Making Use of Mother Nature: Converting Fog into Drinkable Water Utilizing a Series of CloudFisher Nets

A Major Qualifying Project

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By

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Abstract

Throughout numerous third-world countries, people have limited access to drinkable and potable water. These communities often have to spend several hours of the day collecting water for their families which can be a grueling activity. One solution to this is utilizing fog harvesting nets and a gravity-driven piping system to transport the collected water. These nets are able to capture the fog, condense it to water, and let it fall down the net. Once the water droplets fall off the nets, it falls into the piping system which then travels to an area that is easily accessible to the community. In this project, the group analyzed how altering wind speed and the orientation and number of nets that fog passes through, affects overall water collection. A Unit Operations lab was also designed for future generations of WPI students. The data collected is also utilized as a comparison to how nets are generally orientated in existing fog harvesting projects, like the site based in Morocco, and if there were any areas where the change in orientation is preferred. Increasing speed does generally increase the rate of collection, and while nets set in parallel series to one another are not as efficient after each netting in a row, areas with dense fog and less surface area would benefit from this type of orientation. Deliverables for the unit operations lab include a theory section, sample calculations, pre-lab questions, and operating instructions for the unit.

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I. Introduction

Throughout contemporary history, renewable energy sources have been highlighted in various engineering projects, but one major area that lacks substantial research and application is harvesting water from outside sources. In particular, fog harvesting is an essential component of obtainable fresh potable water for numerous communities around the world. Fog harvesting provides an alternative source of collecting freshwater through a technique used to capture water droplets from the wind-driven fog. Utilizing fog has the potential to provide an alternative source of water in rural, arid regions which can be harvested through the use of low-cost collection systems and nettings that are easy to set up and maintain. The water acquired can be used for domestic use, agricultural irrigation, and as a product to sell. Fog collectors primarily work best in areas with frequent and long fog periods including coastal regions and mountainous landmasses.

One of the critical aspects of this project that drew us in was how fascinating everyday fog could be transformed and converted into drinkable water that truly brought a difference to the daily lives of numerous rural communities. The ability of engineering technology to alter the facets of daily life in a positive manner is astonishing to see. When this notion of humanitarian engineering came across our educational career, it immediately sparked our interest. Seeing the fog water collection process through videos and documentaries piqued our interest, but on the other hand, we also came to the realization that this process could be further improved upon and implemented in a vast amount of other regions in the world.

To convert this research into a project, our group focused on gathering statistical data that correlates the water collection rate of CloudFisher against other types of nets, the efficiency of the netting set up in a parallel series, and creating a lab experiment for WPI students to replicate and provide further research data. This lab experiment for students is based in WPI’s Unit Operations Lab which focuses on the key topics of Chemical Engineering including heat transfer, mass transfer, and fluid mechanics. In particular, our project scope will focus on mass transfer of water and chemical design processes. Our motivation for converting this research project into a Unit Operations lab is to educate fellow students and showcase the humanitarian aspect of Chemical Engineering. Humanitarian engineering revolves around the application of improving the well-being of disadvantaged people and marginalized communities, usually located in the developing world. This aspect of engineering usually focuses on programs that are sustainable, affordable, and based on local resources that are easy to access. Viewing the science behind a project that genuinely helps others while being able to analyze and understand the mathematical concepts behind the research will instill confidence in students and prepare them for the workforce and strive to make a real impact on the world. However, this is not the only reason for conducting this experiment. Teaching students the humanitarian aspect of all engineering projects is also critical. In the case of this project taking fog and converting it to water is useful for sustaining human life or as a resource to benefit the existing surrounding environment. As convenient as this process may seem, using aspects of the surrounding environment may have critical impacts on the ecosystem in response and can cause a negative reaction. This is a principal lesson that is crucial for students to learn outside of standard classroom practices.

II. Background

This background presents an overview of the components necessary to understand the conditions of the Morocco Project site, the equipment utilized in the experiment, different netting structures, and potential regions of interest in the United States to expand upon this research. The first section provides an understanding of the Dar Si Hmad foundation and the achievements of this individual concerning the Berber community in Morocco. The second section describes the official CloudFisher net used in this experiment with regards to its functions and specific characteristics. In addition, differences between the old nettings used in the lab in comparison to the CloudFisher net are also illustrated. In the third section, potential regions of interest for continuing this project in the United States are showcased, including how much fog each region contains on a year-round basis. Section four describes the effects of removing fog from the environment and any potential backlash of harming surrounding plant life and ecosystems. The final section provides an alternative netting structure used in a different project to collect water from a project site in California.

2.1 Morocco And The Berber Community

Dar Si Hmad is an organization that wants to advance culture and improve education for future sustainability in southwest Morocco (Dar Si Hmad Administration, 2016). Many of the moral principles of the organization were adopted by one man. Si Hmad Derhem, the man behind the name of the organization, is from the village of Taloust in the Ait Baamrane region, born in 1909. In the 1960s Si Hmad advocated for restitution for Atlas Sahara until his death in July 1982. Si Hmad's heirs decide to continue the legacy and support/improve Morocco. With some areas having small areas of precipitation, collecting water can be a hassle. One solution is well water, but because of location even well water can be difficult. An example of this is in Morocco. In Morocco, it is common for women to go and fetch water for the family. Women in Morocco spend around 3.5 hours a day collecting water to support their loved ones. Families had to adapt by leaving the village to move into cities, and selling livestock. Sadly, on top of leaving their homes, they left their culture and heritage as those were not passed on. With the fog system, families are able to support each other and continue the lifestyle they had. Other improvements from being able to collect more water and collect it easily are

- The environment has had an increase in floral and fauna with the abundance of water
- Fog is now seen as a serious source of water and more research has been done since the production of the project
- Children can learn from hands-on, innovative teaching at the Water and Oasis School also started by the Dhar Si Hmad

On top of the fog harvesting project, the Dar Si Hmad organization also puts great importance on education. With an award-winning Ethnographic field school, people can do fieldwork and research. Students can get a close-up and experience local culture, economy, and projects going on. They also have an exchange program that brings young women of color to join cultures between women of the states and the indigenous people of Morocco.

2.2 Fog Unit Equipment

The following sections details the different net designs utilized in this experiment. The official CloudFisher nets were generously provided by the CEO of Aqualonis, Peter Trautwein.

2.2.1 CloudFischer Nets

CloudFisher nets utilize atmospheric water vapor, generally fog, as a primary source of clean sustainable drinking water. These fog nets harvest water in the air by condensing water droplets on their mesh-like surface. This pioneering technology has supplied people and communities in many countries and arid regions with affordable and clean drinking water. The water obtained in this cost-effective manner can also be utilized by farmers for reforestation projects or crop watering. It is also the world's first production fog collector capable of withstanding wind speeds of up to 120 kph and is simple to install and maintain, requiring no energy input. The CloudFisher nets can supply up to hundreds of thousands of people with top-quality drinking water of up to 600 liters per day per net, and can be used in all coastal regions and arid mountainous regions which have long periods of foggy weather.

Figure 1: CloudFischer Nets (WIPO, 2018).

CloudFischer nets are 3D woven spacer fabrics made from a specialized mono-fiber. The mesh is connected to steel frames with rubber expanders and the posts connected to the frames are concreted into the ground surface. The lifespan of the steel support ranges from 50 to 100 years while the fabric and support mesh lasts for 10 to 20 years. A full-size CloudFisher net of 54 cubic meters can provide up to 52 L/hr of clean drinking water under ideal conditions. In our specific region of interest, Morocco, 31 fog collectors were installed providing approximately 800 individuals with 18 liters of water per day (Trautwein, 2022).

2.2.2 Different Nettings Used

At the beginning of this project, the group used two nets, a white net and a B&W net, which can be seen in the images below. The Aqualonis nets were not obtained around halfway through the project. This section is used to show the differences between the nets. The Aqualonis net and thick white net are comparable in all dimensions, the B&W net has a similar height and length, and its thickness is about a third of the other two nets. The main difference in the nets comes from how the stitching was done. The B&W net was stitched in a way to form hexagons and one side is white, while the other side is black. The black side also has a line going through each hexagon up until the stitching ends. The Aqualonis nets, while not also multi-colored, are also stitched to have hexagons with only one side having a line go through the hexagons. The hexagons seen from the Aqualonis nets are much more compact and the net itself is more rigid. The thick white net is stitched in a way to have oval-like shapes in it, and unlike the other two nets, both sides of the white net are the same with no line going through any of the porous openings.

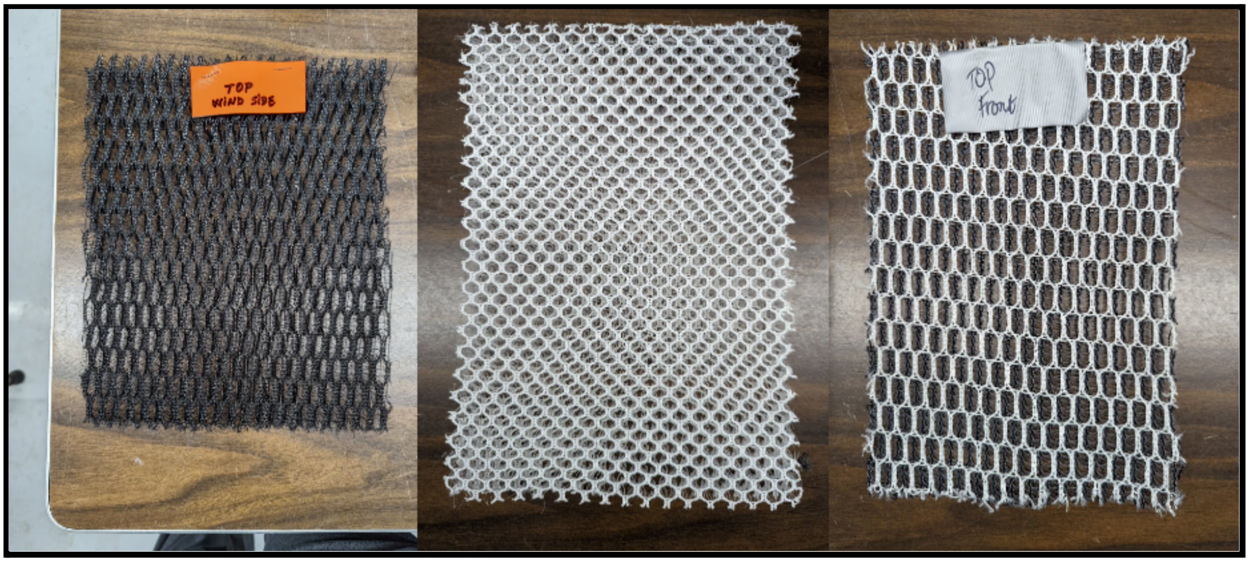

Figure 2: Different Netting Types

(From left to right: Aqualonis Net, Thick White Net, and B&W Net)

2.3 Potential Regions To Implement Fog Units In The U.S

This section delves into possible areas in the United States where fog net installations can serve as alternative water sources for the public. Fog develops when two different ground-level air masses of different temperatures collide and condense to form a low-lying cloud. Regions with cooler temperatures especially those over bodies of water contain fog. In addition, the micro-climate of the present landmass such as valleys or mountains can dictate how fog can get trapped thus requiring a longer time to get evaporated by the heat of the sun. Numerous areas in North America receive fog at certain times of the year, but for some particular regions, fog is abundant year-round and is an everyday occurrence.

