Examining the Turbulence of a Buoyant Plume in a Flume

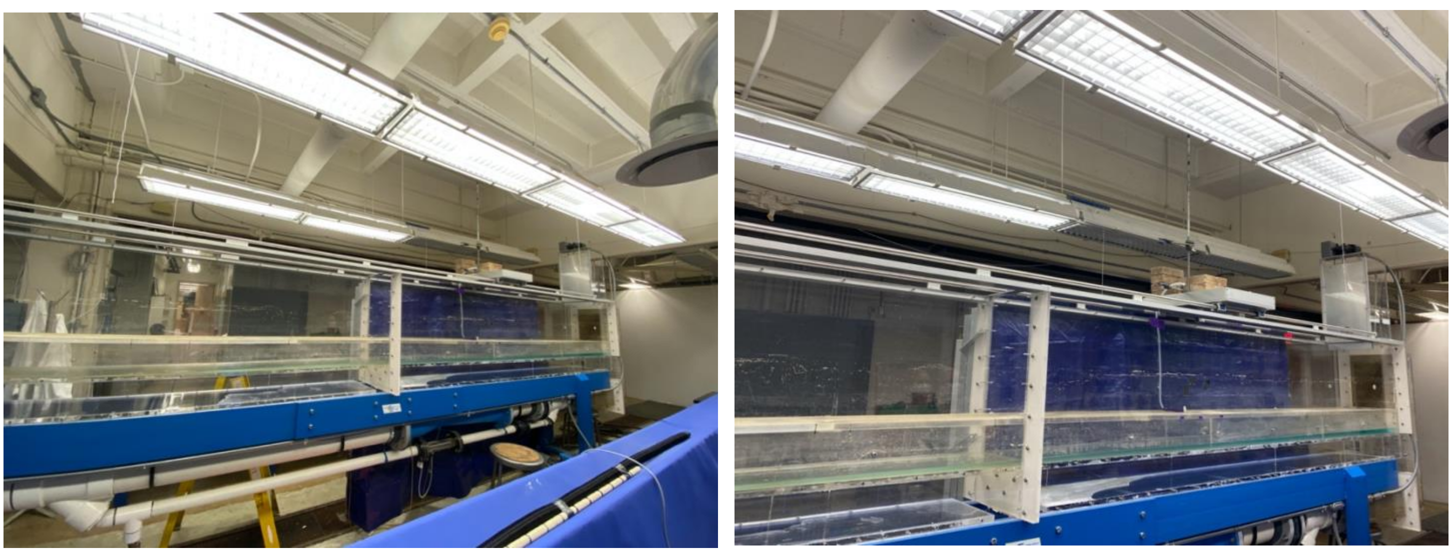
ABSTRACT

The study of buoyant plumes is crucial to understanding fluid dynamics within an environment. This can often be applied to real world events when discussing the spread of buoyant pollutants in air and water. In this study, we investigated the turbulent nature of a buoyant plume within a background flow. In order to do this, we used a flume to create the background flow and a flow meter to create a buoyant plume. The flow meter pushed a buoyant blue liquid solution through a tube into the flume. The different flume speeds used were 0.04m/s 0.1m/s, 0.2m/s, and 0.3m/s. The size of the plume was controlled by the flow meter, and we used flows of 10 ml/min, 20 ml/min, 30 ml/min, 40ml/min, 50ml/min, 100ml/min, and 140 ml/min. We used the programming platform MatLab to quantify the results into dark, medium, and light shades of the blue solution, to determine the low, medium, and high concentrations of the plume as it is dispersed within the flume. With the Vectrino profiles, we measured 3D velocities allowing us to create velocity maps at three locations down the flume and away from the plume source. The results of this study have shown that the highest concentration of the plume is located near the source of the plume with an increase of mixing as the plume moved down the distance of the flume. We also found that most of the 3D mixing occurred within 1cm of the bottom boundary, due to the large vertical shear seen in the along and across flow velocity components. The shift in shear between the along and across velocity component along the flume, could be due to the vortices' created downstream of the buoyant plume point source. Data from this study can provide a background for further investigation of buoyant plumes of varying buoyancies, from different source configurations and within different background vs plume flows environments.

