



A mechanical design approach to testing fluid turbulence over a rough surface

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NONTECHNICAL SUMMARY

This experiment took a mechanical design approach to analyzing aquatic energy loss through observing small scale water movement across a rough surface. The project was conducted in three phases. The first involved designing and building an instrument to observe water movement and critically accounting for factors such as material costs and environmental limitations. Phase two involved repeated deployment of the instrument, evaluation of its structural integrity, and data collection regarding the scientific issue of water movement. Finally, phase three integrated an in depth examination of one design aspect, specifically the portion of the design used to imitate surface roughness. This led to the observation of the importance of surface areas of the materials used and how this could be implemented when considering possible design changes.

ABSTRACT

This experiment was done as a study of the design and build process for engineering an instrument to address a scientific research question in ocean science. The question for this project was inspired by recent developments in tidal energy extraction and chose to analyze the assumption that fluid energy dissipated due to turbulence has a linear correlation with distance from a uniformly rough surface in an aquatic setting. An instrument was designed and built, taking into account the predetermined aspects needed to be considered to answer this question. The instrument was deployed in Barkley Sound, Vancouver Island, BC three times during January 2013 to depths ranging from 15 m to 40 m. Due to a lack of adequate current flow at the deployment sites, the subsequent data collection was unsuccessful. Following the design/build, deployment, and attempted data collection stages, a critical analysis of the design aspect was conducted. It focused on the elements of the instrument that induced the experimental turbulence. Acrylic sheets formed as triangles with their faces set perpendicular to the direction of water flow simulated a rough seafloor surface. Triangles, with a ratio of 1:4 to the originals, were placed in a laboratory flow tank. Ink dye was used to indicate turbulent flow. Changes in the velocity were recorded on video and provided the means to derive the energy dissipation due to the rough surface. The results suggested that the combination of the triangle height and flow velocity was the dominating factor in determining energy loss due to turbulence.

Understanding and harnessing tidal energy is a necessary step to providing unlimited renewable energy on a small scale. To achieve this, many aspects of the energy availability at a given site must first be measured. A primary concern is to know how much energy dissipation is occurring, which refers to diffusion due to random induced particle scattering (Egbert, 2000). While much of the dissipation will be due to

vertical mixing, such as over a sill, bottom turbulence over a significant area could become a contributing factor as well (Klymak 2005). By directly measuring the horizontal and vertical components of the current along the sea floor at various places, the differences in flow velocity between these points can then be assumed to represent the energy dissipated through turbulence. Knowledge of tidal patterns and energy dissipation

also provides an understanding of the remaining energy available to be harnessed at a given site (Polagye 2010).

Equally important is to determine how much energy is initially provided through an analysis of the tidal amplitudes at a given location (Thomson 2011). Then the amount of energy that is being removed through turbulence and mixing will need to be measured and calculated. This, however, can be done in a number of different methods. Each of these could be limited by requirements for parameterizations and numerous assumptions.

This experiment proposed to explore the limitations of indirectly measuring bottom turbulence by analyzing the reduction of flow velocity over a rough surface between two points. The velocity changes were then assumed to be a representation of the kinetic energy flux of the flow. Energy reduction was also assumed to be a direct result of the induced turbulence.

This method oriented experiment focused also on the design and build process required to make an instrument that addresses the current question in ocean science. Specifically, it aimed to test the assumption that energy is dissipated due to turbulence in a linear fashion over various distances and that the ratio between energy loss and increasing distances is 1:1. That is, if the current velocity at two different points was measured and the velocity difference calculated, then if the distance between the two points was doubled, the velocity difference would be doubled as well. In order to test this, a platform was built to address the issues of how to measure the specific variables of this problem and to collect the necessary data. This instrument was then deployed in Barkley Sound, Vancouver Island, BC. Following recovery, certain design aspects were then analyzed to determine their feasibility and various effects on the amount and distribution of turbulence created by the instrument.

METHODS

This experiment was completed in a three phase process. The first focused on the requirements to design and build an instrument centered on the scientific question of measuring energy flux due to turbulence. The second involved the deployment and data collection process. This was also an observation of the functionality of the instrument and was dependent on the successful implementation of the design and construction. Completion of the second phase and analysis of the collected data would also allow for the initial scientific question to be answered. Regardless of the results from the first two, the final phase involved an in depth analysis of a critical aspect of the design. This gave rise to a new experiment to determine what design qualities would have the greatest impact on the energy flux through the instrument.

