shows that as angle increases so should mixing and vice verse. While this is not very useful, the histograms of color generated were. They could prove very useful in categorizing the state of a mixing system and to this author have not been used in analyzing fluid mixing in the field. Further investigations should be done towards this end as this is the most important accomplishment of this paper.

[1] *Essential highlights of the history of fluid mechanics*, Website (2005).

[2] J. S. Theiss, personal communication.

[3] *Introduction to pipe flow*, Website (2011), universitetet i Oslo, www.uio.no/studier/emner/matnat/math/MEK4450/h11/undervisningsmateriale/modul-5/.

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