2.3.1 Grand Banks, Newfoundland.

Figure 3: Image of Grand Banks, Newfoundland (MossandFog.com, 2019).

According to weather studies, the foggiest area in the world is this small region off the island of Newfoundland, Canada. This area is subjected to the cold Labrador Current from the north as it meets with the much warmer current of the Gulf Stream from the southern region. This collision between currents creates a fog-like environment year-round generating approximately 206 days of fog per year (WeatherSpark, 2018). Since this region is located off an island, the surrounding water causes fog to linger around. Fog tends to burn off starting with inland areas and slowly makes its way to the coast so therefore the fog in this area takes longer to dissipate. By installing fog nets on the coast of Newfoundland, Canada we can take advantage of the year-round fog without having a significant impact on the surrounding environment. The water collection system would be easy to transport by boat and can potentially supply the coastal island region with sustainable water. This would save the region from having to purchase additional water in the future and would make for a sizable investment for the years to come.

2.3.2 Point Reyes, California.

Figure 4: Image of Point Reyes, California (Weller, 2017).

Point Reyes, California is renowned for two distinct key features. This area is known as the windiest place on the Pacific Coast with wind speeds up to hurricane-force levels of 75 mph. In addition, it is also known as the second foggiest place on the North American continent. As it resides on the coast near the Pacific Ocean, the saltwater from the ocean contributes to dense fog by providing ample amounts of moisture yearly. The cool temperature of the Pacific Ocean contrasts greatly with the surrounding air from nearby land masses. This results in the area getting approximately 200 days of fog per year (Nps.gov, 2022). This fog is generally persistent and can stay around for weeks on end. During the summer months, the fog is particularly thick and lingers around for longer periods of time, thus visibility is commonly reduced to mere feet. This region does not greatly benefit from this fog, so setting up a large fog netting installation can provide Point Reyes with a new source of reliable income. Since the fog is so dense in the summer months, collecting fog water will slightly mitigate the visibility hazards present and serve as a backup supply for the region to store in water tanks or potentially sell.

2.3.3 Cape Disappointment, Washington.

Figure 5: Image of Cape Disappointment, Washington (Nps.org, 2021)

Another region that is significant to locate and collect fog water would be Cape Disappointment, Washington. This area is located in the extreme southwest corner of the state of Washington. Unlike the previously mentioned areas with almost year-round fog, Cape Disappointment has nearly three and a half months of thick fog each year. Despite the shorter time span of fog, this region contains really concentrated fog that is supplied by the Pacific Ocean as well. By installing cheaper netting setups, the local region can benefit greatly from this dense fog and truly take advantage of the natural water source at hand. Washington is also the most overcast state in the western hemisphere of the United States and contains around 160 days of fog a year on average (Meteoblue, 2022). This region may benefit greatly from setting up a series of cheaper harp nets as the installation is quicker and profit is easier to generate with less expensive netting material and design. The series of nets is also a better application in this situation as the fog is very dense and more water can be collected in the concentrated area over time.

2.3.4 San Francisco, California.

Figure 6: Image of San Francisco, California (White, 2017).

Despite San Francisco may not be one of the top regions in terms of the number of days with prevalent fog, fog is the notoriety of San Francisco. This region is heavily associated with fog as the Golden Gate Bridge is renowned for being enveloped in fog. This region typically receives fog for 80-100 days throughout the year and during the winter month periods, San Francisco gets enveloped by a tule fog (White, 2017). This is a type of radiation fog that develops in humid conditions, for instance after a rainstorm, calm winds, and abrupt cooling of surrounding air temperatures. This is extremely prevalent during the night, hence during the winter when nights are the longest. The Californian mountains in this area trap cool air clouds and force them downward into nearby communities. Considering this situation, it would be best to implement several fog net units on top of these mountains or a series of nets in a row near the Golden Gate Bridge due to the region being narrow.

2.4 Effects Of Removing Fog From Surrounding Environment

Throughout several of the world's driest environments, atmospheric moisture is a critical source of water for native ecosystems and human communities. For instance plant life, insects, and algae in the Namibian and Israeli deserts generally get much of their needed water from the humidity, dew, and fog. Even some cacti species have evolved to collect fog droplets on their spines to adapt to their environmental conditions. As previously mentioned, several areas that could benefit from fog water collection are located in California. The Californian Redwood forests also derive a largely significant amount of their moisture from this fog source. Even some Californian residents along the coast have suggested fog water collection units as an additional water supply to combat possible droughts and have a clearer view of the Pacific Ocean.

Around the world, few places obtain drinking water from coastal fog. Most of the communities that take advantage of this are rural areas with abundant fog but little other available water or hard-to-reach water resources. Fog harvesting typically yields one to three gallons of water daily per square yard of fog mesh. This means that a normal household of three people using around 300 gallons of water a day would need 1,000 to 12,000 square feet of fog mesh (US Davis Center, 2015). Thus, for a fit on a single-family lot, the length of the fog unit needed would be about 50 feet wide and 21 to 250 feet tall. Once scaled to an entire population of a city, this seems very impractical in first-world countries. This is one of the major factors limiting developed countries from implementing fog netting units. The sheer amount of water removed from the fog would severely impact the surrounding ecosystem with such a great deal of nets. However, the current setup of fog nets at the Morocco site mentioned earlier illustrates how effective several Cloud Fischer nets can sustain a whole community. Therefore, the lingering question is how does removing water from fog affect the ecosystem of life around the region? Although water collection using fog nets amounts to high volumes, only a small percentage of fog is actually collected. Each different environment has its own value for how much water is needed for removal before it affects the ecosystem ranging from 1 to 10%. One aspect that can be further tested is using Lichen which is a sensitive and accumulative biomarker that has poor absorptive selectivity due to the lack of external defensive tissues to test this. Further in this paper, we will discuss and calculate the percentage of collected water to total fog in the Morocco site.

2.5 Alternative Netting Solutions

The beauty of cheaper fog harvesters is that they generally take very little effort to maintain after their initial setup. These harvesters can be used in remote areas without the need for constant supervision. One major downside to this is some nets are simply not very efficient, due to the size of the mesh and its varying hole sizes. If open spaces in the net are too large, water droplets will escape through it, but if the spacing is too small, the water collected will clog within a matter of seconds from surface tension. This prevents water from sliding down the net on its own and will not be easily collected.

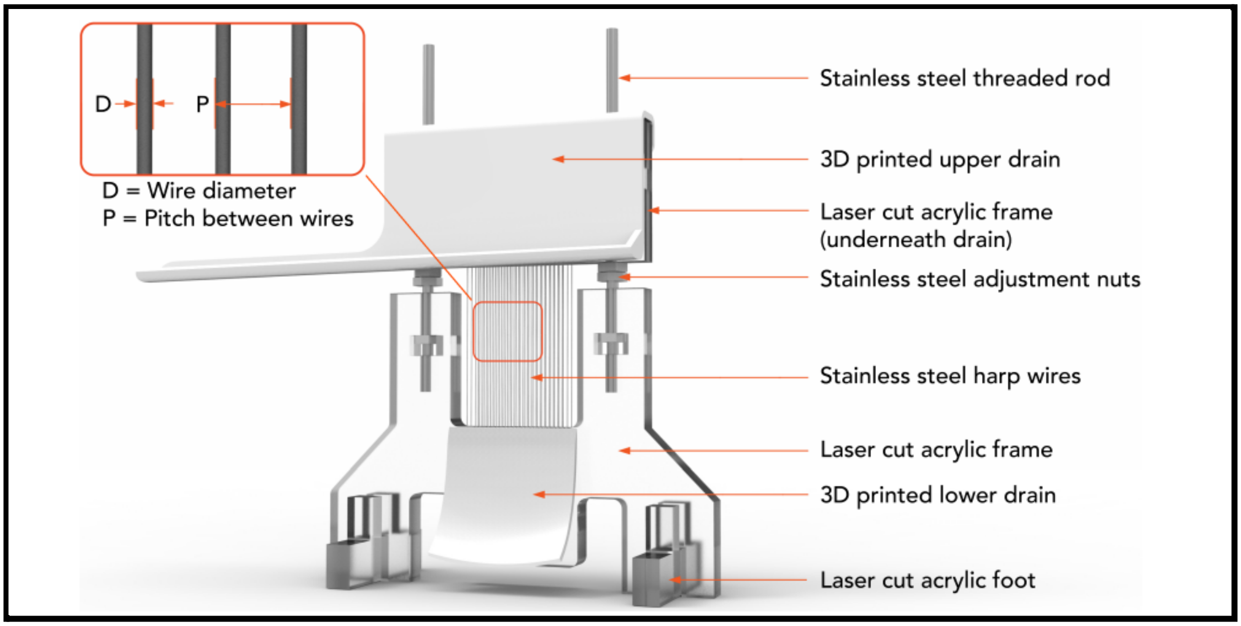

Figure 7: Structure of Fog Harps (O'Neil, 2021).