I. INTRODUCTION

Buoyancy is the ability to float in a fluid or gas. In this experiment, we observe the turbulence of a buoyant plume in moving water with a boundary layer. A flume is a deep narrow

channel or ravine with flow of water through it. In order to properly gather data for this experiment, we used a controlled flume to construct an experiment with a buoyant plume. This experiment was observed through color concentrations of the plume, as well as 3D velocities using a Vectrino profiler. A Vectrino profiler is an acoustic doppler current profiler that can measure the 3D velocity at rates up to 100 Hz. A picture of the Vectrino Profiler is shown to the left. MatLab is a programming platform that is used to analyze the image and velocity data, which is further used to quantify and describe the flow patterns associated with the buoyant plume.



This is a picture of the flume set-up that was used to create a controlled environment for out experiment. Typically, the flume is filled with water about two-thirds of the way.

In order to properly begin this experiment, we needed to find the velocity of the flow within our flume. In order to do this, we used the Vectrino profiler to measure velocities at the different frequency levels that were used on the flume. The speeds we wanted were 0.3m/s, 0.2m/s, 0.1m/s, and 0.04m/s. By recording the frequency levels, we were able to create a histogram (Figure 1) of the data to determine the approximate velocity of the flume.

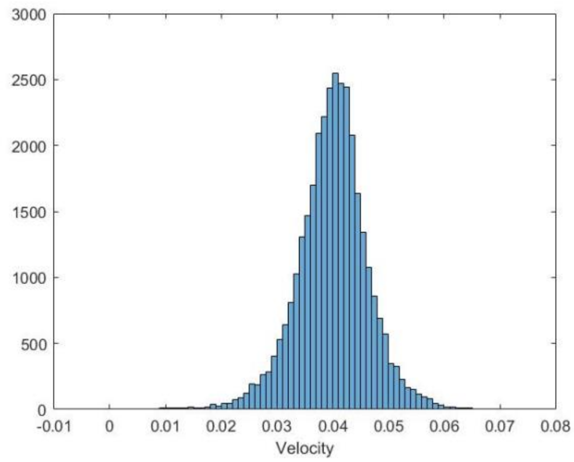


Figure 1: This depicts a histogram to determine the along flow water velocity of the 11hz frequency in the flume. The histogram shows that the velocity was approximately 0.04m/s.

Another measure that was necessary before determining the velocities of the water column, was a minimum signal-to-noise ratio (SNR) of 30 dB in order to obtain accurate results. This was achieved through seeding of the water using silver coated glass spheres with a buoyancy of 1.13 kg/m^3. In accordance with minimal SNR values dictated in the Vectrino manual, we kept our SNR above 30 for the duration of the experiments.

Throughout the experiment, our buoyant plume is a solution made with nine parts water, one-part Isopropyl alcohol, and 5mL of blue dye. The average density for this solution was 0.978g/cm^3, whereas the density of the background water in the flume was roughly 1.00g/cm^3.

II. EXPERIMENTAL SET-UP

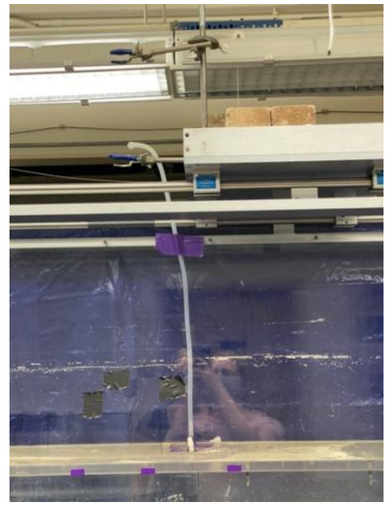
Materials:

- Flume
- Flow meter that pushes liquid or water
- Tubing
- Water
- 99% isopropyl alcohol
- Blue dye
- Beakers with mL measurements
- Stirring rod
- Camera
- Vectrino Profiler

Part A: Dye Experiment

This experiment was completed in a controlled environment in a flume with a width of 30cm, max height of 40cm, and a length of approximately 6m long. After obtaining our materials, we began by creating our buoyant solution, which was a solution of one parts 99% isopropyl alcohol, nine parts water, and approximately 5mL of blue dye. We created around one liter of this solution for each experiment conducted. Each buoyant solution had a density of approximately 0.978 g/cm^3, while the density of the water in the flume was 0.9984 g/cm^3. Before beginning the experiment, setting up a proper environment to effectively capture the dye on camera was needed. To do this, we created a white background for the flume with lights behind the white curtains to illuminate the flow better.

After, the background was in place, the blue solution then was moved to a beaker that is attached to the flow meter through clear tubing. The plume entrance, pointed directly upwards, was located 2m downstream from the head of the flume, and was connected through tubing to the flow meter as shown in the pictures below. In order to secure the tubing, we used clear tape to avoid the tape being picked up by the camera.



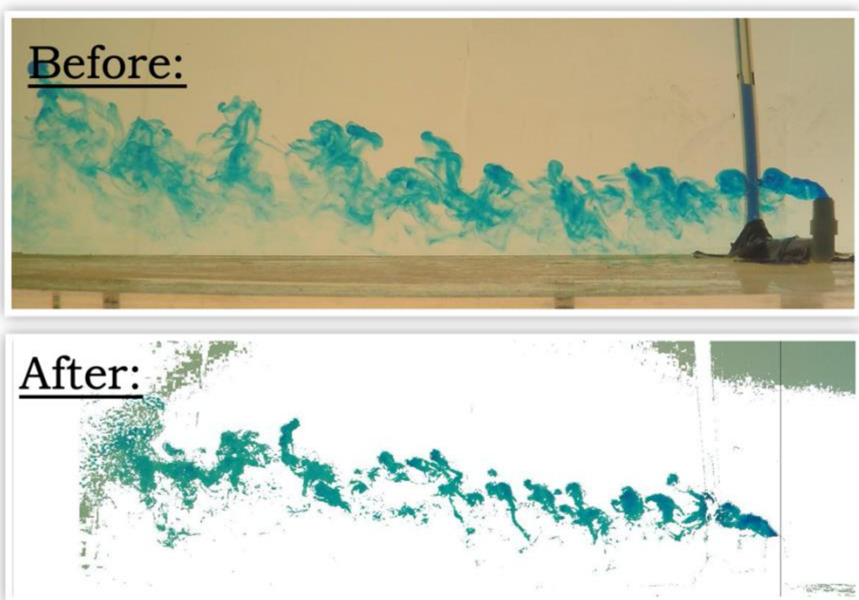
Once the tubing was set up, we set up a camera to capture the flow from 2m to 3m along the flume. At each background speed (0.04 m/s, 0.1 m/s, 0.2 m/s and 0.3 m/s) we conducted experiments with flow rates of 10 mL/min, 50 mL/min, 100 mL/min and 140 mL/min. For each experiment, we recorded 1 minute of footage. After completing all of the experiments, we used MatLab to analyze concentrations of blues in the water through their image processing software. To identify actual concentrations and correlate them with the perceived color concentrations, we created a range of known water and dye concentrations and captured them on camera under the same lighting conditions as the experiments. The concentrations of the high, medium, and low values are provided below:

Finding concentration of the blue-

1. 1mL dye/1400mL water was stock
2. High concentration-
    a. 1.78*10^-4 to 7.9*10^-5 mL dye/mL water
    b. 79-178PPM
3. Medium concentration

    a. 3.76*10^-5 mL dye/mL water
    b. 37.6PPM
4. Low concentration
    a. 1.83*10^-5 mL dye/mL water
    b. 18.3PPM

Then we used Matlab to quantify the red, green, and blue (RGB) values for the pictures that matched our RGB values for the concentration gradients we found. (Figure 2) In order to do this, we processed 10 seconds of the video that we captured with the camera through 3 separate files that read 30 frames per second to get a total of 300 frames. Thus, we were able to correlated the actual dye concentrations (low, medium, and high) to their equivalent color concentration values, that are specified in the calculations above.



Figures 2 & 3: The top figure depicts the buoyant blue solution within the flume and the bottom figure depicts the blue concentrations that were picked out using MatLab's image processing software. This specific picture was from the experiment with a flume speed of 0.1m/s and a flow rate of 100mL/min.

Part B: Changing Velocities Experiment

In order to set up the Vectrino profiler, we submerged the device into the flume approximately 7cm from the bottom of the tank. It is also important to have the Vectrino standing directly upward and level so that it does not alter the readings for the velocities. We were able to stabilize the Vectrino with a lab stand and clamps, to ensure that the Vectrino was held tightly and did not vibrate during the experiment.

Before conducting the experiment, we completed a series of background measurements at each of the predetermined flume speeds (0.04 m/s, 0.1 m/s, 0.2 m/s and 0.3 m/s). For each speed, 1 minute of data was recorded at 100Hz. This was completed at three locations in the flume, directly downstream of the plume entrance and downstream at 2 inch intervals. Each experiment in Part A was repeated with the Vectrino recording 1 minute of data at each of the three locations downstream.

We then used the data at these three locations to analyze the flow in the along, across and vertical directions. In order to do this, we used MatLab to calculate the mean velocities for the different components (along, across and vertical) for each experimental setup at each location. (Figures 4 & 5) This allowed us to observe how the velocity components varied with depth from the bottom boundary layer and up to 2.4 cm.

