SLATT UNDERGRADUATE RESEARCH FELLOWSHIP
FINAL REPORT

SCHOLAR NAME:	Yi-Chung (Andrew) Chen
FACULTY ADVISOR:	Dr. Hirotaka Sakaue
PROJECT PERIOD:	Spring 2020 to Fall 2020
PROJECT TITLE:	Drag Reduction in Pipes Using Hydrophobic Coating Pattern
CONNECTION TO ONE OR MORE ENERGY-RELATED RESEARCH AREAS (CHECK ALL THAT APPLY):	**(O) Energy Conversion and Efficiency** **( ) Smart Storage and Distribution** **( ) Sustainable Bio/Fossil Fuels** **( ) Sustainable and Secure Nuclear** **( ) Transformation Solar** **( ) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS

Summarize your research goals and provide a brief statement of your accomplishments (no more than 1-2 sentences). Indicate whether you were able to accomplish your goals by estimating the percentage completed for each one. Use the next page for your written report.

RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Create prototypes to observe flow behavior on surfaces	Created four prototypes (example image and video attached in the email) and was able to observe the flow behavior. I had originally planned to make more prototypes and observe them in a condition where there is water travelling over the entire surface, rather than just a thin stream.	80%
Determine an optimal pattern through experimentation for drag reduction	Ran about 280 different tests for different patterns and determined certain patterns that work better than others (I did notice my scope for this is a bit ambitious as there is an infinite number of patterns that could be tested, so I limited myself to simple shapes). Due to COVID, I switched my method to running computational simulations, and I regret not having the opportunity to validate my results through physical experimentation	75%

RESEARCH OUTPUT

Please provide any output that may have resulted from your research project. You may leave any and all categories blank or check with your faculty advisor if you are unsure how to respond.

CATEGORY	INFORMATION
EXTERNAL PROPOSALS SUBMITTED	(Sponsor, Project Title, PIs, Submission Date, Proposal Amount)
EXTERNAL AWARDS RECEIVED	(Sponsor, Project Title, PIs, Award Date, Award Amount)
JOURNAL ARTICLES IN PROCESS OR PUBLISHED	(Journal Name, Title, Authors, Submission Date, Publication Date, Volume #, Page #s)
BOOKS AND CHAPTERS RELATED TO YOUR RESEARCH	(Book Title, Chapter Title, Authors, Submission Date, Publication Date, Volume #, Page #s)
PUBLIC PRESENTATIONS YOU MADE ABOUT YOUR RESEARCH	(Event, Presentation Title, Presentation Date, Location)
AWARDS OR RECOGNITIONS YOU RECEIVED FOR YOUR RESEARCH PROJECT	(Purpose, Title, Date Received)
INTERNAL COLLABORATIONS FOSTERED	(Name, Organization, Purpose of Affiliation, and Frequency of Interactions)
EXTERNAL COLLABORATIONS FOSTERED	(Name, Organization, Purpose of Affiliation, and Frequency of Interactions)
WEBSITE(S) FEATURING RESEARCH PROJECT	(URL)
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	(Please describe each item in detail)

RESEARCH EXPERIENCE

Please let us know what you thought of your research experience: Did this experience meet your expectations? Were lab personnel helpful and responsive to your needs? What else could have been done to improve your experience or achieve additional results?

Did this experience meet your expectations?

Yes, I learned a lot and developed into a better independent researcher, which was what I hoped to achieve. Here is a list of key takeaways I took from my experience:

- I learned to schedule my own research, and COVID taught me to adapt and adjust my schedules and methods when external influences affect my plans.
- I learned to be incisive in determining the different parameters that should be tested. This hones my ability to analyze problems because it trains me to analyze which tests will be more critical and allows me to get a good comparison without a lot of trial and error that wastes time and money.
- I adapted to the situation caused by the external factor and conducted my tests on computational fluid dynamics (CFD) simulations. This was not something I planned for but I am glad it happened because it familiarized me with CFDs, which will be helpful for me in the future, as researchers usually run tests in CFDs first before conducting physical experimentations.
- Practiced being more independent by doing things independently first and then getting feedback from my advisor and the graduate students to spark creativity and augment my learning experience
- Got more practice in analyzing the phenomenon I was seeing and coming up with my own reasoning/hypothesis for it.
- I learned that as an independent researcher sometimes we need to recognize what our limits are and narrow down the scope of our research. In other words, I learned that it is okay to admit that I was too ambitious and adjust myself so I am not overwhelmed and keep my research doable for me. I also learned to understand that research is not like a normal, in- class project. There is a less definitive end: sometimes you find things along the way and sometimes it doesn't always go your way, and I shouldn't be too hard on myself because it is out of my control.
- I was also able to talk to other researchers about their research and help them with what they are doing.