One effective alternative to this is an efficient netting design called a "fog harp". This design was pivoted from the original cross-hatching pattern on traditional mesh nets to a simple linear netting. Brook Kennedy, an industrial designer, researched the Redwood Forests in California and concluded that almost one-third of the collected water from trees comes from rolling fog passing through the Pacific Ocean. The needles on the trees were not shaped like crosshatches or screen door meshes, but rather they were completely linear. This insight led to Kennedy's final design of netting with just vertical wires.

This design might seem deceptively simple as only the horizontal netting is removed, but experiments using a lab humidifier revealed that there was no way for the harp design to clog because droplets simply have to slide down the wires which are propelled with just simple gravity. This design also saw an increase in the collection of water three times more than the traditional cross meshing of nets. The fog harp is a low-tech improvement on the traditional fog harvester units, collecting about 1 to 3 percent of the fog that passes through the region. Other alternatives have been suggested by researchers as well as manipulating the electrical forces around fog. This would imply having a vertical structure a few inches from the fog nets containing electrodes that essentially zap the air, thus electrically charging water droplets and propelling them toward the fog nets as the two forces attract leading to almost 100 percent efficiency.

III. Methodology

This methodology section contains our primary objectives and goals for this project that highlight the different purposes for our research. This includes the design of the additional unit we built to generate an experiment to test the effectiveness of orientating nets in a parallel series. Additional equipment to power the lab are also discussed in detail, including the House of Hydro mist generators and the power supply boxes located in the lab. An experimental procedure is also provided in this section that details all the specific steps needed to execute this experiment precisely again.

3.1 Objectives and Goals

A.) Manipulate Parameters To Increase Water Production

Using the unit from the lab, the group changed different settings to find what can increase water production from the nets. The two parameters the group looked at was changing the fan speed of the unit and the orientation of the nets. Many projects done with fog harvesting using netting have nets set side by side to one another, so the group designed a unit that can have nets parallel to another to test a different orientation.

B.) Design UO Lab Experiment

A unit ops lab was planned to help teach future students. With it, students would be able to get a deeper understanding of mass transfer and the humanitarian side of engineering. A focus will be put on how projects like these can have a large impact on communities and also how nature is affected by engineering. This report will have the following deliverables: a theory section, the procedure to run the unit, and questions for students taking the project.

C.) Design Multi-Net Holder

To be able to put the units in the orientation of being parallel to one another, a new unit had to be designed as the current unit could only test one net at a time. The multi-net holder was designed in Fusion360 and assembled using a laser cutter.

3.2 Designing A Parallel Series Of Nets

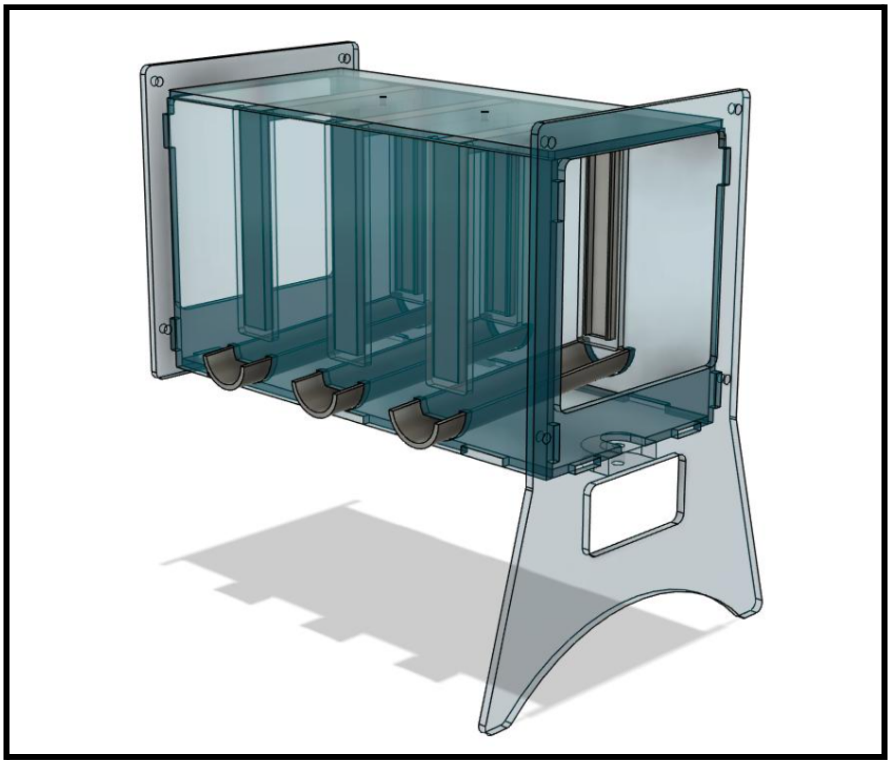

Figure 8: Fog Unit Series of Nets Design

Figure 8 showcases the series of fog nets designed by the team members using Fusion 360 Autodesk. The entire unit is approximately 1’-5” long by 6.4” wide and encased on 3 sides with plexiglass. The unit is built to contain fog and prevent excessive water vapor from escaping to produce efficient and accurate water collection measurements. The system contains 3 push-on metal trim frames that are fitted with spring loads to hold mesh nets. The top part of the unit is removable to allow easy access to the frames for any adjustments after each trial run. Half-inch ceramic pipes with an exterior diameter of 1.67 inches. These half pipes are tilted on a platform at a slight angle of 10 degrees to allow the collected water to freely flow into beakers for measurements and data collection. The tray itself also contains a cutout for further water collection in case water vapor condensates in the unit that cannot be captured by the pipes. Three inches of space is allowed between each metal frame to simulate an actual series of nets to account for the width of metal framing and support rods. The end portion of the unit is left open to simulate the actual environment of the mountains in Morocco. This opening allows fog to escape which alleviates the issue of fog back up with the water vapor bouncing off the plexiglass and possibly passing through the nets again. Overall this design was built by our team and constructed by WPI's mechanic Ian Anderson through several revisions and iterations to simulate conditions similar to actual fog heavy regions. The renderings of the unit are provided below.

3.3 Ultrasonic Mist Generators

Ultrasonic mist makers are common devices found in many households. Their purposes vary from sustaining hydroponic farms to generating fog for large events and celebrations. In our lab these ultrasonic mist generators are used to produce fog from water in our scaled down unit. These mist makers generally contain a piezo atomizer disc/transducer which is a ceramic humidifier that includes a built-in sensor that detects the presence of water and activates the transducer plate (The House of Hydro, 2021). It then works by transposing high-frequency sound waves into mechanical energy. This is then transferred into liquid water creating standing waves. As the water leaves the atomizing surface of the disc, it is broken down into a fine mist consisting of uniform micron-sized droplets. These high-pressure compression waves are created on the water surface, causing vapor molecules to be released into the air and guided by motorized fans to create a fog with constant velocity. The water particles in the fog are of a size of less than 5 microns. Some critical aspects to consider when using the ultrasonic mist generators include, utilizing a sufficient amount of water to allow the fogger to function and supplying water that needs to be distilled or deionized. Furthermore, unlike thermal or heat-based foggers, the fog-like mist generated by an ultrasonic fogger is cold and wet and simulates conditions that mirror those of real fog heavy regions high in elevation. Overall, these mist generators are small, compact devices that are cost-effective and only rely on an external AC/DC adapter for their power supply.

Figure 9: Ultrasonic Mist Generator (The House of Hydro, 2021).

3.4 Power Source For Experiment

In order to power the fans in our experiment, a set of three power supply boxes were utilized. Each power supply box correlates to a different fan section. These sections include the interior array, outer fans, and the center fan only. The parameters on this power supply included current and voltage knobs. By adjusting the current and voltage our group was able to manipulate the speed at which the fans on the scaled-down unit ran and be able to pre-set wind velocity values in accordance with this.

Figure 10: Power Supply Boxes

3.5 Experimental Procedure

The following instructions detail the exact procedure our group conducted in collecting statistical data for this research project. This same set of steps is utilized in our proposed Unit Operations lab as seen in section 4.3.

Lab Instructions

For Single Netting Structure:

1. Make sure the system is fully drained and dry before conducting the experiment.
2. Measure out 6000 ml of water using the large graduated cylinder provided and pour it into the base of the unit.
3. Record the height of the water using the ruler attached to the side of the unit. Note the dimensions of the rectangular water reservoir. Include all parameters such as the room temperature and humidity.
4. Adjust the voltage and current of the interior, center, and exterior fans to replicate the desired wind velocity.
5. Turn on the switch to the fans and record the wind speed using the provided anemometer. Utilize the 9-point frame of point velocities mentioned earlier.

6. Adjust the angle of the interior fans to obtain maximum fog output.
7. Turn on the fog generator
8. Allow the system to reach a steady-state as the fog will evenly disperse and flow through the opening of the system.
9. Set up a measurable beaker below the half-pipe structure to collect water.
10. Attach the desired netting frame to be tested with clips to ensure no movement occurs.
11. Begin the water collection experimental trials. Allow the netting to collect water for appropriate timeframes within 10-30 minutes depending on the time allotted.
12. Record the amount of water collected in equal time intervals.
13. Turn off the fog generator.
14. Record the total amount of water collected and any build-up of condensation in the unit.
15. Drain the rest of the water in the unit by turning the valve attached to the pipe located on the bottom of the unit.
16. Allow the water to drain into the provided bucket and note the height of the water left in the unit, then completely drain and clear all water from the unit using paper towels.
17. Turn on the fans again and allow the whole system to completely dry before using it for the next trial.

