Water Recovery From Cooling Tower Plumes

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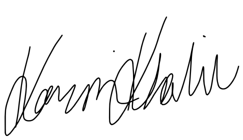

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ABSTRACT: According to studies by the UN and the US State Department, we are on the path to an extreme freshwater shortage by 2030. The US's largest water withdrawal source is power plants, which account for 39% of total US freshwater withdrawals, mostly for cooling. Cooling towers are the most common cooling system. To solve these problems and enable efficient water-based cooling – Infinite Cooling's novel technology uses electric fields to ionize the air, charge the escaping water leaving cooling towers and direct the water toward mesh collectors where it collects and gets recycled for use in the cooling system. This technology was developed at MIT and was reduced to practice on a lab-scale prototype, and a prototype at the MIT Cogeneration Power Plant. This DOE award funded taking this technology from a lab-scale prototype to TRL 5 on an operating cooling tower in the field at the MIT Nuclear Research Laboratory. The funding helped to design and optimize an electrostatic plume collection system and test it in high-fidelity lab setting and in actual field conditions on a cooling tower. Throughout the award, Infinite Cooling investigated the formation of plumes on cooling towers, used that information to optimize the design, material and electrical properties of the collection device and quantified the collection yield via flow rate and water quality.

EXECUTIVE SUMMARY:

According to studies by the UN and the US State Department, we are on the path to an extreme freshwater shortage by 2030. The US's largest water withdrawal source is power plants, which account for 50% of total US freshwater withdrawals, mostly for cooling. Cooling tower systems are the most common cooling technology and are rapidly growing in number. Cooling towers therefore account for much of the water consumption of the power industry (~2.5 trillions gallons per year). Coal power plants are particularly water intensive and a reduction in water consumption is needed to maintain the competitiveness of coal plants in a more and more water-constrained world. Another approach to improve plant efficiency is to improve the condenser efficiency. However, any improvements to the heat transfer efficiency for example would affect balance of plant systems and the excess heat has to be dissipated. In plants where water is constrained, reducing water consumption in cooling towers would allow for more cooling and thus would enable the use of more efficient condensers. Finally cooling tower water requires treatment before usage if the water source is polluted and after usage in all cases for blowdown discharge. These treatments are based on toxic chemicals that are no longer environmentally acceptable.

The goal of this project is to examine the applicability for Infinite Cooling's WaterPanel™ technology to be retrofitted to cooling towers to capture the plumes that are being emitted out of them so that the water can be re-used and recycled on site. This water is high-purity water which can also be upcycled for higher value applications on site, or reduce blowdown needs. The overall technical objectives of this work is to build and optimize the electrical plume collection system, Infinite Cooling's WaterPanel™, and test it in a high-fidelity lab cooling tower setting and in actual field conditions on an industrial cooling tower. The objectives of the award are to understand the lab cooling tower plume properties; use that to optimize the design, material and electrical properties of the collection device; and quantify the yield by flow rate and water quality.

To elaborate further - the project consists of the study of plume formation and collection on mechanical draft cooling towers: partly in a high-fidelity controlled environment and partly on a full-scale industrial cooling tower. The initial phase of the project included the design and build of a laboratory cooling tower setup and installing various sensors on the lab cooling tower. At the same time a CFD (computational fluid dynamics) model was implemented to get precise full-scale plume models. Using the insights on power-plant plume characteristics, iteration on and experimentally testing electrodes and collectors, which make up modular panels, on the lab cooling tower was completed. Learnings from this testing were then used to develop a prototype model of the collection system for a live operating industrial cooling tower. Portions of this design were prototyped and tested on the lab cooling tower to evaluate collection efficiency. The result was a ready-to-deploy design for a high-throughput water collector for cooling tower plumes on an industrial cooling tower. The second phase of the award was focused on manufacturing of the modular collection panels for our field testing site (aka “Site-2”) of the MIT Nuclear Research Laboratory. Here, performance of the collection device (aka “collector”) was measured on an actual industrial cooling tower, where we measured the efficiency of the design and sample the water that is collected, analyze its properties, and determine the presence of possible contaminants.

ACCOMPLISHMENTS BY TASK

Task 1 – Project Management and Planning

The project team successfully managed the multi-phase project, meeting all deadlines for reports, presentations, and success criteria. All milestones and reporting requirements were met. The kickoff of the project began in 2019 and included a peer-review in 2021. R&D meetings with presentations in front of the DOE/NETL staff were also attended several times throughout the award.

Task 2 – Plume Characterization

A hot wire sensor capable of measuring the liquid water content of a plume was designed and produced on a printed circuit board. Heat generation from an electrical current keeps a wire at a fixed high temperature, and the wire releases heat to its surroundings through convective heat transfer and evaporation of liquid water that impacts it. By independently measuring the plume velocity and subtracting out the velocity-dependent

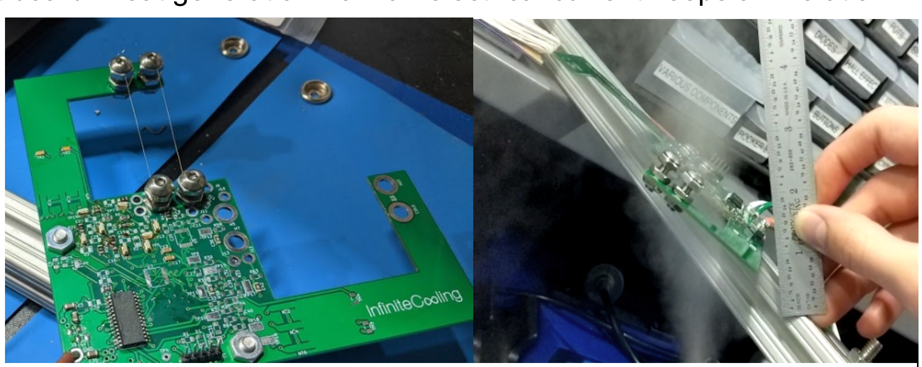


Figure 1: Liquid water content sensor and testing in the plume from a humidifier. The plume passes the two platinum wires and the circuit adjusts the voltages to keep the wire temperatures fixed. Voltages are transmitted and converted to liquid water content.

losses from convective heat transfer, we can calculate the flux of liquid water passing the wire given the current. Our sensor design took inspiration from LeBoeuf et al. (2015), though no experimental results were reported in their article to compare to. After calibrating the convective losses with dry air and a fan at varying speeds initial testing on plumes from ultrasonic humidifiers has yielded values for liquid water content consistent with expectations based on the rate of water consumption. Figure 1 shows a photograph of the sensor and its usage in a humidifier plume. Testing of the sensor was conducted on the lab-scale cooling tower and the liquid water content was compared to model predictions and values inferred based on collection tests.

We have measured droplet size distributions with an optical particle counter (OPC) under varying conditions on the lab cooling tower. Figure 2 shows mass-weighted histograms of droplet sizes from lab cooling tower plumes at two inlet water temperatures when operating indoors at room temperature. These histograms show that the cooler plum contains smaller droplets than the hotter plume. We quantify this difference by calculating the median drop diameter by mass such that 50% of the liquid water mass is contained in larger droplets and 50% is contained in smaller droplets. With this definition, the median drop diameters of cooler and hotter plumes from Figure 2 are respectively 7.6 and 10.6 μm. Comparing median drop diameters from other tests with varying temperatures support the correlation between temperature and drop diameter.

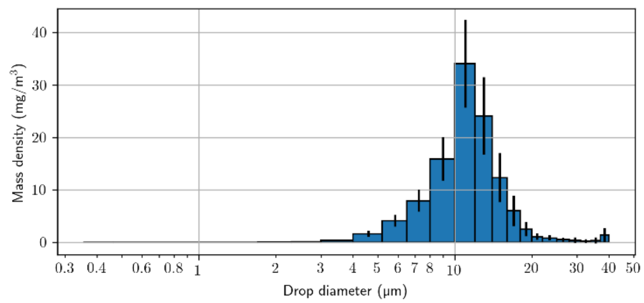


Figure 2: Mass histograms of droplets in the plume above the lab-scale cooling tower for average inlet water temperatures of (top) 127 °F and (bottom) 138 °F. The median drop diameters by mass are respectively 7.6 and 10.6 μm for these cases.

The above tests were performed at a low fan speed, and changing the fan speed setting while maximizing the inlet water temperature revealed an inverse relationship between plume velocity and median droplet diameter, shown in Figure 3. The higher fan speed cases also had lower inlet water temperatures, however, so these tests should be repeated at a fixed temperature to separate the velocity dependence from the temperature dependence. The high fan speed cases (1.6 m/s) had water temperatures of 127 and 129 °F, so the median drop diameters of ~5 μm are less than the 7.6 μm from the low-speed 127 °F case of Figure 2, suggesting that drop sizes do indeed depend on plume velocity in addition to temperature.