Were lab personnel helpful and responsive to your needs?

My fellow researchers in the Sakaue Lab were all very willing to help. In our weekly meetings they would not only give me feedback on my research project but also share their experiences with me when I am feeling down about not being able to do something perfectly while doing research. When I was able to go back into the lab, they were all very eager to help me make the most out of my experience.

What else could have been done to improve your experience or achieve additional results?

To improve my experience, I believe I will definitely learn a lot more if I was able to work with the team in person over the summer because there will be more interactions and moments where I can learn from these experienced researchers. I also wished I could conduct physical experimentation to ensure that my CFD results are correct, but both of those are a luxury during this time.

In order to achieve additional research results, I think if I was able to get more out of literature, it would help me to do more. However, it was also difficult because 1) there is not a lot of literature on this topic, and 2) even the ones that are somewhat relevant did not make much sense to me because I think I still lack knowledge fundamental to those papers and those will take a long time to find and teach myself, so I just dived into the testing.

FINAL WRITTEN REPORT

(Please use the space below to describe your research project and objectives, any findings and results you can share, and graphs, charts, and other visuals to help us understand what you achieved as a result of this research experience.)

Introduction

It is known that superhydrophobic coatings can cause a reduction in skin friction drag. This means that these coatings can have significant implications to the maritime industry or piping. When these coatings are applied onto cargo ships, the reduced drag can increase the range and speed of the ship, while making it more fuel efficient. Similarly, when applied in pipes, the reduced drag from friction will reduce losses, which means less energy will be required to transport a liquid to a certain location. Despite the advantages of superhydrophobic coatings, it is not ubiquitous because the current coatings are fragile and they wore out relatively quickly (in 6 months to a year), which requires the surfaces to be re-coated, which can be troublesome and costly. Therefore, the purpose of this research project is to determine superhydrophobic coatings patterns to reduce the amount of coating required while maintaining enough drag reduction so it is more practical economically.

To achieve this, in this research project, different shapes and patterns were determined and their effects on drag reduction is studied. Since there could be an infinite number of potential patterns, the experiment is limited to simple shapes and patterns to ensure that the project is not overly ambitious. The different shapes and patterns of coating was to be applied onto the interior of a water pipe, and that pipe section will be attached to the existing water tunnel in Sakaue Lab to determine drag across that section. A study of the basic behavior of flow interacting with the coating on an external surface was also conducted, which was done by spraying water over patterned surfaces and observing them. In other words, there are two objectives to this research project, the first is to determine a coating pattern (limited to simple shapes and patterns) that will reduce the amount of coating applied but also maintain a decent drag reduction. The second objective is to visualize and observe how the flow behavior changes on the patterned surface.

It is important to note that this project was affected by the COVID pandemic. Originally, the bulk of this research was supposed to be conducted in person in the laboratory during the summer, when the researcher has the most time. However, undergraduate students were not allowed into the labs over the summer, and therefore the data collection was transitioned from physical experimentation to computational fluid dynamics simulations (ANSYS AIM) during the summer, with the hopes of being able to validate key results from the simulations with physical experimentation in the Fall. Due to the limited capacity in the research laboratories, and that there are higher priority research that must be done in the lab, the computational data was not validated and only the prototypes were studied, but the researcher was able to assist with the higher priority research.