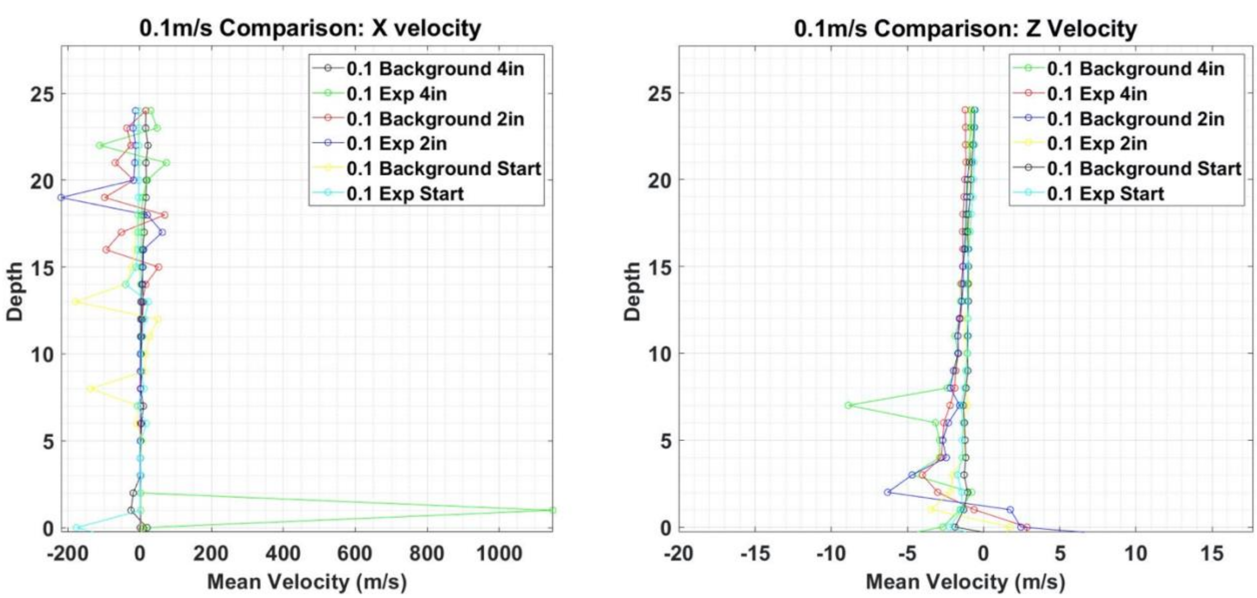
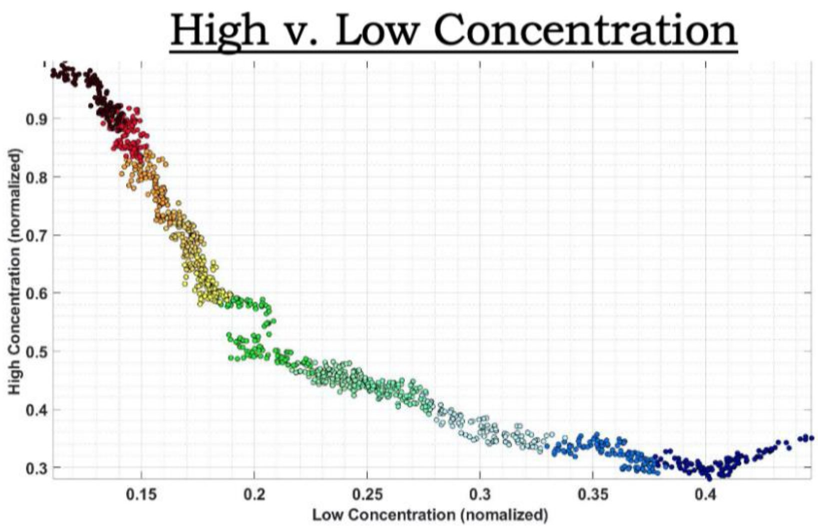


Figure 4 & 5: The above figures show the mean x (cross-sectional) and z (vertical) velocities as a function of depth from the bottom boundary of the flume, for a background flow of 0.1 m/s and plume flow rate of 100 mL/min.

III. RESULTS

We were able to determine three levels of blue concentrations, later referred to as "low", "medium", and "high" values. The low concentration is 18.3PPM, medium is 37.6PPM and the high ranges from 79-178ppm. We also found that the density difference between our solution and the water in the flume was 0.0204 g/cm^3. General trends depict that as the high concentration decreased, the medium and low concentrations increased. (Figure 6 & 7)



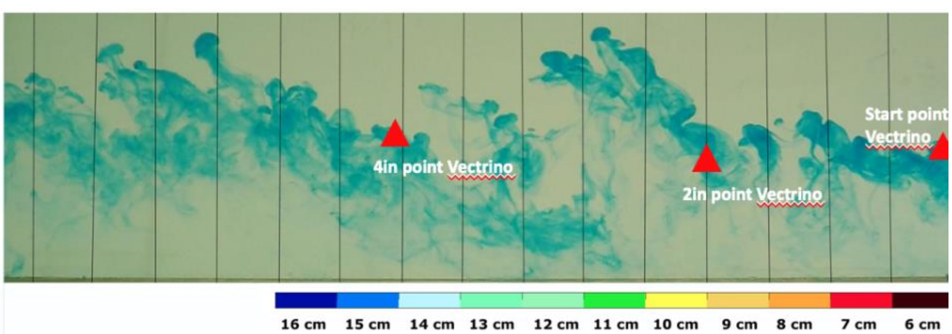


Figure 6 & 7: Figure 6 shows the occurrence of the low (18.3PPM) versus high (37.6PPM) dye concentrations, colored by distance downstream of the plume entrance. Figure 7 shows an image of the section with the location of each color used in figure 6.