For A Series Of Nets:

The intended process of water collection is essentially the same besides a few steps. The metal frames for each net slide into their slot in the attached unit. Each water collection half pipe will need a beaker of its own to record the collected water. All accumulated condensation can be drained out of the structure using the additionally provided drain spigot at an angle. Note the back end of the attached unit is left open to simulate real conditions of fog escaping while the top of the unit is closed off with a top layer to ensure ample fog passes through the netting frame structures

IV. Findings and Analysis

This section details the analysis of our collected data in the lab. The first section describes the difference of water collection rates for the official CloudFisher nets in comparison to the two best water collection rate nets provided in the lab. The second section entails the analysis of three netting slots when used in a parallel series. Differences in water collected, efficiency, and the max saturation point of the nets are noted as well. The final part of this section provides a proposed Unit Operations Lab for A term of the senior year Chemical Engineering Sequence. This lab provides a different approach from the existing labs as it encompasses Humanitarian Engineering. This lab includes a pre-lab section, theory, related questions, and any additional references that a student may need to complete the assignment.

4.1 Comparison Of CloudFisher Nets To Other Nettings

Runs were done comparing the nets already owned and the newly obtained Aqualonis nets. This process contained several parameters that had to be considered to create a more efficient run. The condensation buildup inside the unit as well as the amount of water left over in the bottom tank of the unit had to be considered to obtain an accurate water collection amount. In order to determine how much water was collected in each run with consideration of how much water was left in the unit, calculations for efficiency and amounts of water were conducted. See Appendix I for sample calculations and further data. Figure 12 below shows a data table of how much water was collected from each net run at the same parameters of wind velocity, angle of the fans, and netting orientation for a 10-minute interval. This is then illustrated in Figure 11 as a bar graph depicting a visual difference. Comparing the two most efficient nets to the Aqualonis CloudFisher net, the Aqualonis net is vastly more efficient than the thick white net and collects 5 more milliliters of water compared to the black and white net. The thicker white netting collects significantly more water than the nylon cording nets provided. As seen below on multiple trials, the official CloudFisher nets have a slight improvement from the dual-sided black and white netting used. This same correlation holds true for the efficiency of the nets. The official cloudfisher netting was slightly more efficient than the other nets at around 19% efficient in terms of the total water collected versus the amount of water vapor created by the mist generator. This showcases that the majority of fog escapes the system and leaves the unit without being converted. Some adjustments that may improve the efficiency of the nets would be to create a backdraft that allows the fog to stay in the area of the unit longer to be converted or changing parameters such as temperature and humidity.

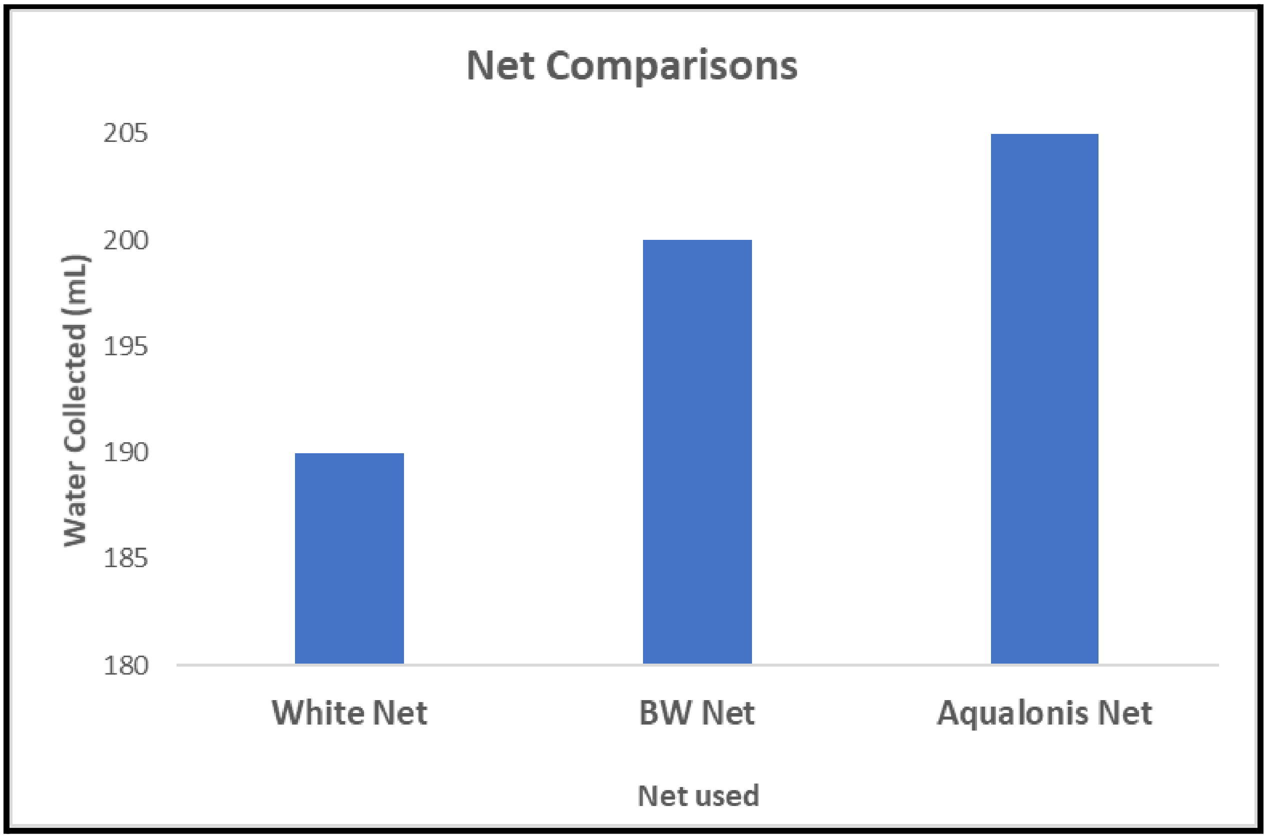

Figure 11: Netting Comparisons between CloudFisher Nets and Old Nets

Net Used	**Water Collected (mL)**
B&W Net	200
Thick White Net	190
Aqualonis Net	205

Figure 12: Comparison of Nets

4.2 Analysis Of Parallel Series Netting

For the analysis of the netting in a parallel series, we considered the orientation of three netting slots each attached to a different frame in the additional unit as seen in Figure 8. All subsequent data is shown in Figures 13-17 for the most consistent runs conducted during this experimental time period. The three graphs below show how much water was collected by nets in different slots at different speeds. Using Figure 18 as an example, all the data shown is from an Aqualonis net in slot 1, the closest slot to the fog being generated. It should be noted that if there is a matching speed in these three graphs, it means that the data was from the same run, meaning that the 0.06 m/s run that's in all three graphs had a net in all three slots when collected. Looking at Figure 18 it can be seen that at higher speeds, more water is collected. At a speed of 0.06 m/s the Aqualonis net collected 340 mL of water while at a speed of 0.175 m/s, 383 mL of water was collected. So a positive correlation can be seen that as speed is increased, the amount of fog converted and collected increases. This trend can also be seen in slots 2 and 3, in slot 2, 24 mL more water was collected from 0.06 m/s to 0.175 m/s, and in slot 3, 4.5 mL more water was collected between 0.06 m/s to 0.175 m/s. Thus there is a positive correlation with wind velocity and the amount of water collected as predicted.

By recording how much water was converted, the group was able to check the efficiencies of all three nets. On average, the first net converted and collected 32.6% percent of the water. At higher speeds the efficiency is greater. With the nets having a max water collection rate, the higher speeds let the nets reach this maximum rate faster. The second net on average had an overall efficiency of 7%. While not as significant as net 1, 7% is still a crucial amount of water. The third net has an average efficiency of around 2%. As hypothesized, the efficiency of each net decreases with each net added. The efficiency seems to drop exponentially with the first net having a 33% efficiency and the third net having an efficiency of 2%. With one of the goals seeing how effective it would be to have nets in series with each other, the data shows that having at least two nets would be worthwhile. 7% is an efficiency that can still be desirable but 2% would only be desired when dealing with large amounts of a substance. These statistical data points are only accurate for the spacing of the nets at 3 inches apart from one another. If another unit is created allowing for each netting frame to be freely moved around, additional different data points may be collected that may or may not mirror our results.

Time (min)	**Net 1 Water Collected (ml)**	**Net 2 Water Collected (ml)**	**Net 3 Water Collected (ml)**	**Total Water collected (ml)**
4	36.5	3	0	-
8	100	14	1	-
12	176	30	5	-
16	253	45	8	-
20	340	62	12	414
Percentage of converted	0.82	0.15	0.03	-
Percentage of total	0.27	0.05	0.01	-

Figure 13: Aqualonis Nets Run at 0.06 m/s Results

Time	**Net 1 Water Collected (ml)**	**Net 2 Water Collected (ml)**	**Net 3 Water Collected (ml)**	**Total water collected (ml)**
4	49	10	N/A	-
8	128.5	25	2.6	-
12	215.5	47	6.95	-
16	302.5	69	10.15	-
20	391.5	94	15.95	501.45
Percentage collected	0.78	0.19	0.03	-
Percentage of total	0.35	0.08	0.01	-

Figure 14: Aqualonis Nets Run at 0.11 m/s Results

Time	Net 1 Water Collected (ml)	Net 2 Water Collected (ml)	Net 3 Water Collected (ml)	Total water collected (ml)
4	55	-	-	-
8	132	-	-	-
12	215.5	-	-	-
16	328	-	-	-
20	459.5	-	-	459.5
Percentage of total	0.38	-	-	-

Figure 15: Aqualonis Net Run at 0.12 m/s Results (One Net)

Time	Net 1 Water Collected (ml)	Net 2 Water Collected (ml)	Net 3 Water Collected (ml)	Total water collected (ml)
4	40	-	N/A	-
8	120	-	13	-
12	200	-	26	-
16	288	-	40	-
20	376	-	54	430
Percentage collected	0.87	-	0.13	-
Percentage Total	0.31	-	0.05	-

Figure 16: Aqualonis Nets Run at 0.12 m/s Results (Two Nets)

Time	**Net 1 Water Collected (ml)**	**Net 2 Water Collected (ml)**	**Net 3 Water Collected (ml)**	**Total water collected (ml)**
4	42	2.5	N/A	-
8	120	17	3.15	-
12	207	39	7.5	-
16	294	61	10.7	-
20	383	86	16.5	485.5
Percentage Collected	0.79	0.18	0.03	-
Percentage Total	0.32	0.07	0.01	-