Results

In this section, selected results from the computational simulations will be provided, along with observations from the flow behavior. To help with the understanding of the results, how the effectiveness of the coating is evaluated must be discussed first. In ANSYS AIM, there is only the option to make the surfaces perfectly frictionless, so that is the setting used to mimic the superhydrophobic surfaces in the simulations. Effectively, if you have a pipe that has the coating applied every where on the surface, the drag present will be 0% of the drag of a pipe with no coating. Although a physical superhydrophobic coating cannot yield this result, this assumption is deemed acceptable. Using this fact, and since the drag reduction will be related to the amount of coating that is on the surface, the effectiveness of the coating is evaluated by comparing the % of drag reduction (drag of this coating/drag without any coating) to the % of area in the pipe with the coating applied. This is especially important when comparing patterns that covers a different sized area.

The research began with the testing of streamwise stripe patterns and banded patterns of hydrophobic coating, illustrated in Figure 1, where the one on the left is the streamwise stripes and the one on the right is the banded pattern.

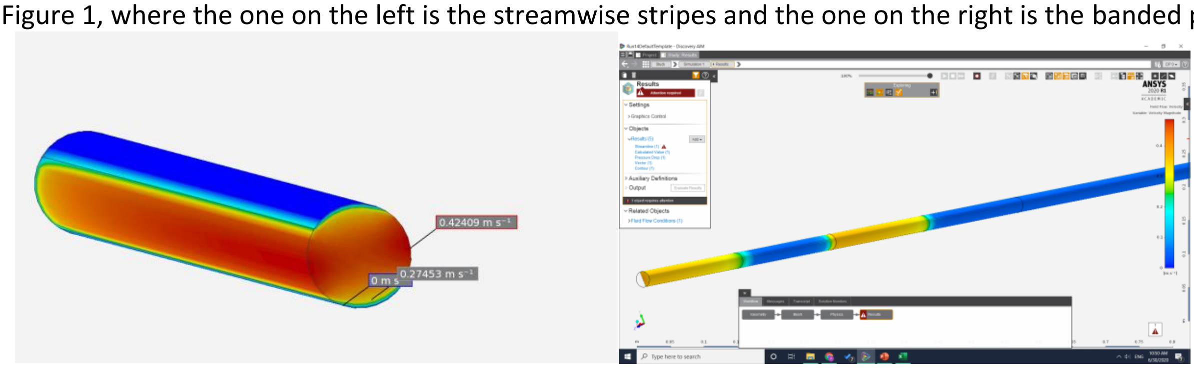

Figure 1. Illustration for the streamwise stripes pattern(left) & banded pattern(right). The blue surface represents the coatings

From these tests, it was determined that the streamwise stripe patterns are significantly more effective compared to the banded pattern. Potential reasons will be discussed in more detailed in the prototype section, which is it could be because the banded pattern leads to more transitions of surfaces that increases resistance of the flow. Figure 2. demonstrates the difference in effectiveness in drag reduction between the stripe and the banded patterns. It can be seen that the % drag reduction for the banded patterns are around the same as the % of wall covered in coating, but for the stripe patterns, the % of drag reduction is higher than the % of wall covered, even up to 10% more. For the banded pattern, when it says 1:1 ratio 0.25 m each, it means that each hydrophobic band is 0.25 m long in the streamwise direction and it borders with another 0.25 m of surface without any coating, leading to an overall hydrophobic area of 50% (due to the 1:1 ratio). With the 3:1 ratio 0.25

m, it has 0.75 m of hydrophobic surface and 0.25 m of hydrophilic surface, leading to a 75% area with the coating applied. For the streamwise stripe patterns, the first 5 patterns have the % of area covered set to 50%. Stripe is 50% of circumference means that half of the cross-sectional pipe surface is covered in the coating, and stripe is 25% means that there are two, non-touching strips of hydrophobic coating that are 25% of the circumference wide (example shown in figure 1). The two 25% stripes are separated by two hydrophilic surfaces that are of equivalent width. The same applies with the 12.5%, 10%, and 5%, but there are now 4, 5, and 10 stripes of hydrophobic coating, respectively. The stripe 5% on the far right is when the hydrophobic surface is three times the size of the hydrophilic surface.