There was a clear trend in each of the experiments with the greatest concentrations of blue at the source of the plume, which decreased as the water travelled downstream. We also found that the highest plume flow rates produced the largest values of the high dye concentration and the most significant decrease in high concentrations down the length of the flume. Also, by examining the minimum and maximum values for each concentration, we were also able to understand the spread of the concentrations within each water column. We believe that the higher the speed of the flume, the more mixing will occur both along and across the flow, which creates the greatest increase in the medium and low concentrations.

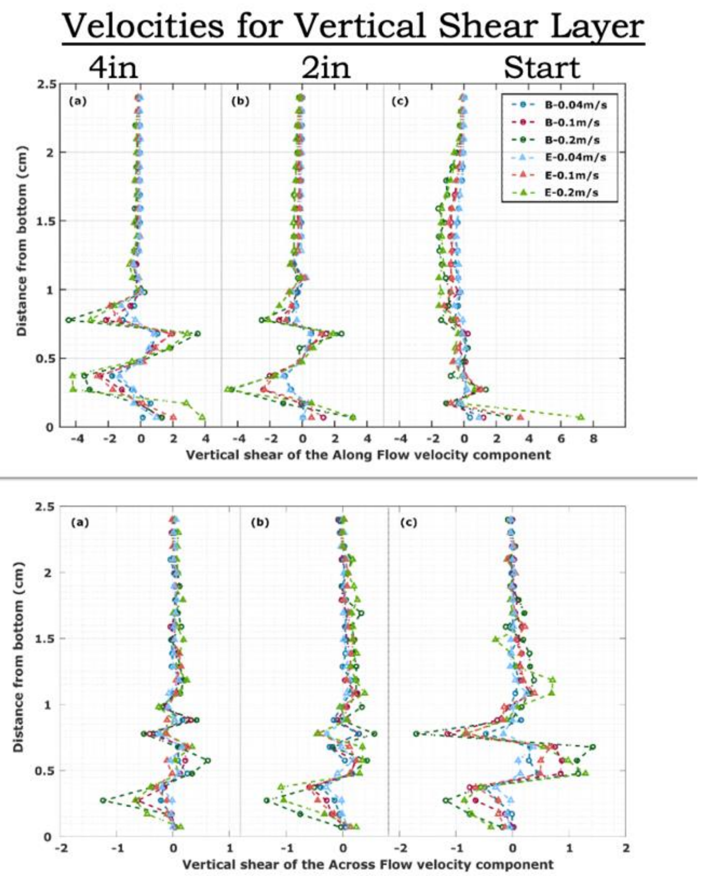


Figure 8: The above figure details the vertical shear of the along and across flow components in relation to depth at the start, 2in down flume and then 4in down flume. Background values are indicated as ”B” and experiment values are “E”.

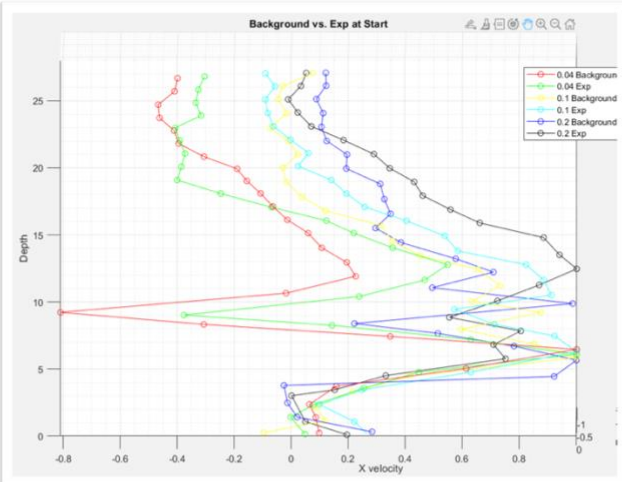
In analyzing the velocities from the Vectrino profiler data, we found large changes in the vertical shear of the along and across flow within the bottom 1cm. (Figure 8). The ratio of the along flow to the crossflow for the different flow speeds ranged on average between 2 and 10. Outside of the bottom 1cm section, some experiments did see a larger ratio of the along and across flows due to a reduced crossflow. We found that as we moved vertically in water column, the along flow tended to the background flow value, as it is outside the influence of the bottom boundary. This means there is a large potential for mixing within the bottom 1cm, which decreases further up in the water column due to a reduction in the shear. Above this 1cm bottom layer, the mixing is suppressed by the positive buoyancy of the plume.