Phase I – Design and Build Process

The purpose of the instrument was to determine if energy in the form of current velocity dissipates as a linear function with distance over a uniformly rough surface. In order to design an instrument to address this question, the following issues were considered:

1. The independent variable is the distance over which the energy is dissipating. Thus, what will be the dimensions of the area of data collection, and how will those dimensions be adjusted?
2. If the current energy is dissipating in the form of turbulence, how will the turbulence be simulated?
3. What sensors will be used to collect data and what are their limitations?
4. How will the platform be deployed?

Figure 1 shows the original design concept for the instrument.

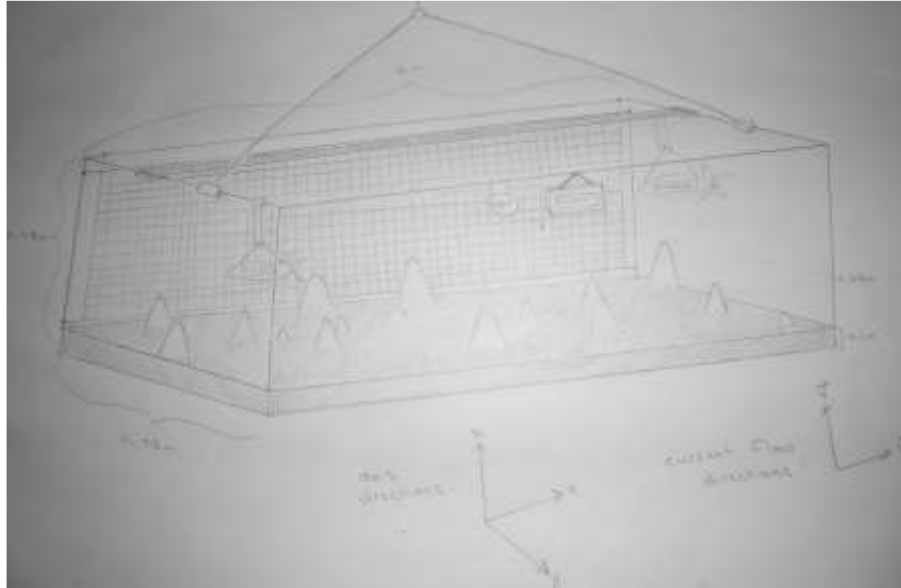


Figure 1. Original design drawing for relative locations of items on the platform: Box frame, two current meters (one can have its position adjusted on a mounted track), GoPro HD Camera, additional light, grid, base with cones to induce turbulence. Note: fin to align box with current is not shown.

Figure 2 shows the completed instrument, hereby referred as the Induced Turbulence Seafloor Instrument (ITSI). The frame was constructed from ½ in. polyvinyl chloride (PVC) pipe and surface roughness was imitated using acrylic sheeting along the bottom of the box. Water was allowed to enter the PVC frame to reduce the overall buoyancy of the entire instrument. A grid was placed along the rear wall of ITSI using wire mesh that had 0.5 cm x 0.5 cm spacings and neon yarn that was threaded to create 5 cm x 5 cm squares. Opposite the grid, a length of ¼ in. PVC pipe was placed (Fig. 2) to serve as a mount for a GoPro HD Hero2 camera which would face the grid and record water particle movement throughout the length of ITSI during deployment. The housing for the camera was waterproof down to 60m, so that resulted in limitations when choosing the deployment sites.