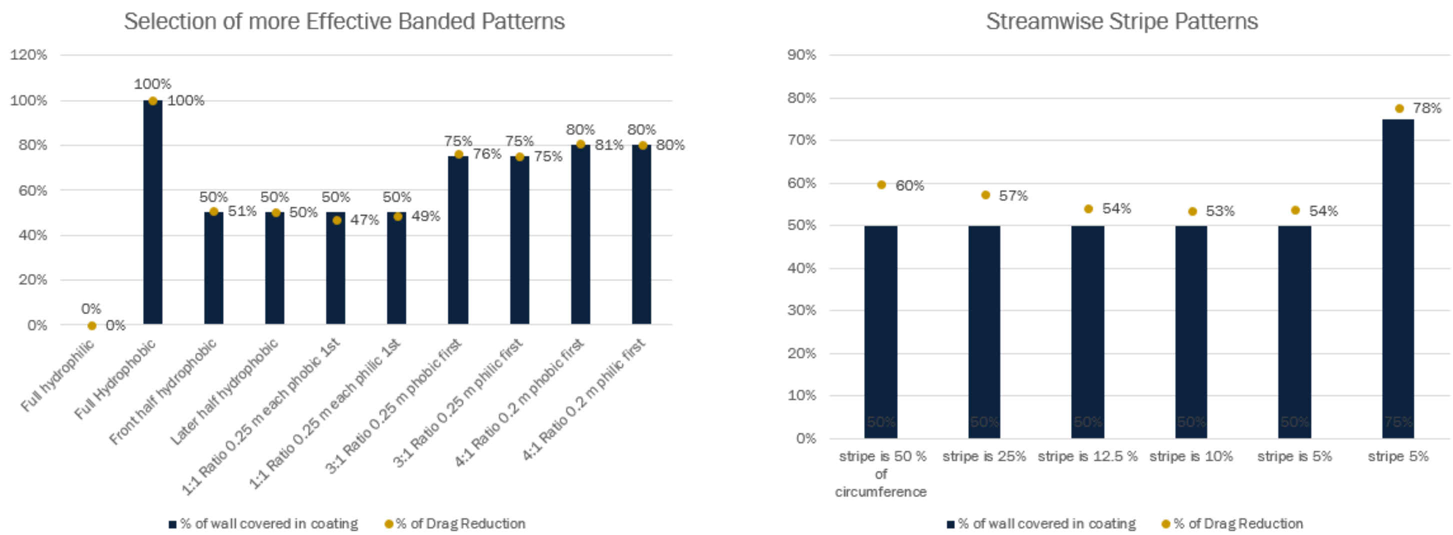

Figure 2 Graphs of the selected band patterns and stripe patterns. It can be concluded that the stripe patterns are more effective because the % drag reduction (dot) is greater than the % area covered (bar graph), while the banded patterns have a % drag reduction of around or below the % area covered

By studying the 50% area streamwise stripe patterns (the first five from the left), it can be determined that the stripes becomes less efficient as the width of the stripe reduce from 50% to 5%, as the % of drag reduction dropped from 60% to 54%. The same trend can be seen in the banded patterns in Figure 3. From this it can be concluded that having smaller pieces of hydrophobic coating, while it has the same overall area, will decrease the effectiveness of the coatings, and this again is due to the transitions.

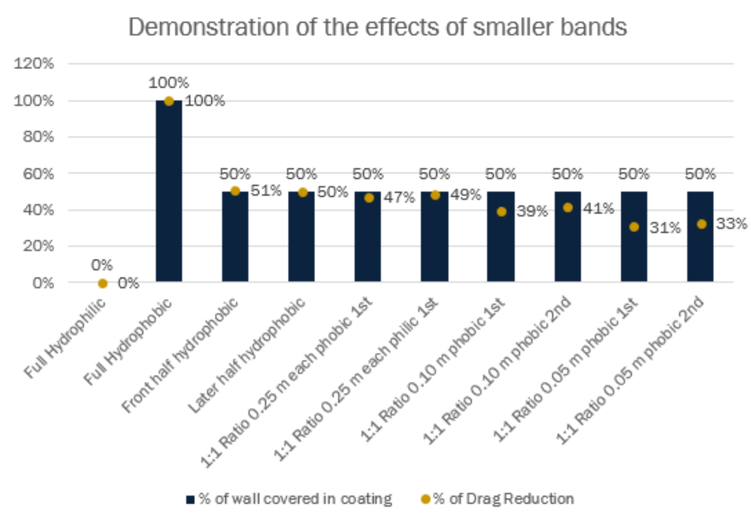

Figure 3 Illustration of the drop in effectiveness of the coatings when each coating surface is reduced.