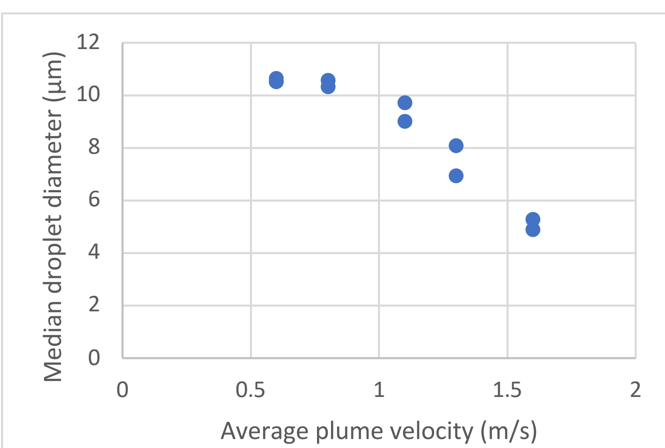


Figure 3: Median drop diameters from tests with varying fan speeds.

All these tests were with the OPC at a fixed height of 50 cm above the top of the shroud (refer to Figure 8 showing the lab cooling tower setup). Lowering the OPC from 50 cm to 5 cm for the low-fan-speed, high-temperature test increased the median drop diameter from 10.6 µm to 13.9 µm.

Task 3 – Modeling

Simulations of a full-scale plume were setup and run in Solidworks Flow Simulator. A major goal was to examine the effects of a mixing from ambient air on condensation and the plume, especially when wind is present. Previous tests of ours have suggested that strong winds can blow the plume away before it's collected, so the idea of a shroud or louvers is to prevent the plume from blowing away while still allowing enough air to mix with the plume and encourage condensation. Figure 4 shows a cutaway view of a cooling tower fan and a set of circular louvers around the outlet. These louvers are oriented to encourage mixing from wind into the rising plume, while Figure 5 shows an alternative with inverted louvers, with a contour plot showing velocity magnitude and streamlines indicating velocity direction. The final configuration is a solid cylindrical shroud of the same height and diameter as the total covered area of the louvers. Figure 6 shows a comparison of the velocity field between

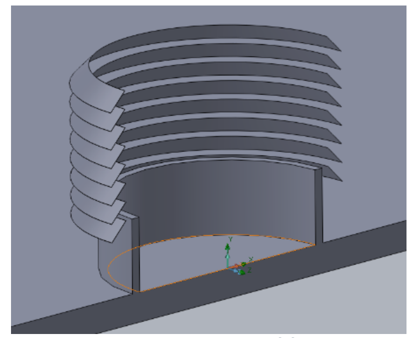


Figure 5: Cutaway view of fan outlet and louver geometry for plume simulations.

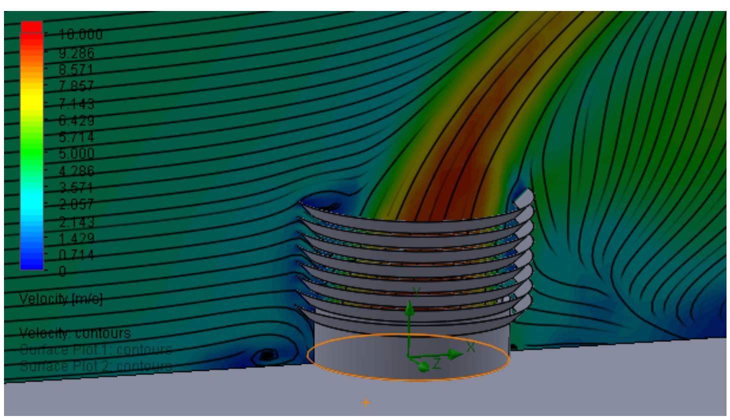


Figure 4: Inverted louver setup. A uniform wind speed of 4 m/s is applied, and the plume velocity is 8 m/s at the outlet. The contour plot indicates velocity magnitude in the central cross-section, and streamlines are plotted in that plane.

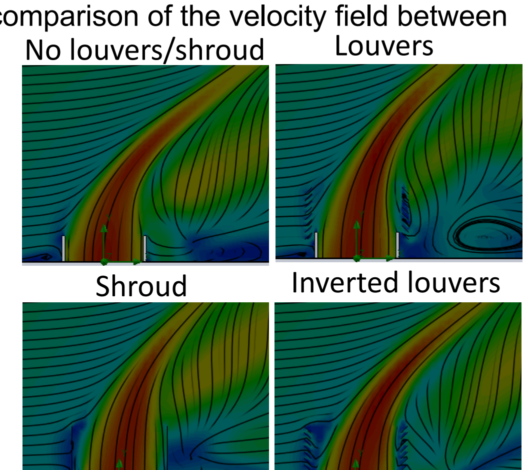


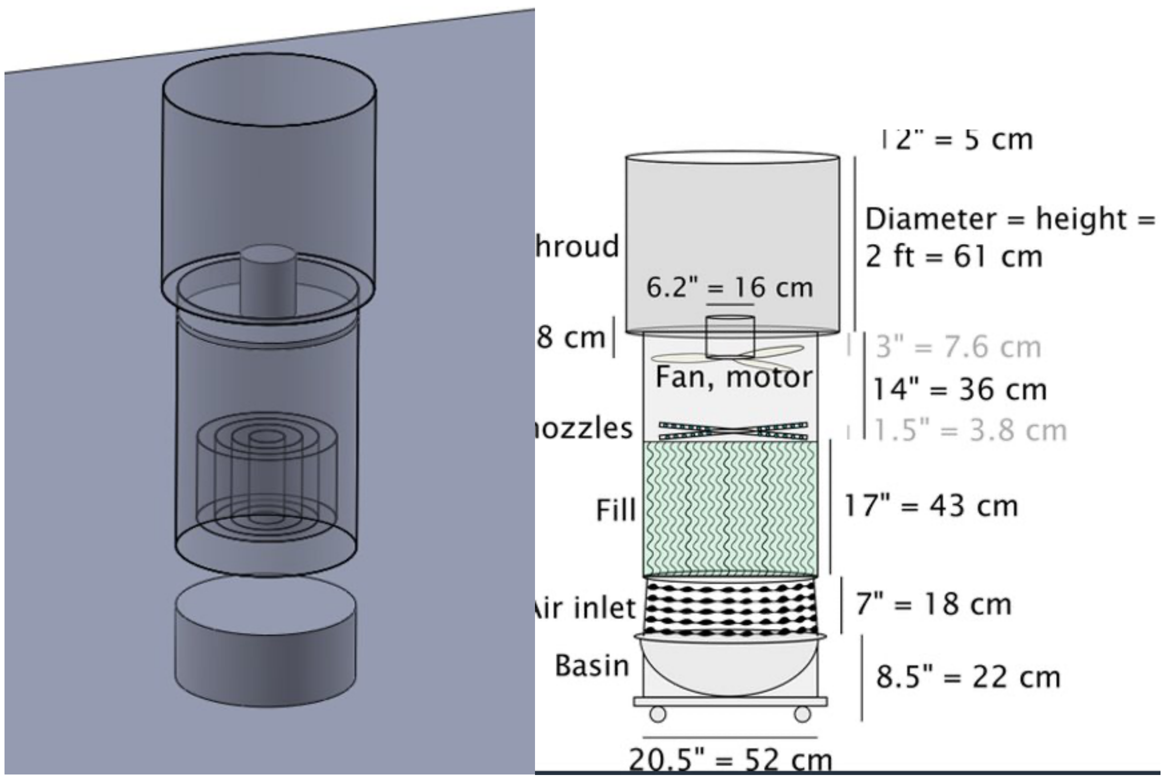
Figure 6: Velocity magnitude contour plot and streamlines for the central plane of flow with all four shroud/louver configurations. The wind speed is 4 m/s and the plume velocity is 8 m/s.

all configurations, where we qualitatively see that the non-inverted louvers and shroud keep the plume orientation closer to vertical in the wind.