Figure 17: Aqualonis Nets run at 0.175 m/s results

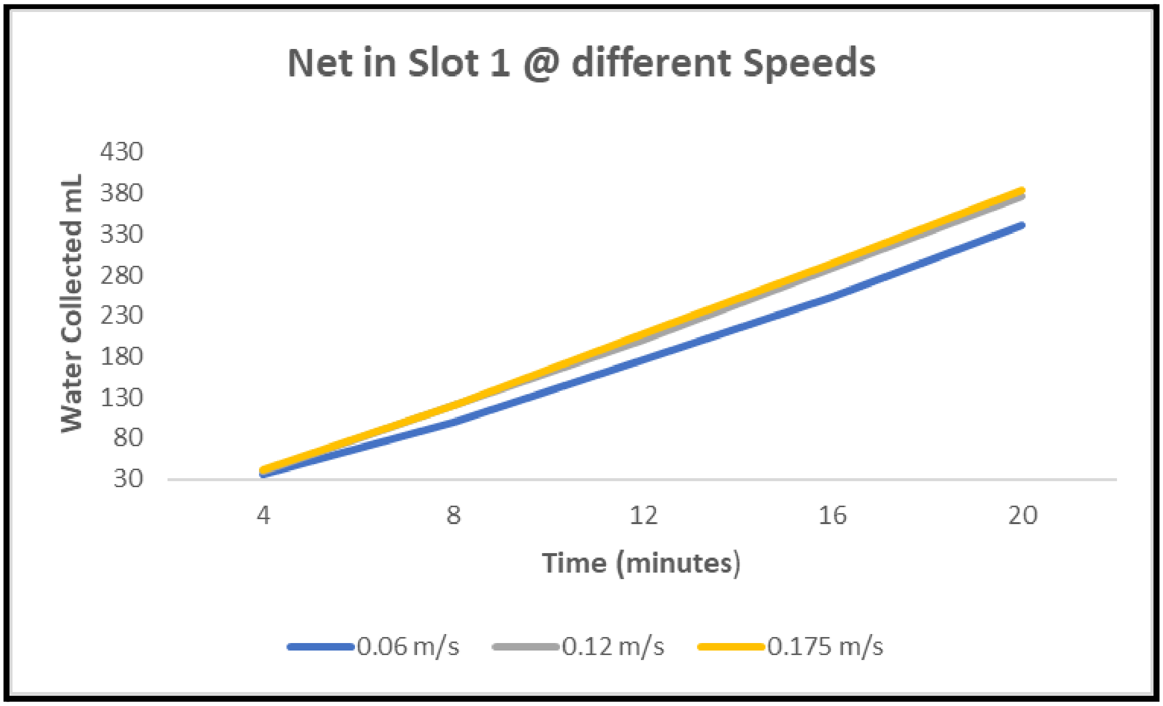

Figure 18: Comparison of Water Collected at Varying Speeds in Slot 1

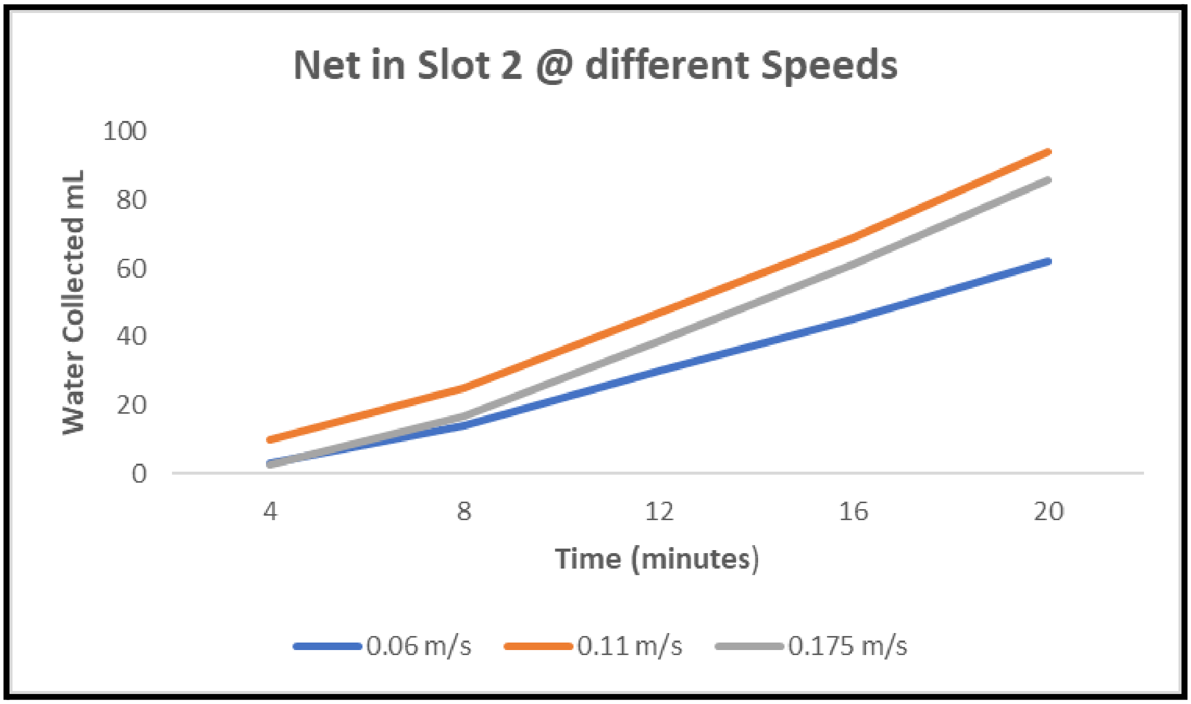

Figure 19: Comparison of Water Collected at Varying Speeds in Slot 2

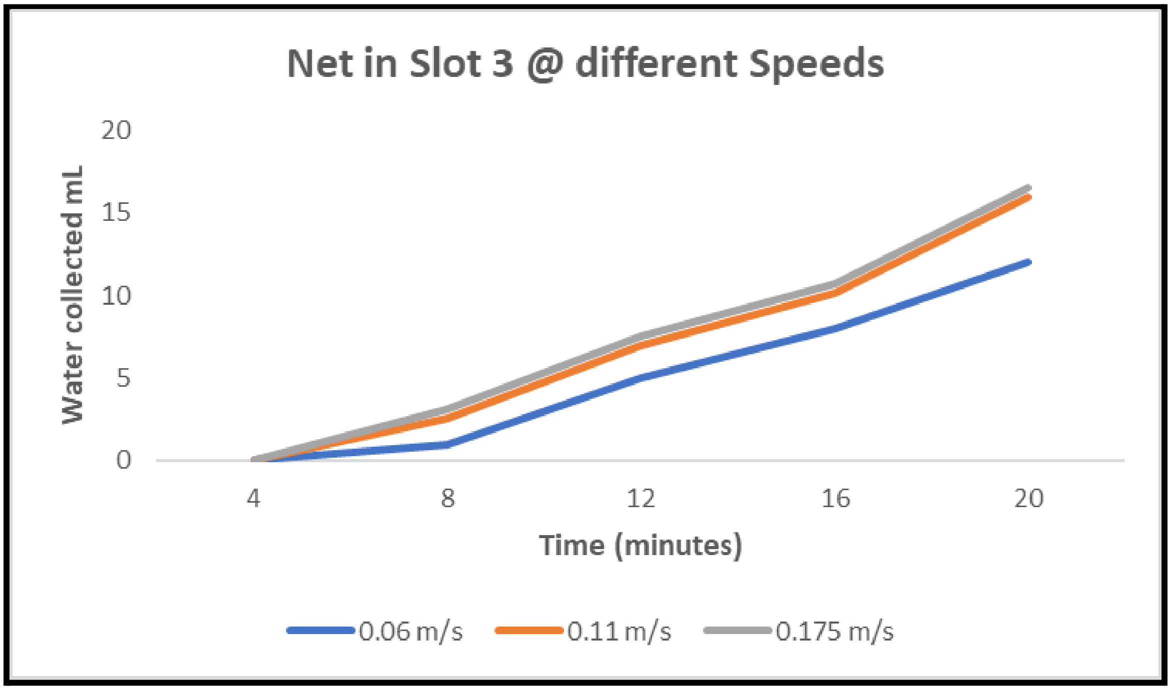

Figure 20: Comparison of Water Collected at Varying Speeds in Slot 3

The group noticed that each net would reach a maximum water collection rate regardless of how saturated the net was. Below are graphs that show the average water collection from each slot from the same data collected in the graphs above. Looking at the average water collection in slot 1, one can see that the three different speeds reach the same collection rate. The data tables can be seen in Appendix II, but the slowest speed had an average rate of 87 mL after 20 minutes, and the highest speed had an average rate of 89 mL of water after 20 minutes. This same trend can be seen in the higher speeds of Slot 2 and 3. At 0.11 m/s and 0.175 m/s in Slot 2, the average water collection was 25 mL after 20 minutes. At 0.11 m/s and 0.175 m/s in Slot 3, the average water collection was 5.8 mL after 20 minutes. What is so interesting about this data is that under the assumption that the water collection rate from Slot 1 is the max collection rate, Slot 2 should have a higher collection rate since Slot 3's rate is not zero. The group believes this has to do with the stitching of the nets and the low density of the fog. It should be mentioned that in a real-world environment, these nets would be running for much longer than the 20 minutes done in the lab, which would increase the saturation of all nets, especially nets two and three.