From this graph, it can be determined that as each band became smaller, the % of drag reduction decreased from around 50% to around 32%.

The next thing that was tested was whether the trend holds at different flow speed or Reynolds numbers. Up until this point, the experiment was conducted at a Reynolds number of around 9000. The test was repeated at a Reynolds number of ~20000 and ~40000 and the results were similar. This shows that trends will be the same at a wider range of Reynolds numbers, and it also enabled the researcher to conduct the other simulations at a Reynolds number of ~9000, as the higher Reynolds number leads to a significantly longer computation time.

Once the fact that the results are Reynold's number invariant is established, other shapes and patterns were tested. This includes checkered patterns, triangular patterns, diamond patterns, and oval patterns. A lot of different variations for the triangular, diamond, and oval patterns were tested. This includes variations in the size of the shape, in the orientation (just for triangles), in the inverse of the shape (so the shape is now the region not covered in the coating), and in the number of the shape in the streamwise direction. However, there is a lot of data from the different variations, so, to obtain an even better comparison between the different patterns as a summary of prominent potential designs, the best performing configuration of each shape was tested at similar sizes of around 25%. The results are shown in Figure 4. In this case, all shapes, except for the banded pattern, has a streamwise length of the full length of the test section (1m). This means the width of each shape was manipulated to achieve an area of around 25%. A new shape introduced here is the pseudo-spiral. This is an attempt to test how a spiral, like a rifling, would affect the flow. However, limitations in CAD means it must be discrete, meaning it has a spiral shape but it is jagged on the sides, hence the name pseudo-spiral.

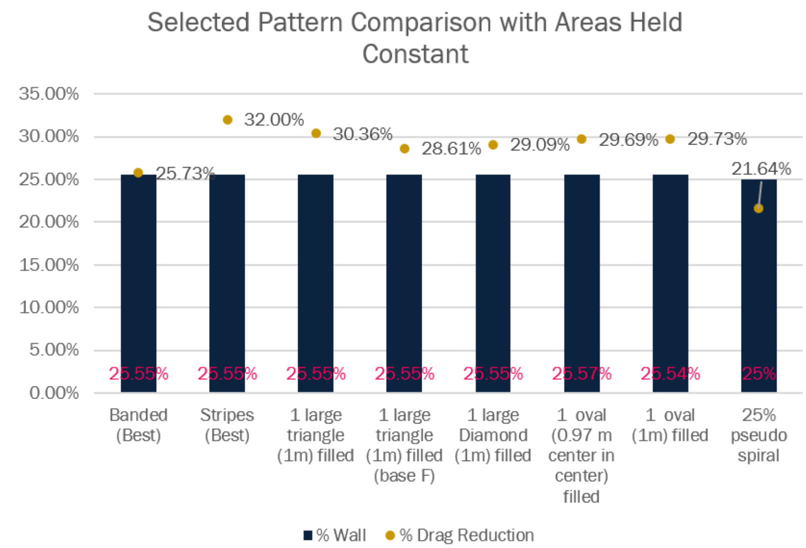

Figure 4. Comparison of different selected shapes and patterns with their areas held constant

From this chart, it can be concluded that the best shape is still the simple streamwise stripe patterns, as it had the highest drag reduction given for a fixed amount of coating.

The next part of the project was the observation of flow behavior and how it interacts with the surfaces using physical prototypes. To do this, the researcher was trained in making and applying (spraying) the superhydrophobic coatings onto a surface. Once the researcher was competent enough in spraying after several training sessions, prototypes of the different patterns were made, as shown in Figure 5. This same image is also attached in the email.