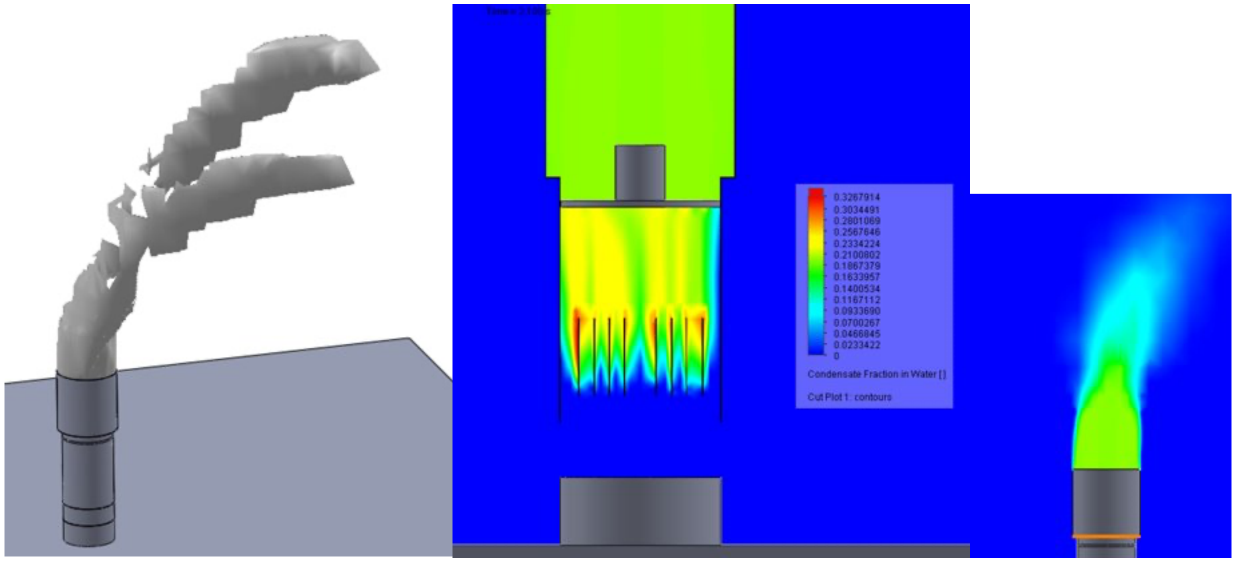
One interesting quantitative comparison we can make is the mass flow rate of air through the louvers, limiting to the upstream half of the cylindrical surface, compared to the mass flow rate through that same surface when no louvers or shroud are present. For the 4 m/s wind speed tested, louvers in the original orientation reduced the flow rate to 64% of the reference value without louvers, while the inverted louvers reduced the flow rate to 38% of the reference value.

No flow is allowed through the shroud, though the streamlines show that some can enter through the gap between the bottom of the shroud and the fan wall.

We were able to use or plume CFD model and replicate the geometry of our Lab-Scale Cooling tower (discussed in more detail in Task 4). The purpose is to produce simulations that confirm our initial results – and confirm the presence and radial distribution of the plume that we visually see. Ambient parameters used in this model are replicated from data collected on the lab-scale tower or estimated.

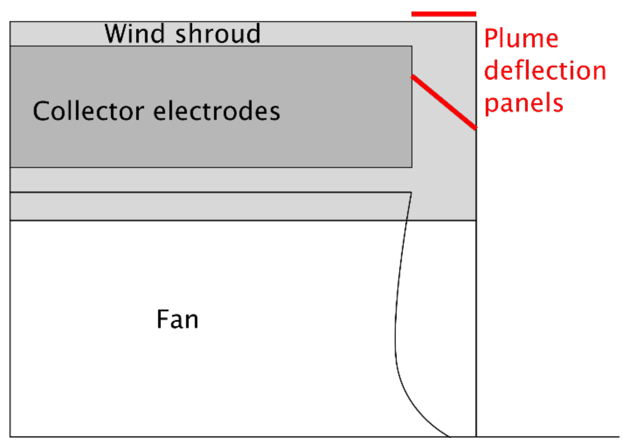


The fill in the cooling tower (heat exchange material to increase residence time between the water and the air in the cooling tower) is simulated with an element interior to the cooling tower. The geometry of the body used to simulate the fill is not exact to the fill geometry in the tower as it will increase the solution time of the CFD model dramatically but it will be sufficient for initial models. We are able to reproduce a condensed core of plume coming out of the tower outlet similar to what is observed in our lab-testing.



The model is able to create an environment where the convective flow mixes with a humid air boundary condition, and that the condensation is transported through the fan of the cooling tower.

Plume Modeling and CFD/Mixing:

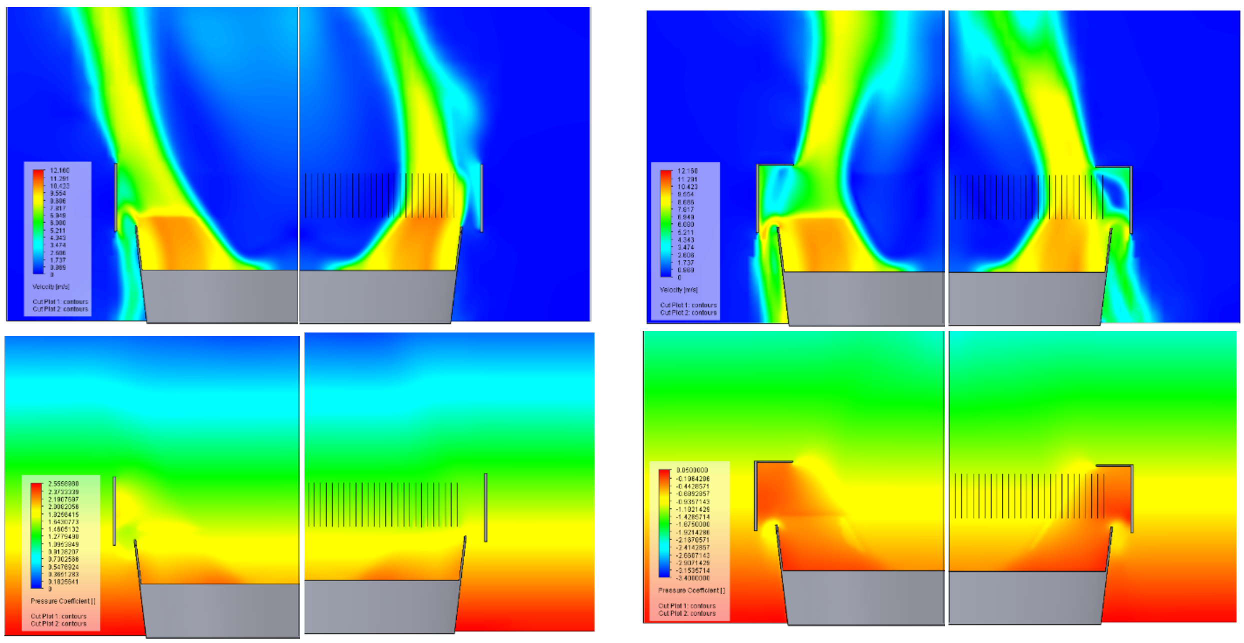


We focused our simulations on pressure drop and plume. We noticed in several of our demonstration systems, including in our Site 2 collection system results, that plume was escaping out at the edges past where our electrodes end, so we used CFD to analyze the potential for panels to deflect the flow away from the edges back toward the center. This redirection would be expected to help in collection and plume abatement.

A series of parametric simulations were run varying the panel position, angle, and width. The red line segments in the cross-section schematic show example panel placements. Results were evaluated based on the pressure drop imposed by our system and the mass flow rate of plume through the edge region beyond the electrodes.

Many configurations were successful in preventing the plume from escaping through the edge region, and as expected, wider panels that block the flow more had larger pressure drops. A good compromise that fully deflected the plume, did not increase pressure drop too much, and made for a simple experimental implementation was horizontal panels on top of our system with width 1.2 times the gap width from the end of the electrode to the outside of the wind shroud. Simulation results for this configuration are shown in the 4 images on the next page. The top images show contour plots of velocity, and the bottom images show the pressure coefficient. We see that the panels prevent plume from escaping up that edge region but also increase the static pressure within our system. These simulations also include a horizontal gap between the edge of the fan shroud and the bottom edge of our system's wind shroud, and the panels lead to more plume escaping downward out this gap. For optimal plume abatement, that gap should also be sealed.

In subsequent simulations with the bottom gap sealed, this configuration still appeared promising, deflecting the entire plume to exit through the center with just a 12% higher pressure drop than the control case.



Task 4 – Lab Cooling Tower Setup

The Lab cooling tower design involved utilizing a CTS cooling tower and a residential water heater as the simulated heat load on the tower. The water flow path was a single loop, going from the reservoir to the heater, into the tower, then back to the reservoir (see Figure 7). Two pumps are utilized, one for the supply flow through the heater into the tower, and another for the return flow from the basin of the tower to the reservoir. Both the supply flow and return flow paths have valves that can be adjusted to make the flow rates match so the system runs continuously (typically around 9 gallons per minute). The return flow valve also allows some flow back into the basin of the tower to keep it high enough for the return pump to operate without sucking in air. The water also passes through a filter in the line to clean up any particulates.