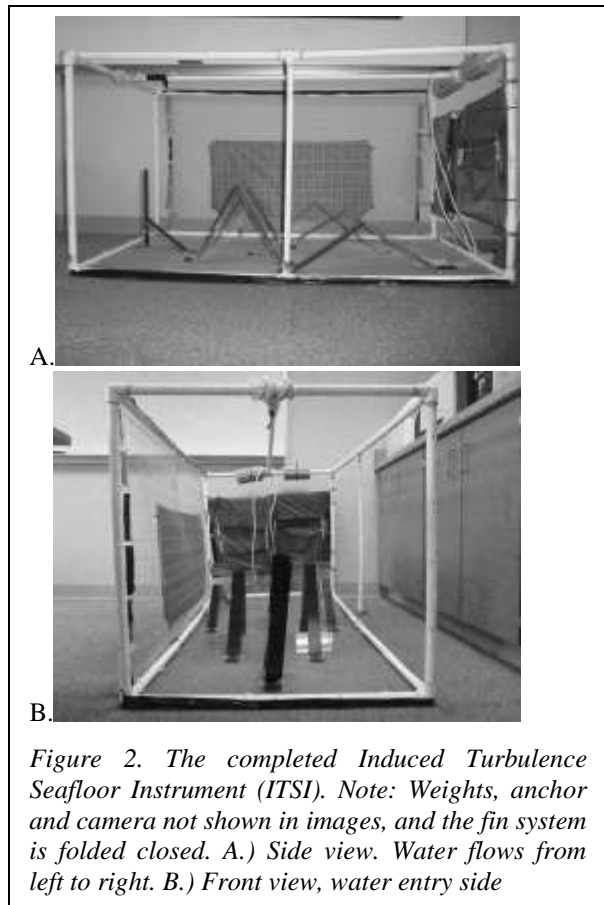


Figure 2. The completed Induced Turbulence Seafloor Instrument (ITSI). Note: Weights, anchor and camera not shown in images, and the fin system is folded closed. A.) Side view. Water flows from left to right. B.) Front view, water entry side

Six angled acrylic sheets were mounted to form triangles on the bottom of ITSI, as shown in the top view of the instrument in figure 3. An important design objective was that during deployment, the box would be aligned with the current such that water would flow through its length and the faces of the acrylic sheets would be oriented perpendicular to the direction of current movement. Thus laminar flow through the box would be disturbed and the mean velocity of the water current would be reduced as energy was dissipated through the induced turbulence that forms over the sheets. This process would then be recorded against the grid using video for future analysis.

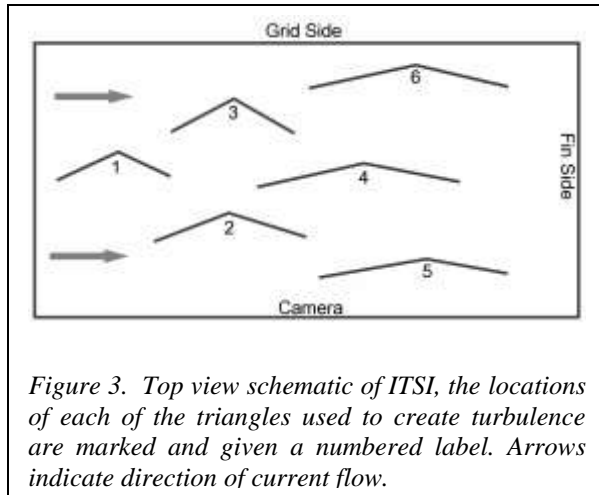


Figure 3. Top view schematic of ITSI, the locations of each of the triangles used to create turbulence are marked and given a numbered label. Arrows indicate direction of current flow.

A weight, float, and fin system was implemented to aid in the alignment of ITSI during deployment (Fig. 4). Two weights were attached to the bottom of the front and back of the box. An anchor was then attached to one end such that it was supported by one of the weights and would not result in the distortion of the PVC. Two fins were placed on the downstream end to allow the box to orient with the current during deployment. A float was connected to the end opposite the anchor to aid in locating the instrument during recovery.

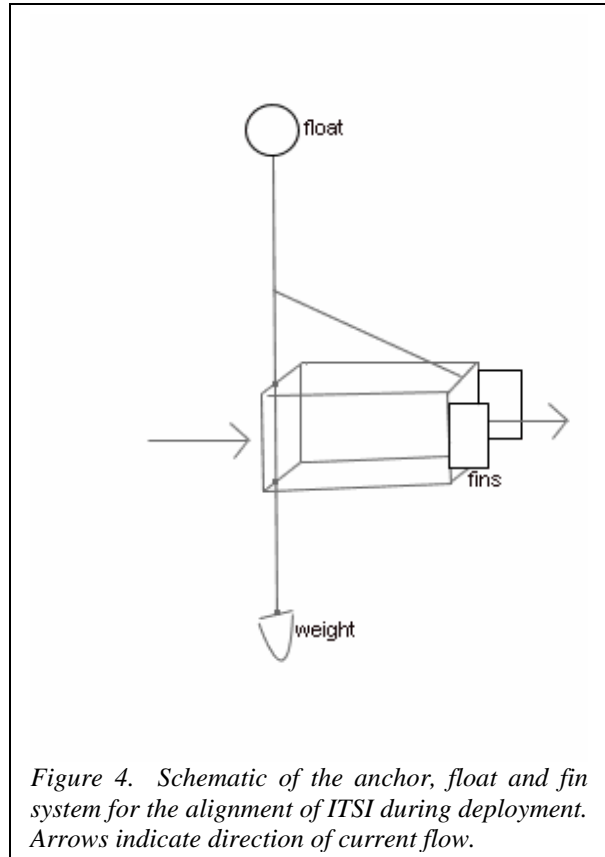


Figure 4. Schematic of the anchor, float and fin system for the alignment of ITSI during deployment. Arrows indicate direction of current flow.