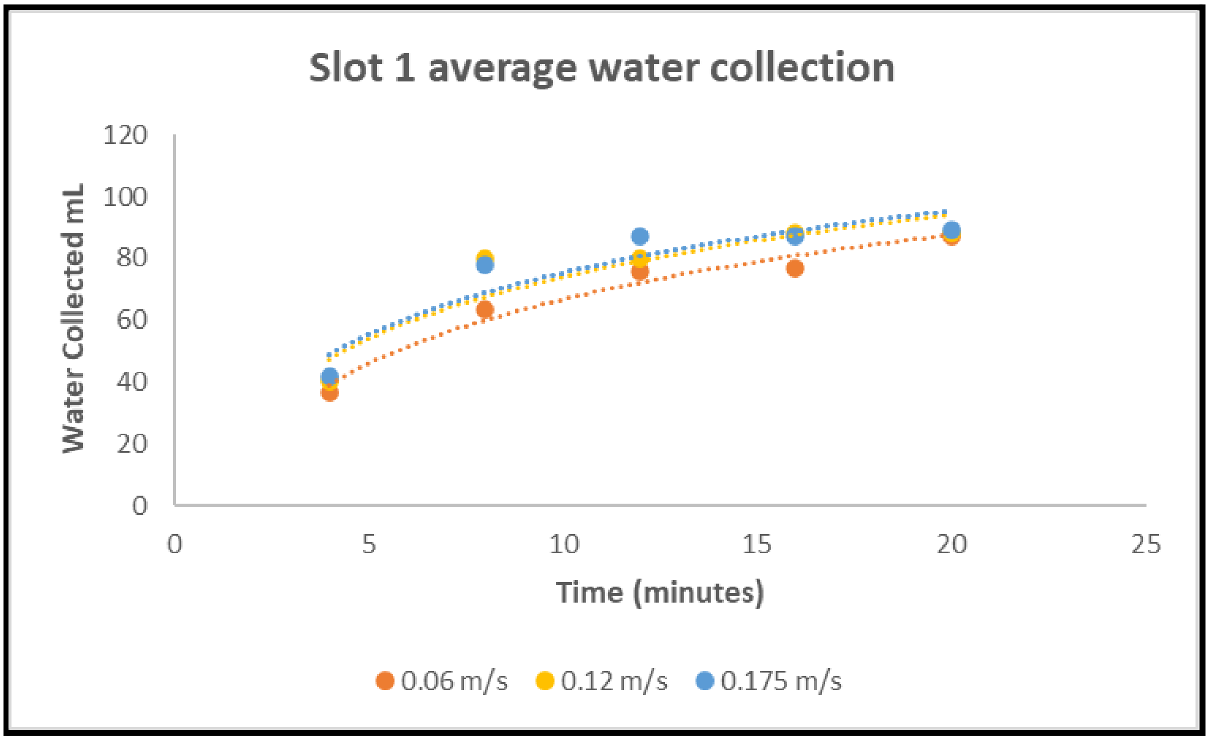

Figure 21: Average Water Collected in 4 Minute Intervals in Slot 1

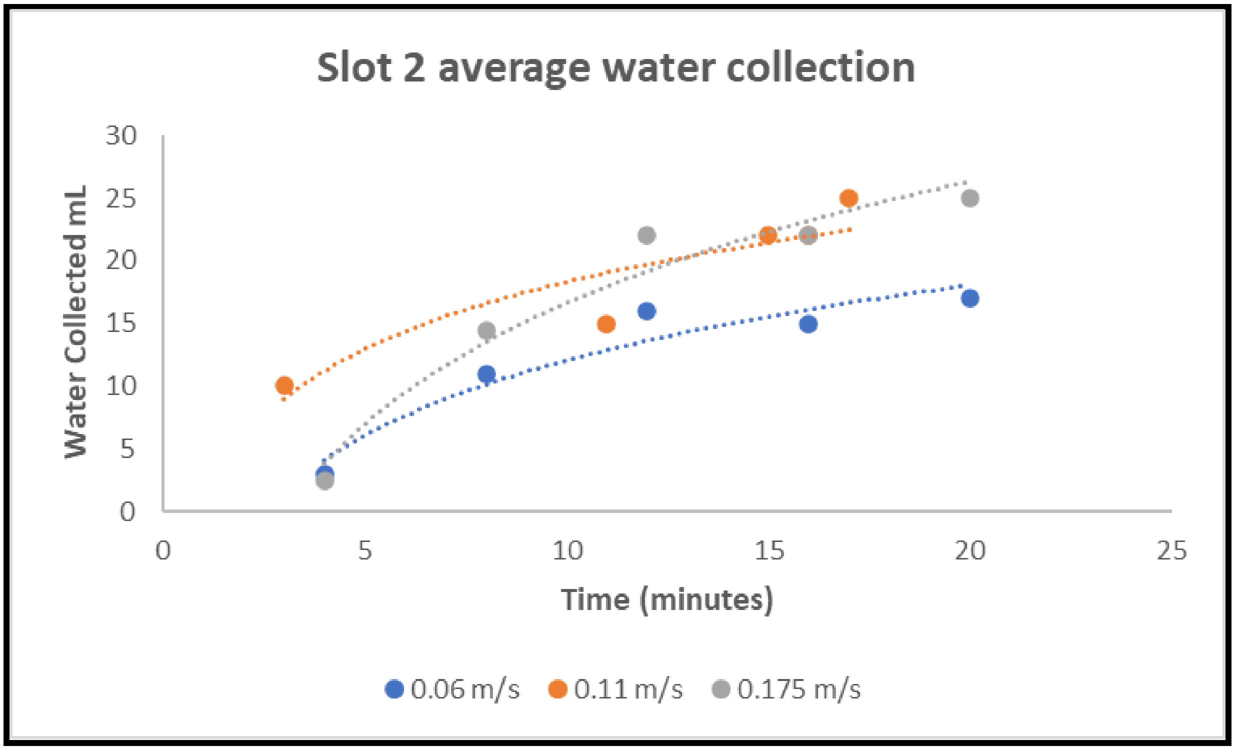

Figure 22: Average water collected in 4 minute intervals in Slot 2

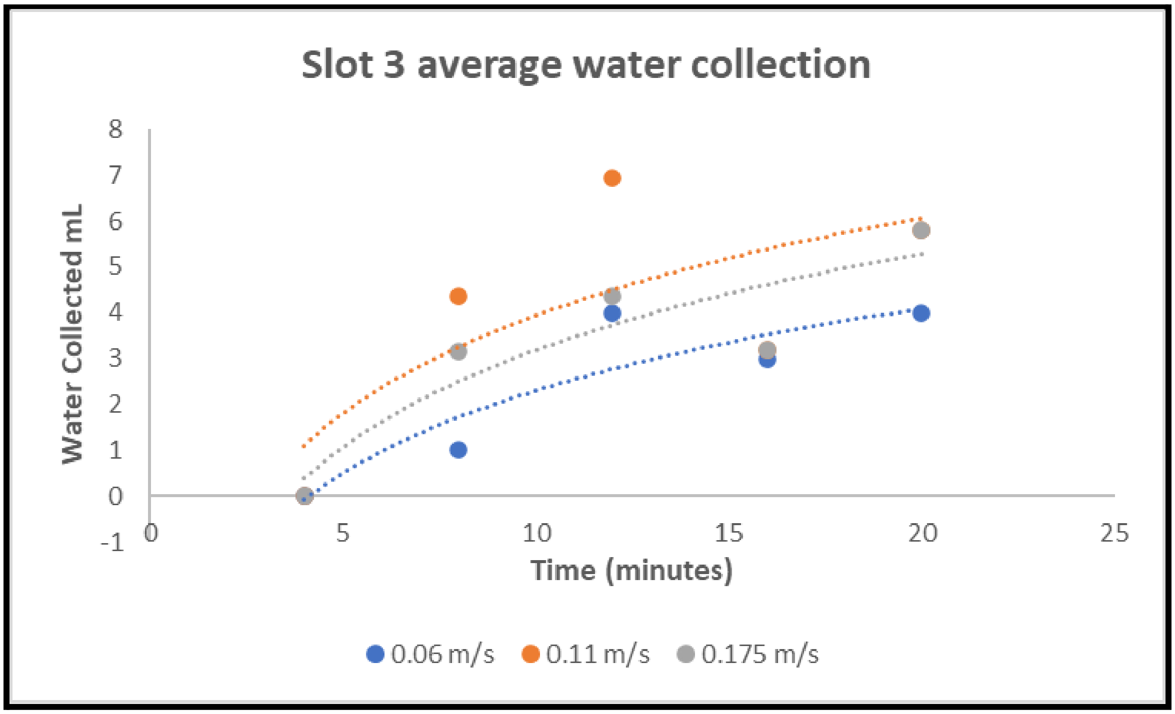

Figure 23: Average water collected in 4 minute intervals in Slot 3

4.3 Unit Operations Lab

The following section details our proposed Unit Operations Lab for WPI senior students to conduct in their A-Term course. This lab focuses on mass transfer of liquids, chemical design, and humanitarian aspects of engineering. By analyzing the effects of water as a transfer medium using fog harvesting, students will gain a better understanding of the core topics in Chemical Engineering and utilize the skills they are currently learning in their capstone design course in a hands-on approach. Our group strongly recommends the Unit Operations Lab curriculum at WPI to implement humanitarian aspects into all future experiments, thus allowing students to gain a broader knowledge base of the impact of these experiments in the real world.

Worcester Polytechnic Institute
Department of Chemical Engineering

CHE 4401 Fog Water Conversion: Utilizing a Series of CloudFischer Nets A Term

Introduction

In this experiment, you have been employed by the company, Aqualonis to research water extraction from fog and create a fog netting system design that will effectively collect water in different regions around the globe. Due to the pandemic and potential future outbreaks, Aqualonis is no longer supporting or working on ongoing project sites in Morocco, Tanzania, or Bolivia and instead focusing solely on research and ways to improve water collection utilizing different netting designs and setups. There are two pilot-scale fog units in our lab that simulate fog-like conditions on different scales. The larger unit is capable of reaching higher wind velocities than the smaller unit, but the smaller unit contains an additional unit attachment that includes a setup for a series of nets with frames separated 3 inches apart. One idea that the Aqualonis lab had experimented with was setting up fog nets in a series to test the effectiveness of having multiple nets stacked against each other in a parallel manner. This setup would be beneficial for regions with less fog landmass such as valleys or enclosed regions in highly populated areas. This additional structure attached to the fog unit provides a more controlled environment that is enclosed to keep fog from easily escaping and collect any condensation that accumulates from the fog creation process.