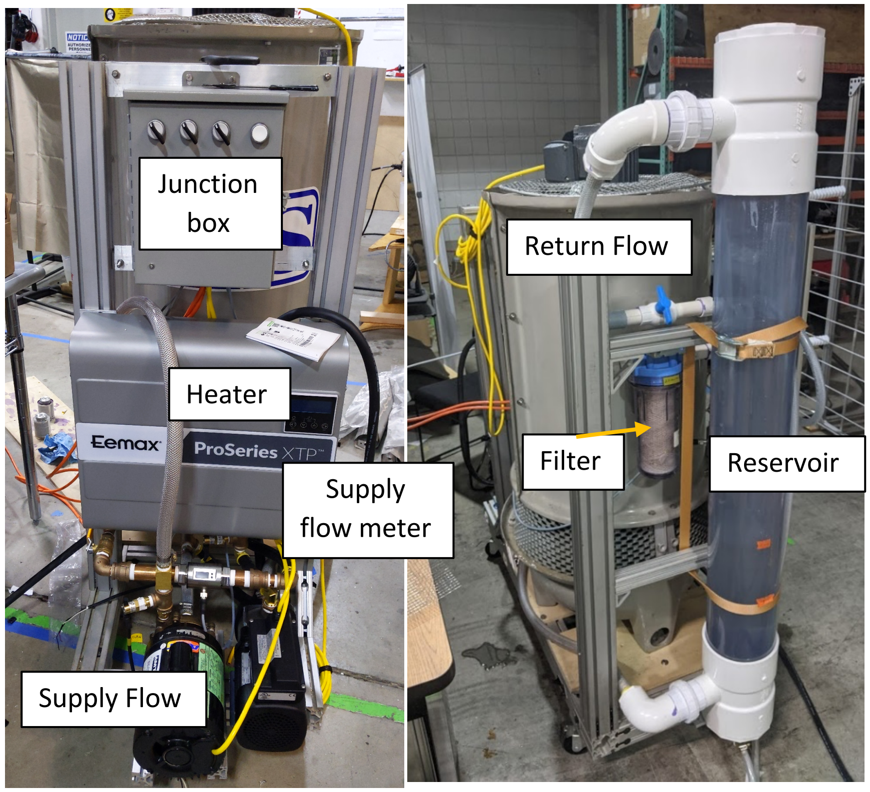


Figure 7: Lab-scale cooling tower with components labelled.

The heater is easy to use, starting automatically after a few gallons flow through it and immediately beginning to heat to its set point, which can be changed on the heater directly and is automatically tracked through PID control. The cooling tower fan is connected to a variable speed controller to allow for a range of fan speeds.

Both flow paths also have flow meters outputting flow rate and temperature. Analog 4-20 mA signals are wired through a junction box and connected to an Arduino for data logging. Four thermocouples have also been placed in the plume, with two right at the fan outlet and two more at the top of a shroud, which was added to redirect the plume upward rather than radially outward when the fan is running. (Figure 8 shows the cooling tower with the shroud attached and a plume above it.) The thermocouples connect to the same Arduino and allow us to generate plots like that of Figure 9 showing the temperature evolution of the system over time. Combined with the flow rate data, this temperature data lets us check the cooling rate of the tower $\dot{Q} = \dot{m} c_p \Delta T$, where $\dot{m}$ is the mass flow rate of water circulating in the system, c_p is the specific heat of water, and ΔT is the temperature difference between the supply and return flow. When the temperature set point is high enough, the heater load will stay at 100% and never reach the set point, and in these cases we calculate cooling rates around 18 to 19.7 kW, close to the heater rating of 20 kW.

Figure 8: Lab-scale cooling tower with shroud attached and a plume above it.

The accuracy on the flow rate measurements from the flow meter is not high enough to calculate evaporation rate by subtracting return flow from supply flow, as the evaporation rate is 1-2% of the circulating flow rate and the accuracy is 2.5%. However, by running the tower until the water levels are too low and the pumps draw in air and automatically turn off, one can then add a known volume of water and run the system until the water level returns to this reference state. Repeating this process has given fairly consistent estimates of evaporation rate based on

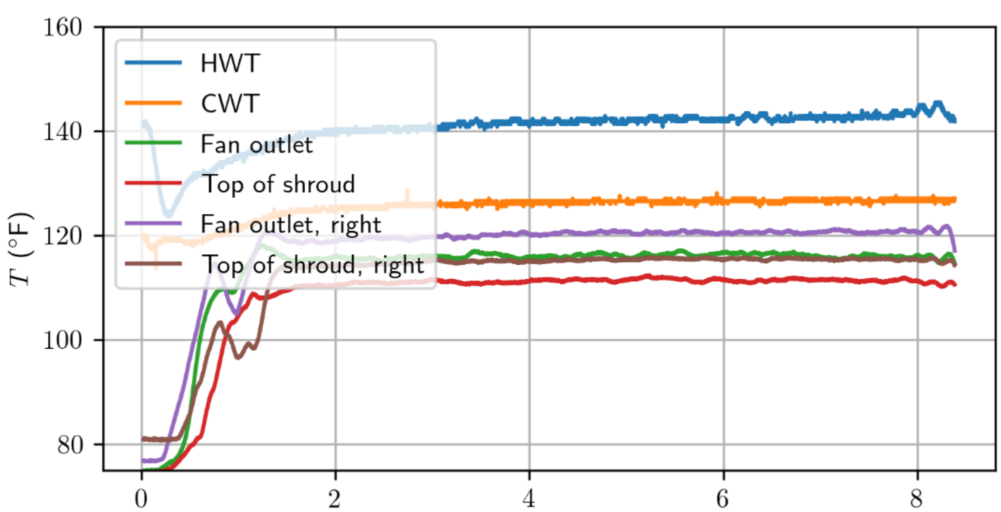


Figure 9: Temperature data from flow meters and thermocouples. HWT and CWT stand for hot water and cold water temperatures and refer to supply and return temperatures from the flow meters. The fan was on the lowest speed but the set point was 150 °F, above the reach of the 20 kW heater.

the volume added and duration of operation. As expected, higher supply temperatures and faster fan speeds result in higher evaporation rates than low supply temperatures or slower fan speeds.

We ran some indoor characterization tests with the lab cooling tower. To check for spatial nonuniformities in plume temperature, we placed 6 thermocouples across the diameter of the tower outlet just above the fan, as shown in Figure 10. Figure 11 shows the measured temperatures from a test with the fans at low speed, with the outer thermocouples (1 and 6) recording lower temperatures than the inner thermocouples. We also ran tests with inlet air to the tower restricted to explore whether higher plume temperatures could be achieved. While the thermocouples measured higher temperatures, anemometer measurements showed that the flow direction was down rather than up in a central core of the tower outlet (see Figure 12), so for collecting plumes this configuration is not relevant. The temperature measurements from these characterization tests and further tests measuring temperatures at different heights in the plume was used to validate our CFD model of the cooling tower.

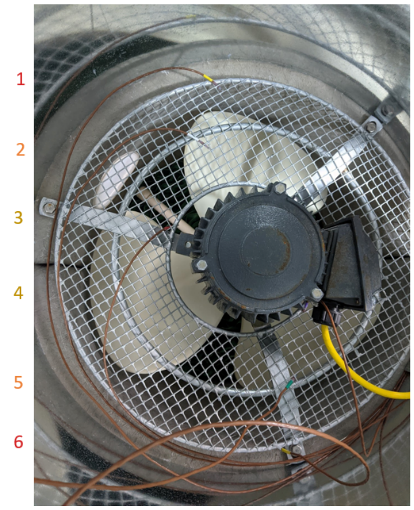


Figure 10: Thermocouple placement for plume characterization at fan outlet.

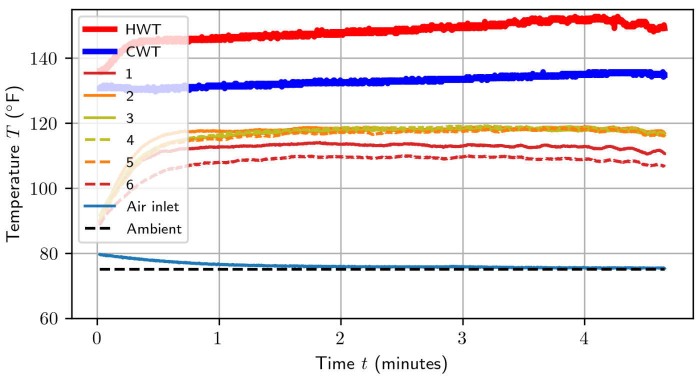


Figure 11: Temperature measurements from plume characterization test.

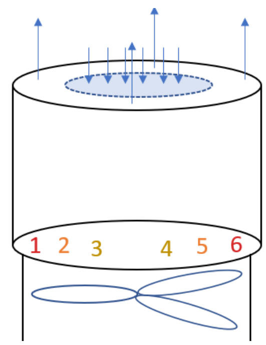


Figure 12: Schematic of flow reversal with restricted air inlet to tower

The lab cooling tower was also cleaned regularly. The basin was drained and wiped down and a vinegar-water solution was circulated through the system for an hour and a half before replacing with water to avoid bio-fouling through the system effecting any heat transfer experiments.

We performed outdoor testing of the lab cooling tower, measuring water collection rates and plume temperatures in a variety of ambient weather conditions and iterating on our collector design. Outdoor tests provide colder ambient temperatures than we can achieve indoors, which results in increased plume condensation and higher collection efficiencies, as the cold air holds much less water vapor than warm air. The collection efficiencies were compared to our model, and we have been able to explore how cooling tower parameters like fan speed and hot water temperature affect collection. Videos taken with a DSLR camera also allow for qualitative assessments of plume abatement.