Phase II – Deployment and Data Collection

Deployment sites and times in Barkley Sound were chosen in an attempt to satisfy the following conditions:

1. The floor of the chosen site should be relatively smooth and flat to minimize the possibility of turbulence and mixing outside of the instrument from introducing any random errors into the data collected.
2. Deployment during the ebb or flood tide in order to take advantage of the maximum current velocities.
3. Site depth of less than 60m due to the camera limitations.

Three deployment sites were chosen. Due to the limitations of the waterproof casing on the camera, the sites chosen for testing ranged from 15m to 40m. Bottom time, which excludes deployment and recovery time, lasted for a minimum of 15 minutes. This allowed excess time for any disturbed sediment to settle and provide the camera with a clear view of the grid.

Data collection was intended to be done by observing water particle movement through ITSI. The relative horizontal and vertical velocities along the length of the instrument would have been measured visually using the camera and grid. However, during each of the deployments there was not sufficient current flow to generate data.

Phase III – Critical Analysis of ITSI Design

A critical analysis was conducted on the elements of ITSI used to generate turbulence. Figures 2 and 3 show the configuration used to simulate a rough seafloor surface. The height and angles of triangles 2 and 3 were equivalent, as are triangles 5 and 6. Thus for the analysis of this aspect of the design, a study was conducted to observe the differences in turbulence distribution between differing triangle heights, face angles, and flow velocities. Smaller acrylic triangles were built with a ratio of 1:4 to the originals. These were then individually placed in a laboratory flow tank. The current flow was varied between three velocities, each approximately twice as high as the subsequent velocity. For each velocity, an ink dye was inserted in front of the flow input. The ink then passed over the triangle and the resultant water movements were video recorded using a Mino HD video camera. This process was repeated for each triangle.

The videos for triangle 1 were discarded due to an error in its construction. The videos for triangles 3, 4, and 5 were chosen for analysis. Table 1 shows that 2 and 6 were considered to be repetitive of 3 and 5, respectively as their heights were within ± 5 cm of each other. For each, five video frames were selected for analysis. The frames were chosen during the time that the majority of the ink was flowing over the triangle, spaced 0.5 seconds apart. Each frame was then converted to greyscale and overlaid with a grid composed of 25x13 cells (Fig. 5).

#	Length (cm)			Angle (degrees)
	front	rear	height	
1	37.47	23.50	27.23	38.64
2	36.83	36.83	32.25	57.73
3	34.29	34.29	29.31	62.47
4	36.83	36.83	24.00	98.69
5	34.29	34.29	18.95	112.89
6	34.29	31.75	15.71	122.92

Table 1. Comparison of dimensions of each triangle used on ITSI. The triangle numbers are listed in the left column and correspond to the numbers in Figure 3. Triangle 1 was discarded in the analysis due to construction errors. Triangles 2 and 3 were considered to have similar heights (± 5 cm) as were 5 and 6.

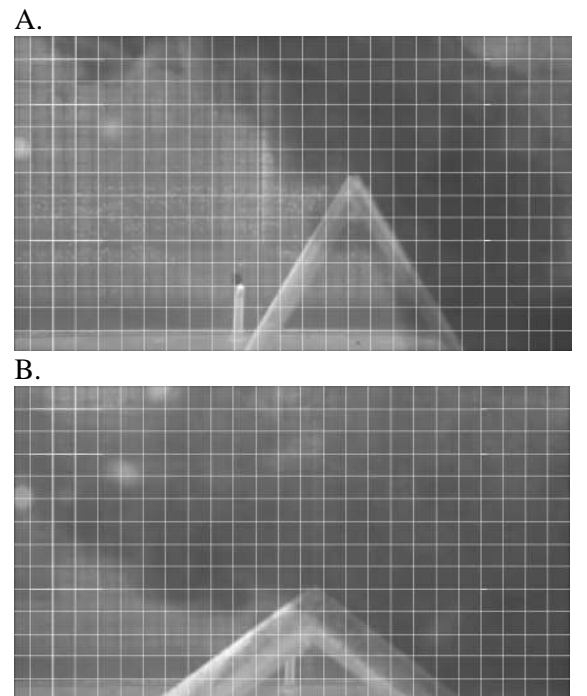


Figure 5. An example of analysis from the videos used to observe turbulence over the triangles in a flow tank. Ink was used as an indicator of flow velocity, with a decrease in color intensity representing a decrease in energy. The screenshots were converted to greyscale and superimposed with a grid. A.) An example of triangle 3 with the medium flow velocity. B.) An example of triangle 4 with the medium flow velocity.