Objectives

Using the numerous different nettings provided in the lab and the scaled-down fog unit installation, design a water collection process best suited for real-world conditions. This includes designing a water piping system with gravity-driven water flow as bringing fog water from the high elevation harvesting sites to local villages is a crucial process. Take into consideration the storage, control, collection rate, and the mixing of vital nutrients to supply as drinking water. Utilize the differing methods of measuring the water rate collection, including Bernoulli's equation, Weisenbach's method, and the Hazen Williams equation. Assume that the series of nettings have a fixed surface area of (278 x 42) meters, wind velocity is approximately 5 m/s, the environment is 10℃ in temperature, and the surrounding fog has essentially 100 percent humidity. Also assume a basis of one day and a max water harvesting rate of 22 liters per meter squared of net area per day.

You should conduct several experimental runs of water collection utilizing different wind velocities and netting orientations, as well as testing the effectiveness of implementing a series of nets. You should compare wind speeds to the amount of water collected per unit and apply this to the additional structure of netting frames. Is it worth constructing the nets in a parallel series considering the additional water collected and how much each netting frame costs? How many nets can we have in a row before this water collection becomes redundant? Your depth of analysis will reflect your knowledge of mass balances, fluid transfer, and mass transfer through porous surfaces. Your overall new netting design should also specify the required dimensions of netting, a desirable wind speed to produce the most water, and the saturation point of the nets indicating maximum water collection.

Attached below are operating instructions and specifications along with a 3-D rendering of the current series-netting design attachment. Additional findings and water collection rates are included in the attached report analyzing the official Aqualonis nets in s series and comparing effectiveness in water collection to the netting provided in the lab. All equipment utilized is provided in detail in the background and methodology section of this report.

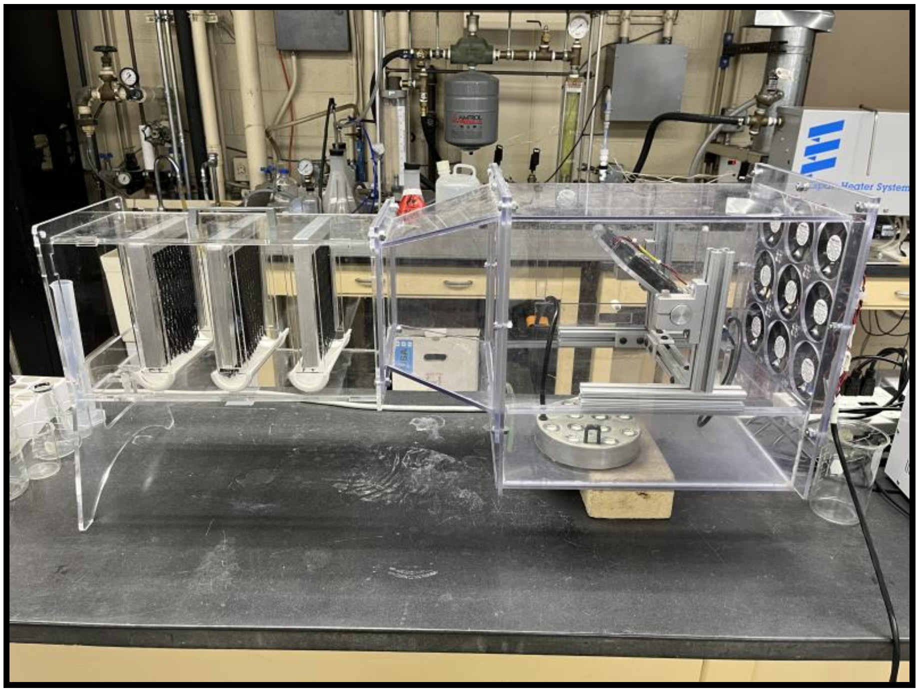

Figure 24: Scaled-Down Fog Generation Unit in Lab

Operating Instructions

Preliminary inspection of equipment

It is necessary that each student understand the operation and arrangement of all equipment In the lab before any experimental work is undertaken. Students should complete a total inspection of the equipment and understand the function of each part of the unit and any additional attachments. A detailed schematic should also be provided by each lab group before the following lab period. Each member of the lab group will be expected to answer questions about the equipment and any theoretical questions during the lab session.

Procedure

Single Netting

1. Make sure the system is fully drained and dry before conducting the experiment.
2. Measure out 6000 ml of water using the large graduated cylinder provided and pour it into the base of the unit.

3. Record the height of the water using the ruler attached to the side of the unit. Note the dimensions of the rectangular water reservoir. Include all parameters such as the room temperature and humidity.
4. Adjust the voltage and current of the interior, center, and exterior fans to replicate the desired wind velocity.
5. Turn on the switch to the fans and record the wind speed using the provided anemometer. Utilize the 9 point frame of point velocities mentioned earlier.
6. Adjust the angle of the interior fans to obtain maximum fog output.
7. Turn on the fog generator
8. Allow the system to reach steady-state as the fog will evenly disperse and flow through the opening of the system.
9. Set up a measurable beaker below the half-pipe structure to collect water.
10. Attach the desired netting frame to be tested with clips to ensure no movement occurs.
11. Begin the water collection experimental trials. Allow the netting to collect water for appropriate timeframes within 10-30 minutes depending on the time allotted.
12. Record the amount of water collected in equal time intervals.
13. Turn off the fog generator.
14. Record the total amount of water collected and any build-up of condensation in the unit.
15. Drain the rest of the water in the unit by turning the valve attached to the pipe located on the bottom of the unit.
16. Allow the water to drain into the provided bucket and note the height of the water left in the unit, then completely drain and clear all water from the unit using paper towels.
17. Turn on the fans again and allow the whole system to completely dry before using it for the next trial.

Series of Nets

The intended process of water collection is essentially the same besides a few steps. The metal frames for each net slide into their slot in the attached unit. Each water collection half pipe will need a beaker of its own to record the collected water. All accumulated condensation can be drained out of the structure using the additionally provided drain spigot at an angle. Note the back end of the attached unit is left open to simulate real conditions of fog escaping while the top of the unit is closed off with a top layer to ensure ample fog passes through the netting frame structures

Cautions:

1. Operating at high voltage and currents can cause damage to the fan system. Note that the center fan is particularly sensitive to this.
2. Turning off the fog generator after each run is required as the piezo atomizer disc/transducer can burn out.
3. Draining the system can lead to minor spills and leakages that can cause slippery conditions on the lab floor.

Theory:

We develop the necessary equations and correlations of water flow in the fog water collection process, as well as the developed water storage piping system. Utilize a mass balance system of equations and the provided equations for gravity-driven water flow below. Gravity-driven water flow in pipes can be analyzed by comparing experimental data with theoretical predictions. In the context of this experiment, bringing fog water from the harvesting site in mountainous regions such as Morocco to the villages below involves gravity flow, mixing of minerals into the water, storage, control of the system, and distribution of water to nearby homes and other surrounding communities. The three primary ways of analyzing water flow utilize Bernoulli's equation, the Moody/Darcy-Weisbach correlation, and the Hazen-Williams equation. Gather data of all water collected by the unit in the lab and make informed conclusions about which method, or a mixture, might be most appropriate. Implement your findings and learnings about the limits of each method, experiments, and the relationship between your predictions and the conducted experiments that may contain inherent errors. How would the design of piping diameter, pipe length, pressure head, and the type of water flow (Laminar vs. Turbulent) affect the rate of transportation?

Bernoulli's equation

Bernoulli's equation is used to predict the theoretical pressure heads which are the height difference needed to achieve the designed flow rates.

$$p + \frac{1}{2}\rho V^2 + \rho gh = Constant \quad (1)$$

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho gh_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho gh_2 \quad (2)$$

Where,

P = the pressure of in the system, Pa/Atm

ρ = fluid density, kg/cm^3

P_1 = Pressure at Elevation 1, Pa/atm

P_2 = Pressure at Elevation 2, Pa/atm

V_1 = Velocity at Elevation 1, (m/s)

V_2 = Velocity at Elevation 2, (m/s)

H_1 = Height of Elevation 1, (m)

H_2 = Height of Elevation 2, (m)

Darcy Weisbach Equation:

The Darcy-Weisbach equation can be used to estimate the pressure head loss due to friction. Compare the actual pressure head designed for the system to the sum of the Darcy-Weisbach result and the theoretical pressure obtained from Bernoulli's equation.

$$\Delta p = f\frac{L}{D}\frac{\rho V^2}{2} \quad (3)$$

Where,

Δp = Pressure loss, psi

F = the Darcy friction factor

L = length of the pipe, (m)

D = Inner Diameter of the pipe, (m)

ρ = Density of the fluid, (kg/cm^3)

V = Flow Velocity (m/s)

Hazen Williams Equation:

The Hazen–Williams equation is an empirical relationship which relates the flow of water in a pipe with the physical properties of the pipe and the pressure drop caused by friction.

$$Pressure\ Drop\ =\ (L\ *\ 4.52\ *\ q^{1.85})/(c^{1.85}\ *\ d^{4.8655}) \tag{4}$$

Where,

L = Pipe Length, (m)

Q = Flow Rate, (l/min)

C = Hazen Williams Coefficient of the Pipe

D = Diameter (cm)

Fog Harvesting Mass Balance:

Assumptions:

Total Net Area: 278 meters x 42 meters = 11,676 m
Velocity = 5 m/s
Temperature = 10°C
Humidity = 100 %
Max Water Harvesting Rate = 22 L/day
Total Area = 1700 m^2

$$1700\ m^2\ *\ 22\frac{L}{m^2}\ *\ 1\ day\ =\ 37,400\frac{L}{day}$$

Using the data from the psychrometric chart below calculate the percentage of water removed from the fog in the region compared to the amount of water harvested per day.

Calculated Harvesting Efficiency = 0.08%

This means that a miniscule amount of water is removed from the fog under ideal conditions. Does this value change depending on the humidity or temperature? At what range would the harvesting efficiency be so high that it causes an impact on the ecosystem?