Figure 13: Setup for outdoor lab cooling tower tests.

The outdoor tests required coordination with multiple team members to roll the cooling tower outside, place the tall collector on top, and connect the various power cables for the heater, pumps, fan, and high-voltage power supply. Figure 13 shows a picture of what our setup looks like, just outside the loading dock of the building.

One important factor that only becomes relevant with outdoor testing is the effect of wind on the plume. Even gentle breezes can push the plume out of our collector, so plates were added to the sides of the collector to keep the plume in. Figure 14 shows images of our collector at each stage in the design; the top row of images show the plume with our system off, while the bottom row showcase the plume abatement achieved with the system running. Version 1 had no solid walls on the collector, so the plume drifted to the side through the mesh. Version 2 added short strips of acrylic to the left and right sides, and version 3 replaced them with taller metal plates, so with the dominant wind direction from left to right, the plume was contained better. For full

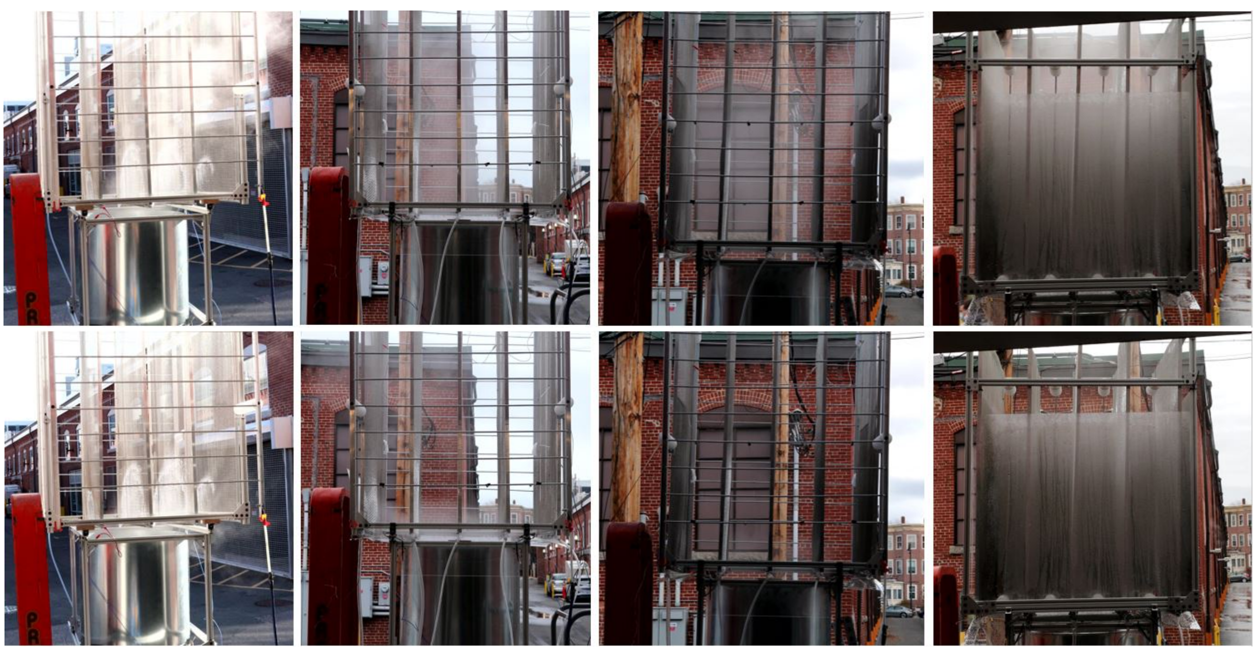


Figure 14: Four versions of the collector on different outdoor test days, ordered from left to right. Our collection system is off in the top row (showing what the plume looks like naturally) and on in the bottom row (showing plume abatement).

containment on all four sides, we had to change our emitter electrode design to use vertical supports rather than the horizontal ones used previously so that the high-voltage components could be fully contained within the walls of the structure. Other changes we made include:

1) Adding a second row of emitters for version 3, as some plume seemed to re-condense above the first set of emitters in version 2.
2) Shortening the whole collector system from 6 ft to 4 ft for version 4, as the majority of the collection occurs near the outlet of the tower. The shorter system is easier to work with and safer under wind load.

With these changes and the progressively colder temperatures for our outdoor tests, our collection efficiency reached 11% in these 6 collection tests – efficiency being a measured by the amount of water collected vs. the amount of the water consumed by the lab cooling tower and released as evaporation. A compilation of all our collection results and a comparison to theoretical optimal collection efficiencies based on our model are shown in Figure 15, with theoretical efficiency on the x axis and experimental efficiency on the y axis. The model takes only plume temperature, ambient temperature, and ambient relative humidity as inputs, and uses a mixing line on a psychrometric chart from plume conditions to ambient conditions to find the maximum potential condensation. The plume temperature is measured with a thermocouple, though there is uncertainty in the exact value due to spatial nonuniformities. The dashed line on the plot denotes where experimental and theoretical values are equal, and while the data have significant scatter, the general trend of experimental efficiencies correlating with theoretical efficiencies is clear. Colder, wetter conditions and/or hotter plumes increase both theoretical and experimental collection efficiencies.

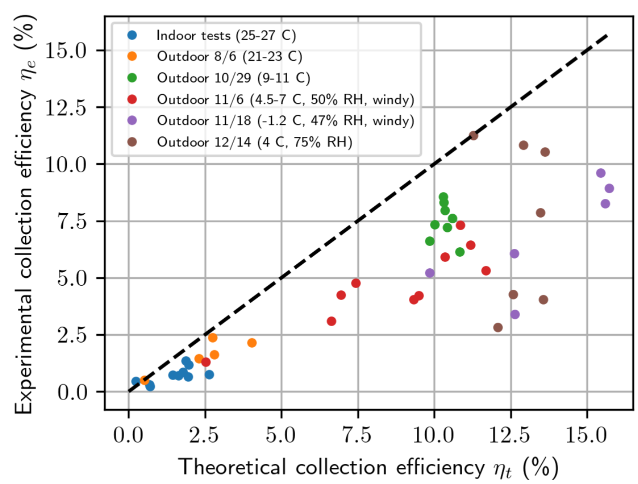


Figure 15: Collection efficiency results from indoor and outdoor lab cooling tower tests compared to optimal efficiencies from our psychrometric model.

We recorded temperatures at various points in the plume, and one such test is plotted in Figure 16. The locations of the numbered thermocouples are shown in the photo on the right, with the cooler colors higher up in the plume, where additional mixing has cooled the plume down closer to ambient levels. The effects of wind are clear based on the large variability in temperatures, and we note that this test did not have any plates blocking the wind. Nonetheless, we can average out the time variations and estimate plume temperatures, and by estimating the initial plume temperature in this case as 45 °C and taking the ambient conditions as 9 °C and 80% RH, we get an optimal plume temperature of 30 °C, which tells us that around or slightly below thermocouples 5 and 6 is where we should place our emitters to collect the optimal amount of water. In our experiments, the emitters are in the lowest horizontal position, which is consistent with roughly where we expect our collection to be maximal.

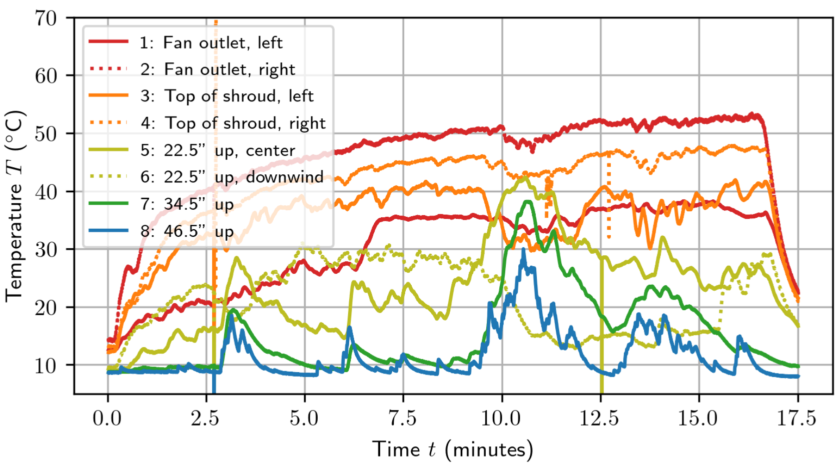


Figure 16: Thermocouple measurements from the plume during a test where the cooling tower is running but not the collection system. The thermocouple locations are numbered in the photo on the right.