For each image the greyvalue intensity was then averaged within each grid cell and recorded. The resulting values for each corresponding cell within each of the five frames were then averaged together. This resulted in a final 25x13 unit matrix showing the average distribution of ink over a 2.5s period. With one final matrix for three different triangles at three various flow speeds each, this led to nine final matrices in total.

In greyscale, the higher the assigned value, the greater the intensity of light. Thus, because the ink used was dark in comparison to the background, lower values in the final matrix indicated the path of the ink. The data would range between the lowest values at the flow source and the highest values where the ink did not penetrate. The lower the value, the greater the laminar flow velocity is. As the values decreased, it was assumed that the ink concentration was reduced due to turbulent mixing over the triangle. This also indicated a decreased flow velocity.

The final matrices were then converted to a color map using MATLAB R2012a. The maps were then compared to each other to analyze the variations in turbulence between various triangle heights and flow velocities.

RESULTS

Phase I – Design and Build Process

ITSI was successfully built according to the predetermined specifications.

The final dimensions were approximately 2m in length with the opening perpendicular to the flow measuring 0.75m x 0.75m. Each face of the box was open. This allows the assumption that there were no changes to the flow caused by interactions with the frame.

Each of the acrylic triangles were designed to be sufficiently high enough, relative to the dimensions of the frame, to induce turbulent flow. The flow was expected to move over the top of the triangles, yet it was still desired to keep it contained within the frame thus none of the triangles were built to be taller than 0.25m. It was also possible that small scale energy loss occurred due to surface drag across the acrylic faces. However, this was considered negligible compared to the expected flow velocity and was ignored.

The sensors attached to ITSI included an HD GoPro camera and a high velocity fluid flowmeter. During deployment, the camera functioned as expected even without additional light. The use of the flowmeter was not successful though, as the flow velocities at the deployment sites in Barkley Sound were considerably less than the minimum required to register.

Phase II – Deployment and Data Collection

The instruments held together during three successful deployments. Thus the mechanical integrity could be considered sound. During deployment, ITSI settled upright on the seafloor so that aspect of deployment was also considered a success. The camera view was valid, as the light levels at each site allowed for sufficient visibility for data collection. Ultimately however, the choice of deployment locations was considered a failure as there was no current flow at any of the sites. As a result, no data collection was possible. The flowmeters also could not be used and it is uncertain if the alignment method developed was successful.

Phase III – Critical Analysis of ITSI Design

The final flow distributions are shown in Figure 6. These include the three varied speeds (labeled slow, medium, and fast) for triangles 3 and 4 (Fig. 4). Due to its height, triangle 5 was determined to have no significant effect on the flow distribution at any velocity.

The slow, medium, and fast velocities were not directly measured. Through an analysis of the flow videos, they were determined to be approximately 5 cm s⁻¹, 10 cm s⁻¹, and 25 cm s⁻¹, respectively.

The solid black sections on each graph (fig. 6) represent the location of the triangle during filming. The slight variations in the location of the triangles between velocities are caused by inconsistencies in the location of the camera during filming. Inflow values of each graph are all normalized to a common greyscale value. This is so that the magnitude of the energy loss over distance can be directly compared between each velocity.