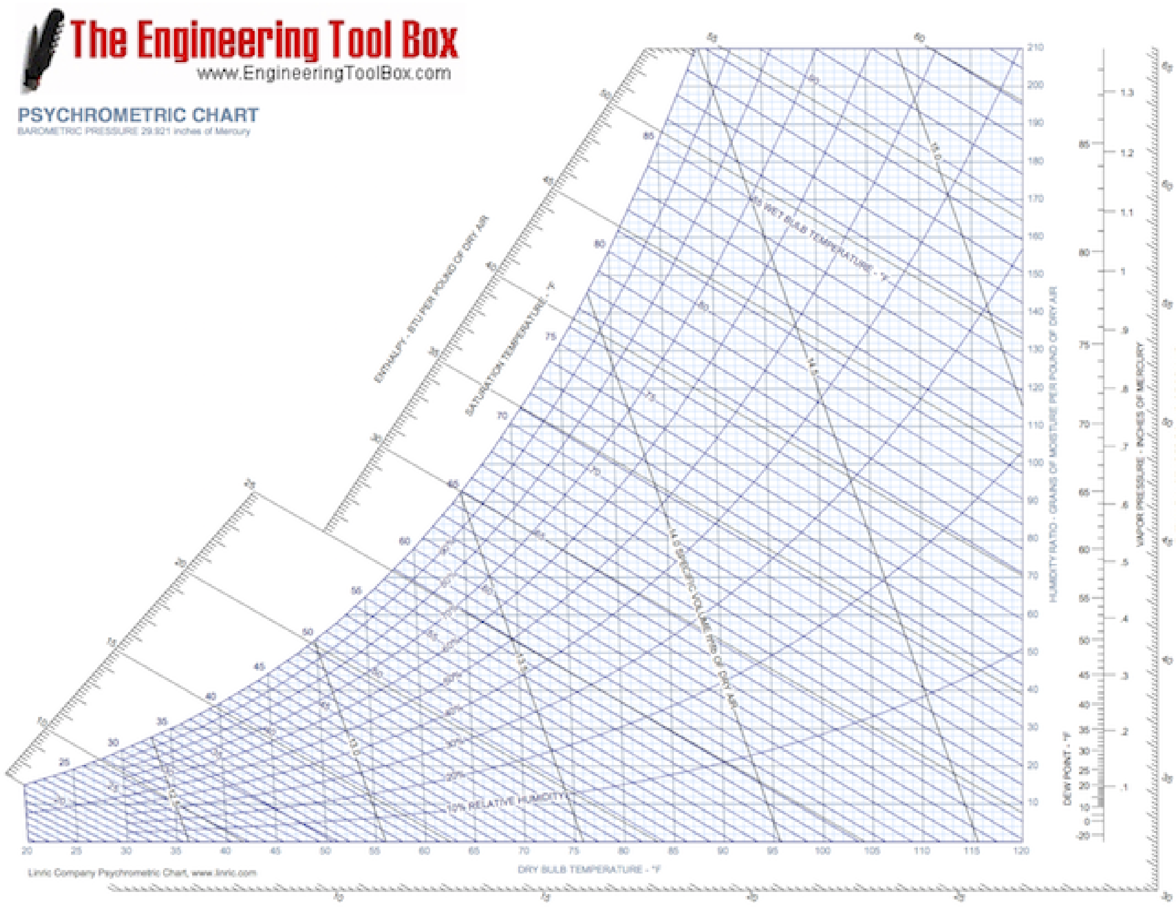

Figure 25: Psychrometric Chart

Pre-lab Requirements

1.) View and study the provided resources to gain a better understanding of the fog collection technology and the humanitarian aspects of this engineering project.
2.) Familiarize yourselves with the provided equipment in the laboratory and draw/render a sketch of all the equipment. This includes all piping, drain valves, and netting orientations.

3.) Prepare a data and results collection sheet that shows the number of trials you plan to run, the data you plan to measure for each run, and the results you plan to calculate for each run. This is acceptable in the format of data tables and an excel sheet.
4.) Study the theory of fog collection and equations necessary for gravity-driven water collection in a piping system.
5.) Complete the pre-lab questionnaire located below and bring it with you to your assigned lab session.

Prelab Questionnaire:

This is to be completed by the lab group and submitted to the assigned advisor of the experiment before the start of the experimental period.

1. Sketch and label a schematic diagram of the experimental apparatus.
2. Provide a list of objectives for the Fog water collection lab.
3. Experimental Conditions:
    a. How many trials for each netting configuration do you plan to conduct?
    b. At what wind speeds will your experiment be run at?
    c. How will you compare the official Cloudfisher nets to the other nets provided in the lab? Will you use a different system than the provided additional component containing a series of frames?

5. Calculate: Assuming that a fog harvesting net region has a fixed netting surface area of (278 x 42) meters, wind velocity is approximately 5 m/s, the environment is 10℃ in temperature, and the surrounding fog has essentially 100 percent humidity. Calculate how much water this region of fog nets can collect in one day. Also assume a basis of one day and a max water harvesting rate of 22 liters per meter squared of net area per day. Compare this to the total percentage of fog still left in the surrounding area. Would this small amount impact the ecosystem around the area?

6. What safety precautions will you have to implement to protect yourselves and the equipment in this lab? Do these precautions mirror the ones in a real-life fog water collection facility?

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V. Conclusion and Recommendations

Overall, our project group found that setting up a parallel series of nets does significantly improve the efficiency and amount of water collected. This finding can be implemented in various regions around the world including the U.S. Specific sites include San Francisco, California, and Cape Disappointment in Washington which have a range of 100-160 days of fog per year. This design of a series of nets in a row provides regions with less land surface area, like valleys to fit compact nets to collect water more efficiently. In addition, the proposed Unit Operations lab was designed for WPI senior students to delve more into the Humanitarian aspect of engineering since we observed that this is an important area to cover and is currently lacking from the existing lab curriculum. We implore students to test differing wind velocities and netting orientations to generate more efficient systems while observing the mass transfer of water from the environment to the netting and into the piping system. In addition, we also want students to utilize the knowledge that they obtain from their capstone courses in Chemical plant design to design a gravity-driven water collection piping system. This includes observations of different correlations to compare the effectiveness of each mathematical method. Additional recommendations for continuing this fog harvesting mqp project include, conducting more research to optimize fog netting structures in changing the stitching of the net, designing an additional unit to attach to the existing scaled down fog generator to minimize condensation, and controlling specific parameters such as temperature and density of the fog to analyze their effects on water collection rates.

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VII. Appendices

Appendix I: Data Tables And Calculations For Netting Comparisons

Additional Data Tables

Time (Minutes)	Water Collected (mL)
5	34
5	34
5	33

Thin Black Net at 0.06 m/s

Time (Minutes)	Water Collected (mL)
5	38
5	38
5	40

B&W Net at 0.06 m/s

Time (Minutes)	Water Collected (mL)
5	35
5	33
5	34

Thick White Net at 0.06 m/s

Time (Minutes)	Water Collected (mL)
5	24
5	25
5	25

Nylon Box Wire at 0.06 m/s

Sample Calculation of B.W Netting

Flow Rate:

$$Flow\ Rate\ =\ \frac{Water\ Collected\ (ml)}{time\ (min)}$$

$$Flow\ Rate\ =\ \frac{49.8\ ml}{5\ mins}$$

$$Flow\ Rate\ =\ 9.96\ \frac{ml}{min}$$

Total Water Produced by Mist Generator:

Knowns:
Length of Unit = 40.64 cm
Width of Unit = 25.40 cm

Mass of Water Produced =
[(initial level of water in the Unit - final level of water left in the Unit)
*(length of unit*width of unit)*Density of water]

$$Mass\ of\ water\ =\ [(IL\ -\ FL)\ *\ (l\ *\ w\ *\ \rho)$$

$$Mass\ of\ water\ =\ [(8.0\ cm\ -\ 7.0\ cm)\ *\ (40.64cm\ *\ 25.40cm)\ *\ 0.997\ \frac{g}{cm^3}]$$

$$Mass\ of\ water\ =\ 1029.16\ g$$

Mass of water collected:

$$Mass\ of\ water\ collected\ =\ Amount\ of\ water\ collect\ *\ Density\ of\ Water$$

$$Mass\ of\ water\ collected\ =\ 49.8\ ml\ *\ 0.997\ \frac{g}{ml}$$

$$Mass\ of\ water\ collected\ =\ 49.65\ g$$

Efficiency of Fog Harvest:

$$Efficiency\ =\ \frac{Mass\ of\ collected\ water}{Mass\ of\ water\ produced\ by\ mist\ generator} * 100$$

$$Efficiency\ = \frac{49.65g}{1029.16g} * 100$$

$$Efficiency\ =\ 4.82\%$$

Appendix II: Data Tables For Nets In A Parallel Series

Time (Minutes)	Water Collected in Slot 1 (mL)	Water Collected in Slot 2 (mL)	Water Collected in Slot 3 (mL)
4	41	8	0
8	120	20	3
12	205	40	7.2
16	290	60	10.2
20	380	85	16.1

Aqualonis Nets at a Speed of 0.13 m/s

Time (Minutes)	Average Water Collected in Slot 1 (mL)	Average Water Collected in Slot 2 (mL)	Average Water Collected in Slot 3 (mL)
4	41	8	0
8	79	16	3
12	85	20	4.2
16	85	20	3
20	90	25	5.9

Aqualonis Nets at a Speed of 0.13 m/s

Time (Minutes)	Water Collected in Slot 1 (mL)	Water Collected in Slot 2 (mL)	Water Collected in Slot 3 (mL)
4	40	9	0
8	123	23	2.8
12	207	44	7.2
16	292	63	10.4
20	381	85	16.3

Aqualonis Nets at a Speed of 15 m/s

Time (Minutes)	Average Water Collected in Slot 1 (mL)	Average Water Collected in Slot 2 (mL)	Average Water Collected in Slot 3 (mL)
4	40	9	0
8	83	14	2.8
12	84	21	4.4
16	85	19	3.2
20	89	22	5.9

Aqualonis Nets at a Speed of 15 m/s