We conducted 5 additional days of outdoor testing, measuring plume temperatures and water collection rates while varying our setup. With these tests, we focused on investigating validity of our model for collection efficiency and how it depends on the mixing state of the plume. As described in the previous report, our model uses a psychrometric chart and mixing line between plume exhaust conditions and ambient conditions, and it predicts an optimal local plume temperature (mixing state) at which the liquid water content of the air is highest due to condensation. The model can be used to predict collection efficiencies for any intermediate plume temperature between the plume exhaust temperature and ambient conditions, so in our tests we setup our system to collect at varying temperatures by varying the height at which we collect (i.e. varying the height at which our emitters generate corona discharge). With our

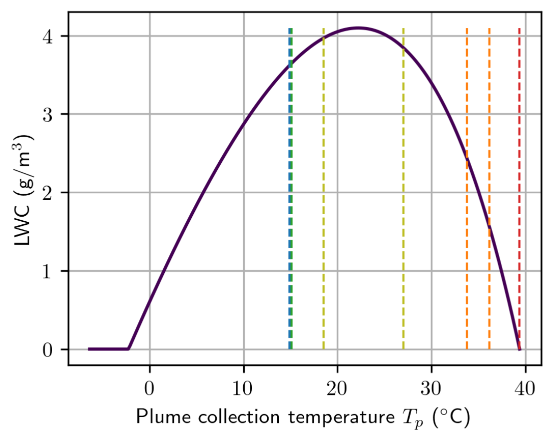


Figure 67: Locations of thermocouples in lab cooling tower collector (left) and corresponding average plume temperatures overlaid on curve of predicted liquid water content (right).

emitters higher up, the plume is cooler due to increased mixing with ambient air.

First, we characterized the temperatures at various heights in the plume using thermocouples. Figure 17 shows the thermocouple locations with colored numbers, and the vertical colored dashed lines in the plot denote the average temperatures recorded by the corresponding thermocouples. The warmer colors are lower in height and closer to the plume exhaust, and we see a significant spread in temperature from 15 C to 40 C at the exhaust. The plotted curve shows the predicted liquid water content (LWC) of the plume based on the model, which only requires the plume exhaust temperature and ambient temperature and humidity as inputs (-4 C and 48% here). As the water our system collects is proportional to liquid water content, this plot suggests that we should place our emitters near thermocouples 4 and 5 (the yellow ones), where the LWC is maximum. It also predicts much lower collection rates (about half as much) for emitters near the bottom of the system.

Figure 18 shows experimental collection efficiencies from tests in which the emitter height was varied within the system. We see a similar shape to that predicted by the earlier figures with slightly lower efficiencies for emitters at the lowest and highest positions, but the intermediate positions didn't show a clear difference with the scatter in results. The ambient temperature also increased during the tests, with the lowest and highest positions for emitters tested latest in the morning, when temperatures were highest. This change could be responsible for the lower collection efficiencies there, as the predicted (model) collection efficiency decreased from 14% to 10% throughout the course of the day as ambient temperature increased from 0 C to 3.8 C.

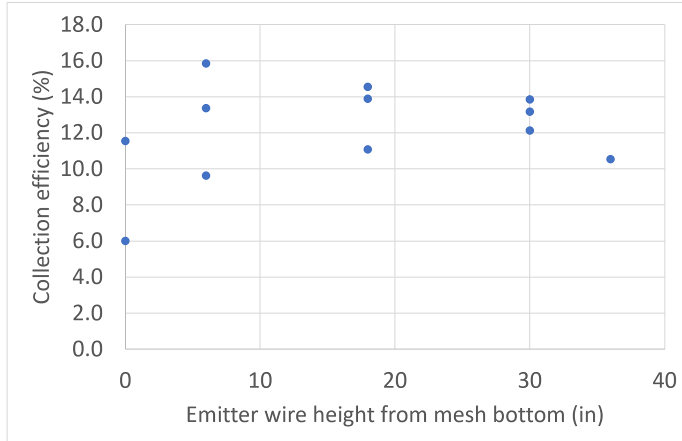


Figure 18: Collection efficiencies from lab cooling tower tests with a single emitters at varying heights in the collector.

Another variation tested was the degree of mixing allowed into the collector. A plastic shroud was wrapped tightly around the collector and tower to block air from getting in through the bottom of the collector, as shown in Figure 19. With the plastic shroud, plume temperatures were more uniform and slightly higher, especially at locations off-center of the plume. As the plot in Figure 20 shows, however, we did not observe a significant difference in collection efficiencies with or without the plastic shroud to limit mixing.

Figure 19: Lab cooling tower test with plastic shroud preventing mixing of ambient air with plume until the plume leaves the collector.

Taken together, these tests suggest that the liquid water content of the plume is more uniform with plume height than the model predicts, which may be due to simplifying assumptions in the model. In particular, the model assumes a uniform temperature at a given height in the plume and no liquid water content right at the tower outlet, which our experiments have shown to be questionable assumptions. At the same time, the varying ambient temperature and external wind speed makes precisely controlled and repeatable experiments challenging in this outdoor scenario. Therefore, future experiments will be attempted indoors using an air conditioner to achieve colder temperatures. Finally, our model still captures the overall dependence of collection efficiency on plume temperature and ambient conditions reasonably well, as Figure 21 demonstrates. Experimental and theoretical collection efficiencies are compared for the entire suite of lab cooling tower tests, and the results cluster just below the dashed line at which experiments would match the optimal values from the model.

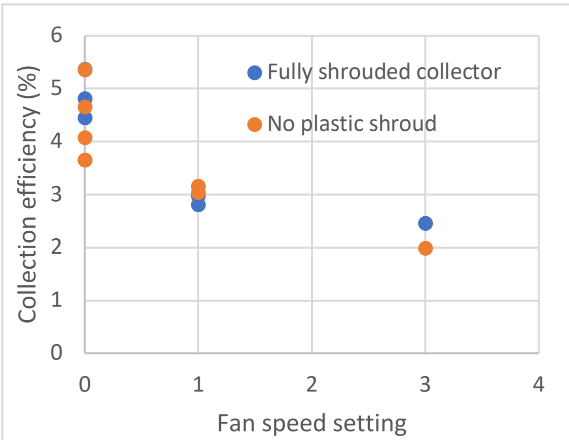


Figure 20: Collection efficiencies with and without plastic shrouding at 3 fan speed settings.

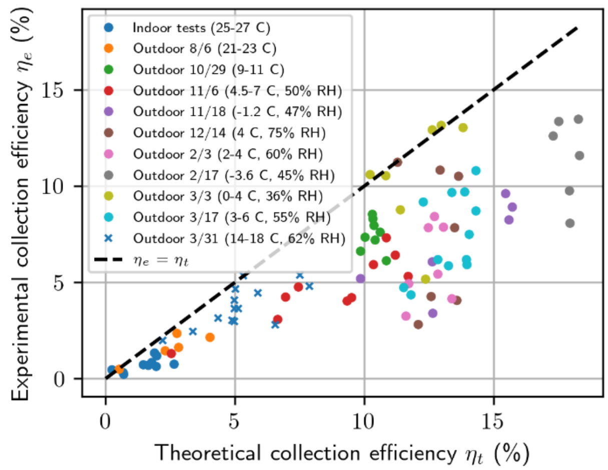


Figure 21: Comparison of experimental and theoretical collection efficiencies for all lab cooling tower tests to date.

Finally we show plume abatement of our system on top of our lab cooling tower showing that it is capable of eliminating the presence of the plume above the cooling tower while the WaterPanel™ is on (see below images)

Task 5-8 – Site-2 Panel Design & Testing at MIT NRL

The final phase of the award was to design and deploy our water collection system at the MIT NRL (Nuclear Research Laboratory) on their cooling tower that services the 6MW Nuclear Reactor. The cooling tower we utilized for our Site 2 demo is shown below in Figure 22.

Figure 22: MIT NRL cooling towers – 25ft TowerTech cooling towers

The Infinite Cooling WaterPanel™ learnings and results from the lab testing on the lab cooling tower were then taken and applied to the 25’ cooling tower at the MIT NRL. We fully designed the water collection system in figure 23 in 3D CAD.

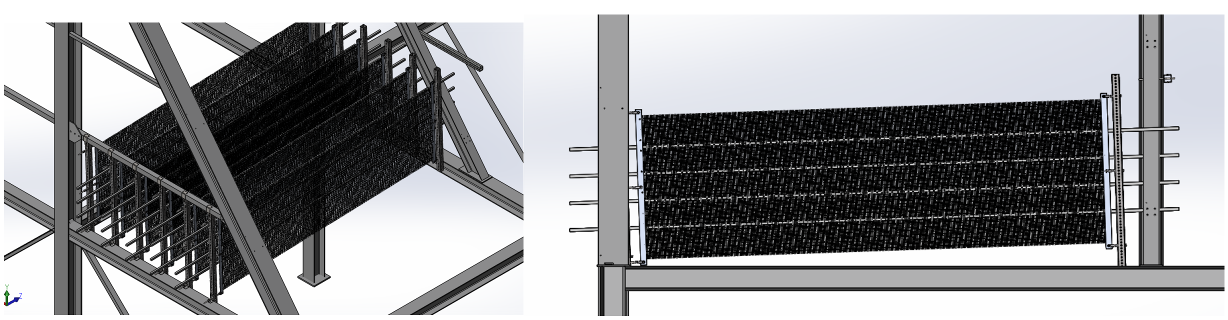


Figure 23: Infinite Cooling WaterPanel™ design for MIT NRL Site 2 installation demonstration

Design work on the collector to reach certain structural and mechanical design requirements were done throughout the award and were elaborated upon in quarterly reports. Upon completion of the design phase of the Site 2 prototype, manufacturing and assembly began. Figure 24 below shows the WaterPanel demonstration built and assembled for the MIT NRL Site 2 pilot.