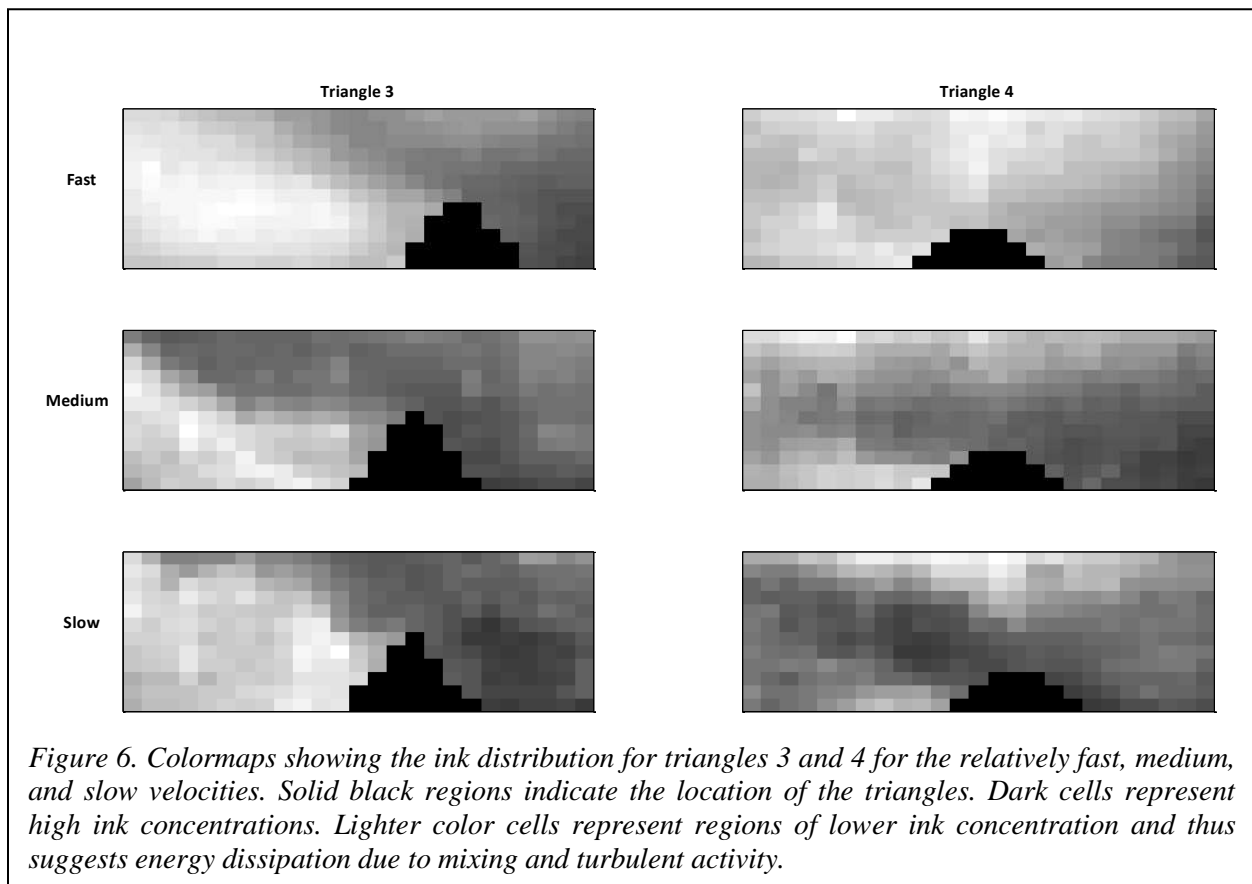
Flow energy reduction was shown in all the flow velocities for both triangles. This is

presumed to be due to turbulence induced mixing. Figure 6 also shows that the incidence angle of flow past the triangles decreased (moved more towards the horizontal) as the flow velocity increased. The incidence angle was also smaller for the triangle 4 than triangle 3.

There was an error source resulting from the inflow not being perfectly laminar. This is particularly evident in the colormap of the fast velocity flow for triangle 4. There it can be seen that the inflow is partially turbulent and thus some of the energy is dissipated before reaching the triangle.

An estimation of the range of measurement errors can also be determined. There is the deduced assumption that the area behind the triangles and below the incidence angle is an area where the ink never reached. Therefore any color variations in that region are presumed to be due to errors in the intensity measurements. These variations were possibly due to light reflecting on the tank and objects located behind the tank

Finally, although relative energy flux over each triangle can be determined, the rate of loss cannot be calculated from the figures. That would require revisiting the videos and sampling more screenshots over a larger time period.



DISCUSSION

This discussion includes an analysis of the Phase III results using a mathematical representation of kinetic energy flux. There is also a reevaluation of the limitations and assumptions involved throughout the entire experimentation

process. Lastly, these topics are taken into account and possible design changes are proposed.