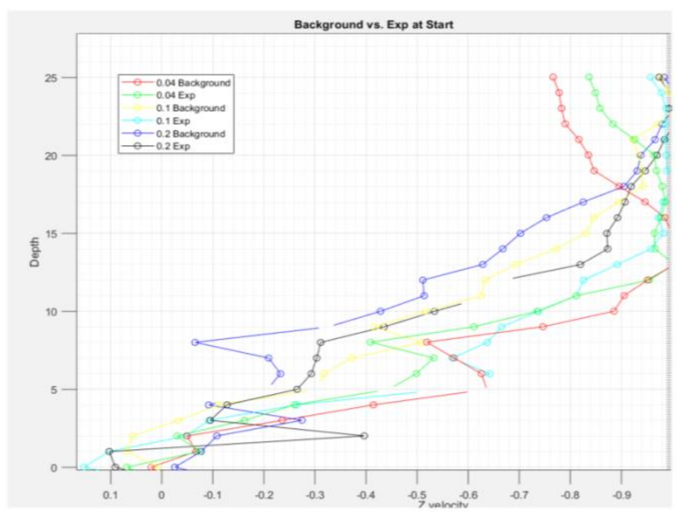
Equations:

- Reynold's Number
    - $Re= (UL)/\nu$
- Strouhal
    - $Sr= (fL)/\nu$

Here U is the mean speed, L mean dimension, f mean oscillation and ν is the kinematic viscosity of water.

Based on our flow speeds and the size of our plume entrance, our Reynolds numbers for the three background flows (0.04 m/s, 0.1 m/s and 0.2 m/s) were 286, 740 and 1420. Using this, we found that our Strouhal values for each flume speed (0.04 m/s, 0.1 m/s, 0.2 m/s) are as follows: 0.1995, 0.2093 0.2129. (Fey 1998) We then were able to compare these values with the calculated mean values of the X (crossflow) and Z (vertical flow) velocities. Figures (9 & 10) The below figures show the X and Z velocities for a background flow speed of 0.1m/s and a plume flow rate of 100 mL/min. These were compared to the depth from the bottom of the tank, with the first centimeter located in the shear layer. By comparing these, we were able to confirm that there was more crossflow directly downstream of the plume entrance than further down the flume.





Figures 9 & 10: These figured depict the mean X (left figure) and Z (right figure) velocities in relation to depth directly downstream of the plume entrance for a background flow speed of 0.1 m/s and plume flow rate of 100 mL/min.

IV. DISCUSSION & CONCLUSION

The concentration of the blue dye solution was examined to investigate variation in concentration levels downstream of the buoyant plume point source. Within the area of water that was analyzed, we were able to determine that there are greater concentrations of the dye in areas that are closer to the point source of the buoyant plume. We expected to find that as the dark concentrations decreased, the concentrations of medium and light dye would increase. By analyzing the data using MatLab, we were able to create graphs that depicted this trend. In relation to this, the measured velocities indicate that there is mixing due to vertical shearing of the along and across velocity components. This is partly due to the bottom boundary, as well as the shedding of eddies from the incoming plume and its cylinder. (Fig 5) We also saw evidence of vortical structures created due to the introduction of a buoyant plume into a uniform stream (these show up as inconsistencies in the 'green' area in figures 4 and 5). Here, it is postulated that these wake vortices originate in the laminar boundary layer of the wall, and in fact travel upward. This can be due to the fact that wake vortices are intrinsically unsteady and the angle trajectory of the flow at different velocities can cause this.