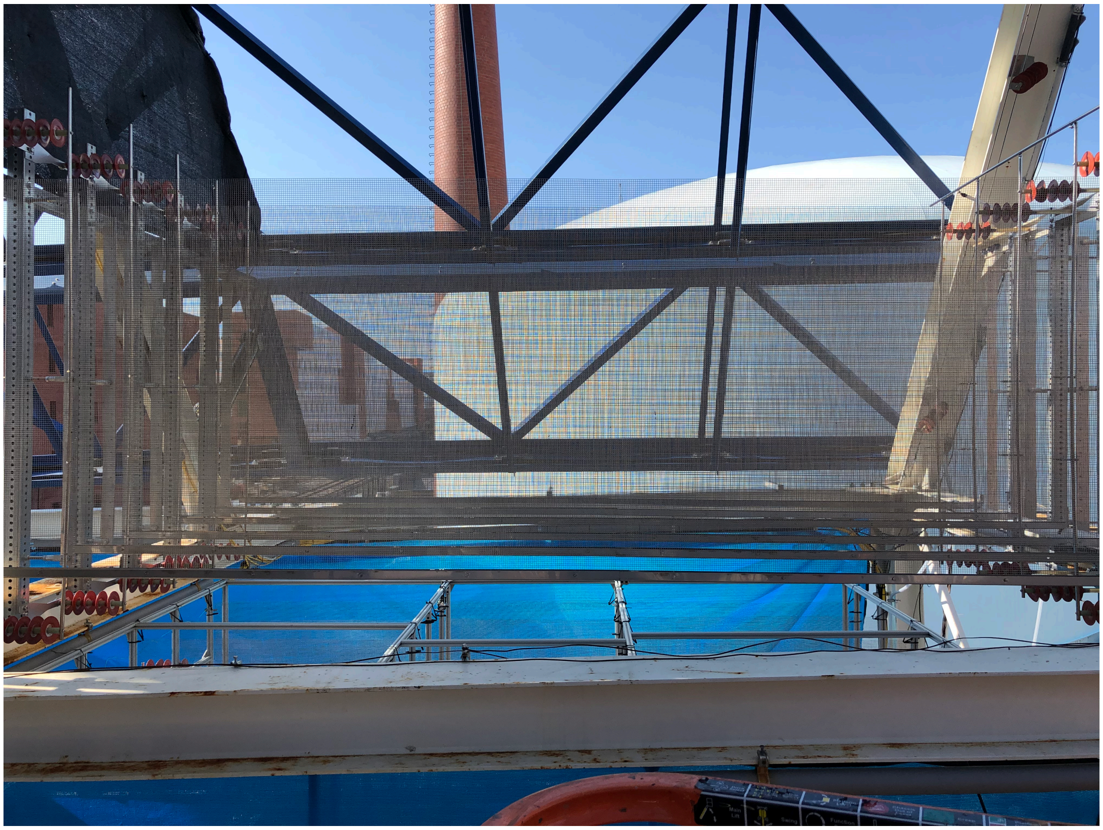


Figure 24: Infinite Cooling WaterPanel™ design installed at MIT NRL Site 2

The system was energized over the course of the Site 2 Demonstration for over 12 months. Plume abatement was achieved in a variety of ambient conditions including winder conditions as shown below in the side by side images from a video camera attached to the cooling tower. The first image of Figure 25 shows the system off, and the bottom image shows the system on in the same conditions, where on the right, the plume is abated above our system and that plume water is being collected and recycled into the cooling tower.

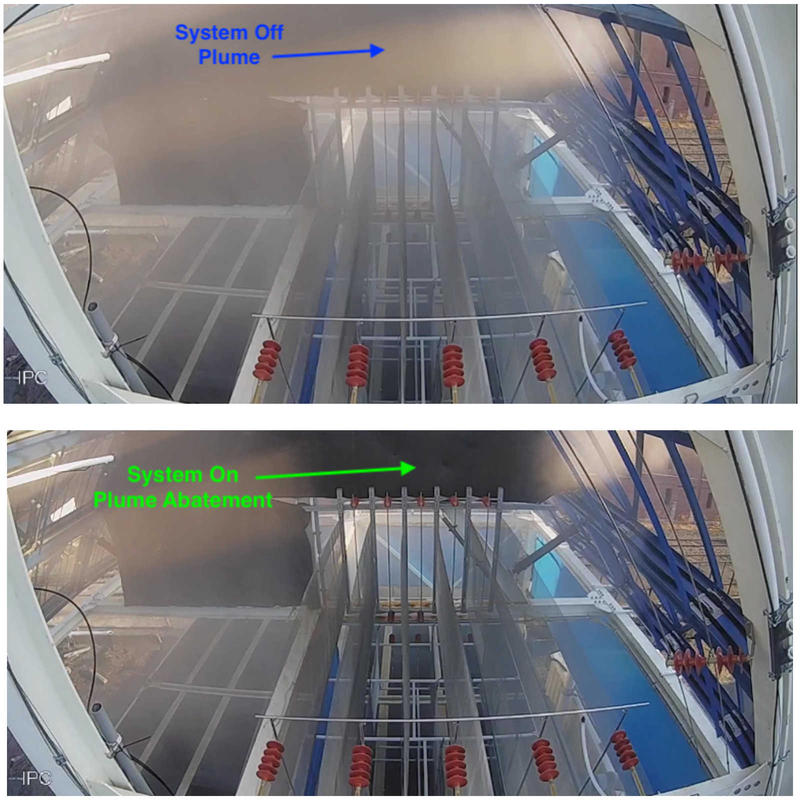


Figure 25: Infinite Cooling WaterPanel™ demonstrating plume abatement feature while the system is energized

While sampling collected water to measure conductivity, suspended debris appeared in the water, discoloring it black in spurts at the beginning and ends of sampling periods. The sediment was found up in the gutters and pipes of our system as well (Figure 26), has been

Figure 26: Overflowing pipe due to clog lower in the system

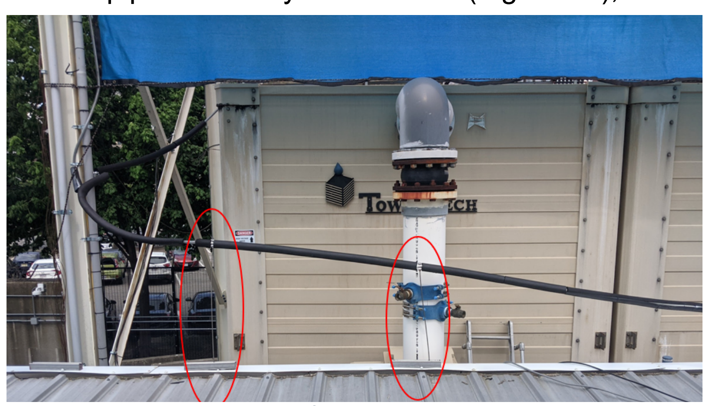


Figure 27: The reattached pipe for collected water with a steeper angle (set by choosing longer attachments circled in red) to prevent future clogging.

analyzed externally, and appears to be a dirt and leaves from the surrounding area. This issue was attributed to the fact that the piping in our system was left open to the surrounding environment in our prototype design, allowing for dirt, and leaves to funnel directly into our system's piping. In future designs, piping that combines the water collected from various meshes within our system will be closed off or shaded from external sources of debris and directly route the drained water from each mesh into the routing piping via flexible tubing and barb fittings.

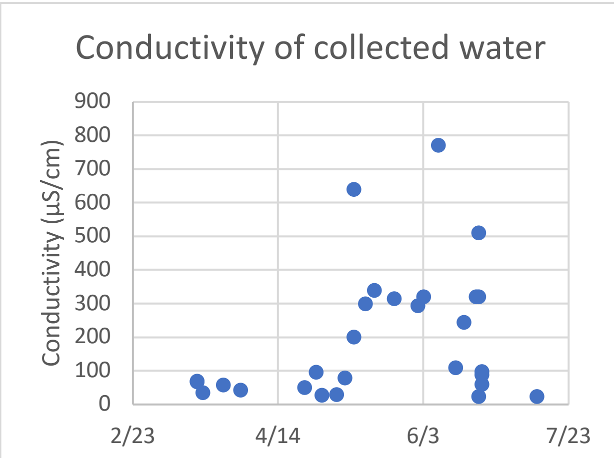


Figure 28: Conductivity measurements versus date of testing.