Effect of Bottom Roughness Height

For this discussion, “surface area” refers to the area of the triangle faces perpendicular to

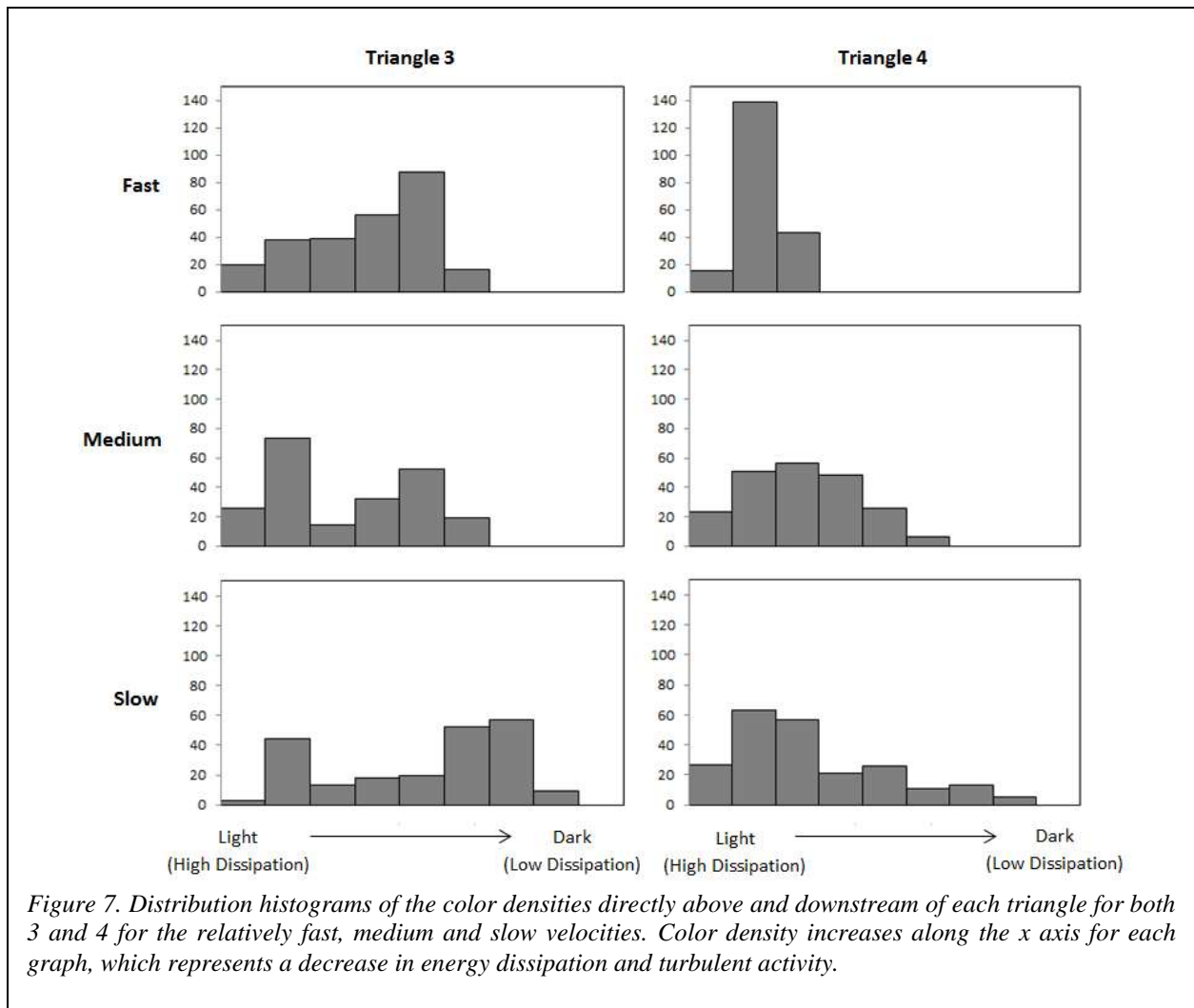
the flow. This is equivalent to the height of the triangle. Figure 3 shows that triangle 3 is the tallest of those analyzed and thus provides the seen in the kinetic energy flux equation for fluids (Kawase, 2011).

$$\text{KE flux} = \frac{1}{2}\rho A\mu^3 \quad (1)$$

For equation 1, ρ is the density of the fluid, A is the surface area of the triangle, and μ is the flow velocity into the instrument. From this it is determined that if the surface area or the incoming velocity is increased, then the flux will increase as well. An increasing energy flux represents an overall decrease in total energy. In addition, a surface area that is too large coupled with a low inflow velocity (or vice versa) will result in a negligible energy change.

greatest surface area. It also shows that the induced turbulence also increased dramatically with increasing flow velocity. This can also be

Figure 7 shows the histogram distribution of colored grid cells from figure 6. It specifically analyses the cells that are directly above and downstream of each triangle. Again, each were normalized in order to correlate the energy distribution directly to the turbulence induced from the triangles. This corrects for any errors in the inflow. It is important to note that the ink concentration increases along the x axis and this actually represents a reduction in energy loss.