Based on our Reynold's numbers, we found that our three experimental setups spanned three separate regimes. (Williamson 488) Our lower speeds transitioned from the wake-transition regime (Re 190-260), to the fine scale three-dimensional instability (Re 261 and 999). Lastly, our highest speeds moved into a shear-layer transition regime, with Reynold's numbers of 1000,200,00. The wake transition regime is where we see finer scale streamwise vortices, with a length scale around one diameter. As we increase in disorder, the primary wake instability begins to behave like laminar shedding, with the exception of a fine scale streamwise vortex structure. From this point as Reynold's number increases, the 3D instability becomes more disordered and increases the length of formation region. (Fric 43) In higher speed, we see the shear layer transition where Strouhal numbers decrease, base suction increases, and the 2D Reynold stress levels increase. This is caused by developing instability of separating shear layers from sides of the body.

If this experiment were to be repeated, we would alter the set-up for the input of the plume into the background flow. Specifically, we would create a false bottom in the flume, such that the plume entrance is flush with the bottom boundary. This will eliminate any mixing due to eddy shedding and cross flow shear. Also, as we examined only 10 seconds of the footage in the dye experiment, we would extend the time at which we observe the concentrations of the flow to 30 seconds, similar to the Vectrino data analysis. Finally, we would change the configuration of the plume shape to expand on the point source. Future research may look into how pollutants disperse through water or air as a result of this turbulent mixing. Or the behavior of wild fire in a background flow. Also, we may examine air pollution that is close to the ground, such as exhaust from a car. This can relate to our set up and it is found that sources of pollutants such as these are in a similar Reynolds number regime as our experiment.

V. REFERENCES

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File notation:

- "11.24" Folder is the Dye Experiment – we used Exp4 data
  - Then labeled by flume speed (0.1ms, 02ms, 0.3ms, 11Hz), then my by flow meter speed (10,50,100,140)
    - Files saved by flume speed, then flow meter speed (Ex: 0.1_10 is 0.1ms and 10mL/min)
  - Files with "_min_and_max "are the minimum and maximum values of the RGB values for the dye experiment.
  - Files with "DML" is saving the dark, medium, and light mean variables
  - Files with "analyzed_RGB" are the saved RGB values

    - Files with "_conc" are the concentrations
    - Files beginning with "Exp" are the data files pulled form video
- "1.8concentrations"
    - The RGB values for the pictures of our concentrations
    - 1.1000-1mL dye, 100mL water
    - 50.1950- 50mL of 1/1400 solution, 1950mL water
    - 100.1900- 100mL of 1/1400 solution, 1900mL water
    - 200.1800- 200mL of 1/400 solution, 1800mL water
    - 400.1600-400mL of 1/1400 solution, 1600mL water
- "Experiment" folder is experiment for velocity Measurements
    - Folder with "Vectrino_Data" is the raw MatLab files
    - Folder with "Analyzed"are the analyzed vectrino files with variables saved for each speed and location
        - Ex: 0.1ms_100_2in.mat means it is flume speed 0.1m/s, flow meter speed 100mL/min at the 2in location
    - "Experiment_Vectrino_Data" folder has the variables for the dark, medium, and light means
- "Background" folder is background for velocity Measurements
    - Folders and naming are the same as experiment folder
- MatLab Scripts Used
    - BuoyantPlumeDyeConcentration
    - compareVectrinoData
    - findDyeConcentrationFromPics
    - findingConcentrations_RGB
    - identifyingLocationConcentrations
    - meanConcentration
    - movingAverageComparison
    - processVectrinoData
    - readVideoData