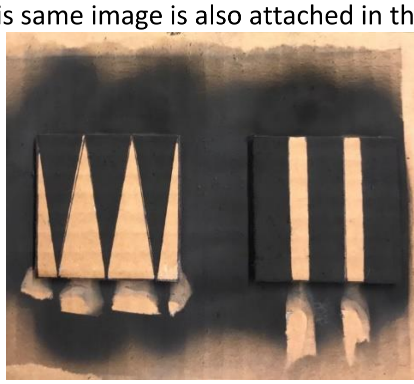

Figure 5. Prototypes of the coating patterns used to observe flow behavior, where the black is the superhydrophobic coating and the khaki is the hydrophilic surface (untreated surface)

To observe the flow behavior, water was sprayed onto the prototype surfaces, and as expected, the hydrophobic surfaces immediately repel the water. What the researchers did not expect was the formation of a reservoir of water on the hydrophilic surface, which is bounded by the coatings. As more water was sprayed at the prototype, the surface tension of the water reservoir sucks in any water droplet that comes into contact with the reservoir and it grows and forms a blob of water. Enough water must be gathered before it can generate enough force to break through the surface tension on the downstream end for the water to continue to flow. This phenomenon was recorded and is also attached in the email. This observation could potentially explain the reason why the smaller each patch of coating, meaning more transitions, the less effective the coating becomes. Using the banded patterns as an example, the reason why they are worse than the streamwise stripes could be because it forces the flows to go through more transitions as it travels down the pipe. The transitions due to hydrophilic bands in between the hydrophobic bands creates reservoirs of water, which will increase the resistance against the flow that is trying to move through the pipe. The resistance increases because the water merges with the reservoir and pushes the water at the downstream end of the reservoir out, requiring enough force to overcome the surface tension. So rather than the water moving downstream smoothly as one continuous action like in the streamwise stripe pattern, the reservoirs slows the flows down and requires it to generate the effort to break the surface tension to allow the water to move on. While this theory does make sense, one could also question whether if a blob of water forms from surface tension while the pipe is fully flooded and flowing. An alternative explanation from the observation is that it seems the water is bounded by the edge where the hydrophilic surface meets the hydrophobic surface. This could be because the hydrophilic surface attracts the water and the hydrophobic surface repels the water, so as the water flow from hydrophilic to hydrophobic on the meeting point, the flow is attracted by the hydrophilic side and repelled from the upcoming hydrophobic section, slowing the flow down as it is retained by the hydrophilic side. There would be losses as the flow will need to generate enough effort to overcome that boundary, forcing the motion to no longer be continuous. In other words, the transition from hydrophilic to hydrophobic surfaces increase the resistance of the flow because the former retains the water and the latter repels the water, disrupting the continuity of the flow. Regardless of which explanation, a fitting analogy would be the transition from a hydrophilic surface to a hydrophobic surface and back is similar to that of a red light on a road that stagnates the flow of traffic.

Conclusion

From the computational simulations, it can be concluded that out of all the different shapes tested, the streamwise stripe patterns are the most effective. At the same time, it was determined that the trend is constant throughout different Reynolds numbers. Another key takeaway is that even if the overall area is the same, having smaller patches of coating reduce the effectiveness of the overall pattern. Studying the prototype offered potential theories to this phenomenon, which is the fact that the transitions between hydrophobic and hydrophilic surfaces prevents the motion from being continuous, but stagnant at points. The exact mechanism behind this has not been discovered, but it could potentially be because as the water moves from hydrophilic to hydrophobic, the flow will be retained by the hydrophilic surface because it attracts water and the hydrophobic surface repels water, preventing it from moving on to the next surface.

The next logical step in this research would be to conduct the physical experiments in the water tunnel to validate the results from the computational simulations. The researcher would also like to dive into more complex shapes and study their effects. Moreover, the researcher is also curious about exactly why the transition regions reduce the effectiveness of the coatings. A more detailed study with the use of coloring dye and a channel flow apparatus could help determine what happens at those transition points. Lastly, it would also be interesting to discover a practical application for the water reservoirs that forms between hydrophobic surfaces.

Video Link:
https://drive.google.com/file/d/1oQveOCCGIkw1iP52CPxiCBU8F_BcsGx9/view?usp=sharing