Comparing between different velocities shows a general trend that as the velocity increases there is a reduced number of darker colored cells. This represents a decreased concentration of ink and thus more turbulent activity. This is expected because equation 1 states that the energy dissipation is proportional to the cube of the initial velocity. This is apparent in figure 7 for all graphs with the exception of the medium velocity for triangle 3. Here the distribution seems to be scattered randomly through all of the bins that tend towards the lighter end of the spectrum.

Comparing the two triangles to each other, the fast and slow velocities for 4 both have a greater distribution of light colored cells than the equivalent velocities for 3. Again, because of the seemingly random distribution for the medium velocity of 3, the two cannot be compared to each other at that speed. However, for the fast and slow velocities, the interpretation is that as the height of the triangle is reduced there is an increase in turbulence. This is unexpected according to equation 1. One explanation is that the energy flux is only proportional to the first order of the surface area. In comparison, the flux is proportional to the third order of the velocity. Here only the height variations are being compared instead of surface area. As a result, the relationship trend between height and flux may not be significant compared to the error introduced when the greyscale values were assigned to the grid cells.

Other Assumptions and Limitations

It was determined that the height of the triangles was the design aspect that most effected the amount of induced turbulence. As long as the heights remained the same, the angle and width of the triangles had no effect. This is true only if energy loss due to drag along the acrylic is considered negligible. That assumption was made for this project.

The reference to energy loss is also a potential misleading phrase. Kinetic energy is dissipated through the instrument, not extracted. Thus, there is technically no “loss” of energy, if

there is assumed to be no heat conversion. The energy is instead diluted through the random particle movements of turbulence and mixing.

This suggests limitations in the phase III analysis. Due to the error ranges in the greyscale observations, there was a minimum ink concentration that could be observed. This implies that some areas of the turbulent flow were neglected. Potential improvement could have been made if the number of grid cells in the screenshots had been increased.

Possible Design Changes

Perhaps the most major flaw that was noted on the design was the lack of a mounted light. If this had been added, then it would have been needed to be oriented such that it does not point into the camera or result in any reflected backscatter off of particles in the water. This would reduce the possibility of visibility being the limiting factor in choosing the depth of deployment. As a result, the instrument could then be deployed at deeper sites within the channels of Barkley Sound that may have faster currents and would allow for data collection.

The initial scientific question addressed in phases I and II was an analysis of turbulence over a uniformly rough seafloor. The design for ITSI included acrylic triangles of various heights and angles. Because it was determined that the energy flux varied with triangle height, it can be determined that ITSI did not accurately represent a uniform seafloor. This results in a necessary design change to use triangles of equivalent height.

Further analysis would be needed on other aspects of the design in order to conclude other possible adjustments. This includes the arrangement, distribution, and density of the triangles. Also, the weight and fin design used for deployment would need to be tested in higher velocity flows.

CONCLUSIONS

This methods oriented experiment analyzed the process of successfully producing an instrument to be used for observing a specific oceanographic process, specifically seafloor

turbulence. It was completed in three phases: the design and build process, deployment and data collection, scientific study of the design. The final conclusions for each phase are as follows:

I. Design and Build Process

- When designing an oceanographic instrument, the limiting factors to be considered include funding, allotted time to build, depth and location of deployment
- An open box design using PVC tubing is best for allowing water to flow through for data collection
- The only sensor required for data collection was a camera, although an attached light would have aided in areas of low visibility
- Sufficient weight was needed at the base of ITSI, to keep it stable in the case of a deployment in a strong current
- An anchor and sail system was developed to allow for alignment with the current during deployment

II. Deployment and Data Collection

- The structural integrity of the design was valid
- Sufficient current moving constantly in one direction is required for any data collection
- The frame design successfully addressed the parameters presented by the scientific research questions, however the deployment design was questionable due to lack of data

III. Design Analysis

- The amount of turbulence induced is proportional to the height of the triangle used and to the cube of the inflow velocity
- The triangle method is valid for representing seafloor roughness if all triangles are equivalent height. The incident angle of the flow would then be primarily determined by the height of the triangle while the amount of turbulent activity would mostly be dependent on inflow velocity. This knowledge can then be applied for determining the necessary number, height, and distribution of triangles for representing a specific type of seafloor roughness for a given flow velocity.

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