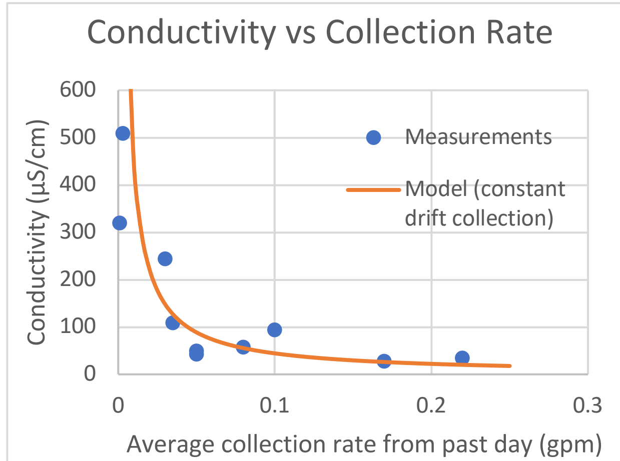


Figure 29: Conductivity plotted as a function of the average collection rate of our system over the previous day.

Conductivity measurements were continued throughout the testing of the unit over the year, with the data plotted in Figure 28. Conductivity readings were generally higher in warmer months, though the highest two readings were a result of flushing the system with tap water (of conductivity 770 uS/cm) to diagnose a separate pipe clogging issue. By correlating the conductivity measurements with collection rate measurements, we see in Figure 29 that the water conductivity increases as collection rate decreases. This observation is consistent with drift, droplets of sprayed circulating water entrained upward out of the tower by the fan, explaining the increased conductivity. Assuming collected drift is relatively constant, conductivity of the total collected water is inversely proportional to the collection rate. With warmer temperatures further into spring and summer, collection rates decrease, so drift makes up a larger fraction of total collected water. Plus, drift should increase somewhat in the warmer months as fan speeds increase.

Generally we observed that our collected water has a 100-150X reduction in conductivity (uS/cm) than site process recirculating water of 3200 uS/cm. We also utilized an external third party testing agency to test a sample of the collected water (in addition to a sample of the process water running through the cooling tower) for a variety of critical constituents that are typically monitored by chemical engineers on industrial sites (conductivity, TDS, chlorides, calcium, magnesium, silica etc.) to avoid fouling and corrosion in their equipment on site. The results of this water analysis are shown below in figure 30. All critical constituents showed a dramatic reduction in their concentration in our collected water, which confirms our systems ability to produce highly pure water that can be used for high-value industrial applications where applicable.

Constituents	Collected water	Basin water
Conductivity (µS/cm)	15	2280
Total Dissolved Solids, mg/L	10	1480
M.O. Alkalinity as $CaCO_3$, mg/L	<2	84
Chloride as Cl^-, mg/L	1.9	599
Sodium, mg/L	0.8	329
Potassium, mg/L	0.1	10.5
Total Hardness as $CaCO_3$, mg/L	1.2	245
Calcium as $CaCO_3$, mg/L	0.7	186
Magnesium as $CaCO_3$, mg/L	0.4	59.4
Silica as SiO_2, mg/L	0.1	16.6
Sulfur as SO_4, mg/L	0.7	86.6

Figure 30: Flowrate vs. Voltage test results (left), collection efficiencies for different high voltage configurations (varying different levels of emitters & ambient conditions changing)

Lastly, we plotted our water collection results for various voltages during the early stage testing of the unit to confirm our internal collection models based on laboratory benchtop and lab cooling tower testing which were confirmed and data is plotted in Figure 31. Additionally, a large subset of data was collected over varying high voltage (varying levels of emitters) and ambient conditions and plotted in Figure 31. We were able to demonstrate collection efficiencies of up to 15% of tower water consumption with our Site 2 demonstration at the MIT Nuclear Reactor Laboratory.

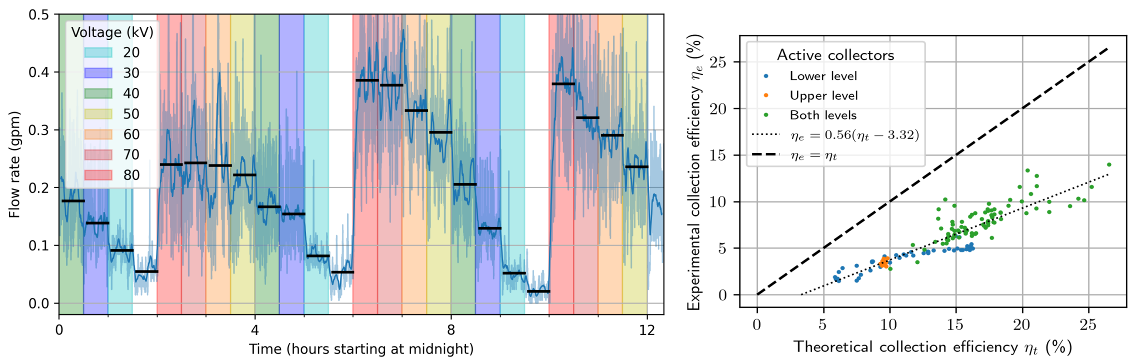


Figure 31: Flowrate vs. Voltage test results (left), collection efficiencies for different high voltage configurations (varying different levels of emitters & ambient conditions changing)

During our Peer Review (Q1 2021) we presented to the Review Panel the status of the project up until that point and then created a set of actions in our response to the review panel's recommendations. The results of this peer review are summarized below:

R1 - Engage a design and construction partner to provide input on construction safety - specifically, the feasibility of performing construction of a single cell on an operating cooling tower.	Completed: Since this review, the team has engaged several construction partners to help install our WaterPanel system on operating cooling towers with multiple cells. We with their support were able to successfully do so, while just shutting down the fan activity on the cell being installed, and allowed for a zero-disruption installation process for our partner power plant/industrial facility
R2: Assess design impact on performance in induced draft cooling towers.	This was measured on both the lab cooling tower and at our site 2 partner site. No measurable change of the cooling tower's performance was measured before/after the installation of our water capture system.
R3: Perform additional testing to determine if the shroud is critical or optional, then design (e.g., materials, positioning, dimensions) and cost accordingly.	We have determined that the wind shroud is a critical aspect of the design and has been included in all of our future design iterations past this initial prototype design. Off-the-shelf envelope cladding materials have been utilized
R4: Include testing and operation during winter conditions in the test plan to evaluate the freezing potential of the technology. The test	This was completed via the 12+ month testing of our system. We encountered winter throughout the pilot of our system and encountered no ice formation on the core

conditions should include operating and non-operating modes of the cooling tower cell.	internal components of the water capture system. This included both operating and non-operating modes of the cooling tower. Some ice did form on the periphery of our system, near where ice typically forms on a cooling tower. These were expected and accounted for on the expected ice load of the system. These observations during our pilot have been re-confirmed with new WaterPanel installations at full-scale power plants that have had over 12+ months of operation with similar results. The primary reason for the prevention of ice formation ***internal*** to our system is due to the residual heat from the exhaust of the cooling tower. During non-operating modes of the cooling tower, not enough horizontal surface area is present in our system for any ice to form (as the collection surfaces are extremely thin and unable to build up ice in their vertical orientations).
R6: Perform corrosion coupon testing of the collected water.	No measurable corrosion of our critical components (collection surfaces and electrodes) in the presence of the collected water. The water analysis of the collected water is presented above in the final report. Given typical corrosion resistant materials (aluminum, stainless steel 300 series etc.) capability to withstand such water chemistries with relative ease, this was an expected result, but confirmed with no measured or visible corrosion on our core components.
R7: Improve model and experimental correlation to validate the performance predictions.	Was completed and presented in our latest data sets showcasing the performance of our collector as a function of ambient conditions.
R8: Align the design basis and marketing direction with regions of water scarcity or areas with high water costs.	Water scarce environments & areas with higher water costs have been a focus of our sales efforts – including some sales to plants with higher than average water rates. The other finding in this area, which is discussed in our TEA – is that the economics of plume abatement and the value of that service to

	our customer base can far outweigh the economic impact of just the water savings. Details on such are presented in the TEA.

Conclusions

To summarize our findings from our pilot testing at the MIT NRL (Site 2) of our WaterPanel™ Collection system:

- Plume abatement seen throughout the year as ambient condition vary. Benefits of Plume abatement are quantified from initial customer discussions in TEA.
- High-quality collected water – up to 100-150X reduction in conductivity and other relevant constituents in water analysis. Water can be used as a feedstock for high-value applications where low concentration water is needed.
- Water savings up to 15% of tower water consumption. Collection efficiency is a function of ambient conditions (ambient temp and relative humidity) as well as tower heat load. More data is required on various processes and cooling towers to determine specific averages in different markets.
- No measurable effects on air flow or cooling performance
- Mitigated robustness concerns throughout testing:
    - Mitigated a variety of high-voltage related robustness anomalies that appeared during testing (5000+ hours of run time)
    - Piping/routing clogging due to foreign contaminants: closed piping systems to ambient