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Final Report on Humidification-Dehumidification Desalination Prototype

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INTEROFFICE MEMORANDUM

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SUBJECT: Final Report on Humidification-Dehumidification Desalination Prototype

DATE: May 6, 2022

CC: Dr. Darin George, Team Adviser/Senior Design Administrator, Trinity University

Abstract

Freshwater available across the globe is decreasing daily due to population growth, climate change, and pollution. The growing scarcity of freshwater affects more than a billion people worldwide and has prompted increased research into desalination processes. Large desalination plants are already in operation but are very expensive to build. Not every community has the means to implement these large systems, advancing the need for smaller, more economical, and efficient desalination plants.

The Desalinators researched and designed a humidification-dehumidification (HDH) desalination prototype that will convert saline water into potable water at a household scale (approximately 5-10 gal/day of freshwater). The sponsor, SwRI, intends to use the results of this project to further their research into the applications and improvements of small-scale HDH processes. Therefore, the prototype need not be perfect as long as it produces results that can be measured and analyzed.

The prototype features four main subsystems: primary heater, air circulation system, humidifier, and condenser. After the team's extensive research, the final prototype was built using a water heater provided by the sponsor, an air pump (for forced convection) provided by the University, a packed bed tower humidifier with Raschig rings, and an ice bath within a plastic bucket with an air separator for the condenser. A schematic of the final prototype can be found in the figure section of the appendix. The team chose these components to maximize the performance of the prototype while minimizing costs.

The six project requirements included the following: the prototype shall use the HDH process to desalinate saline water into potable water; the prototype should operate within ±20% error of design parameters, including operating temperature, humidity at inlet and outlet, and outlet salt content; the prototype shall allow the operating temperature, humidity at inlet and outlet, and outlet salt content to be measured; the prototype should allow efficiency to be measured and compared to current desalination processes via gained-output ratio (GOR), recovery ratio (RR), or other efficiency measures; the prototype should allow outlet water samples to be collected and tested by instruments provided by SwRI; and the prototype may produce between 5-10 gallons/day.

To meet these requirements, several "complete prototype tests" were conducted in which temperatures, flow rates, humidity, and salinities were measured at 3-minute intervals during a 21-30 minute test. The complete prototype tests were conducted at a variety of water heater setpoints and flow rates. An additional "long test" was conducted as well where the same values were measured but for 100 minutes at 4-minute intervals. Using the results of these tests, the team was able to show that the prototype successfully met all but the last project requirement regarding potable water output volume and selecting optimal operating conditions. The potable water volume production rate could be increased if the tubing used within the prototype was upgraded to better withstand moderate pressures as well as using larger water and air pumps to increase flow rates.

Final Project Report for a Humidification-Dehumidification (HDH) Desalination System

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I. Introduction

All across the globe the amount of potable water is decreasing every day. The growing population is depleting reservoirs and other sources of potable water, thus increasing the demand for clean drinking water. More than a billion people are affected by this problem and many of them get illnesses from drinking non-potable water [Narayan & Lienhard]. Large desalination plants are in operation across the globe but are very expensive. Impoverished countries cannot afford to implement these systems, so smaller, more economical, and efficient desalination plants are necessary to fill this demand.

To address this problem the Desalinators team researched and designed a prototype to convert saline water into potable water at a household scale using a humidification-dehumidification (HDH) process. The main objective of this project was to design, build, and test an HDH desalination prototype. The sponsor, Southwest Research Institute (SwRI), intends to use the results of this project to further its research into the applications and improvements of the HDH process. Therefore, the prototype need not be perfect as long as it produces results that can be measured and analyzed.

The prototype was built with several constraints. First, it had to be built within the available budget of $1,200 and be manufactured using parts either provided by the sponsor or university, easily accessed online, or purchased at local hardware stores. The prototype had to have a total volume of fewer than 1,000 ft^3 to make it easy to transport to the Southwest Research Institute campus. Lastly, the prototype was to be tested using artificially salinated water by measuring the salinity of the water before and after processing.

The team's work this year produced a proof-of-concept prototype that is not intended for public use. However, since the design involves potable water, if the prototype is later commercialized the design should be governed by the United States National Primary Drinking Water Regulations (NPDWR). The Environmental Protection Agency (EPA) outlines "legally enforceable primary standards and treatment techniques that apply to public water systems" in the NPDWR which will be important to future applications of the prototype if it is to be used for public consumption [United States Environmental Protection Agency].

The prototype must satisfy several project requirements:

1. The prototype shall use the HDH process to desalinate saline water into potable water.
2. The prototype should operate within ±20% error of design parameters, including operating temperature, humidity at inlet and outlet, and outlet salt content.
3. The prototype shall allow the operating temperature, humidity at inlet and outlet, and outlet salt content to be measured.
4. The prototype should allow efficiency to be measured and compared to current desalination processes via gained-output ratio (GOR), recovery ratio (RR), or other efficiency measures.
5. The prototype should allow outlet water samples to be collected and tested by instruments provided by SwRI.

6. The prototype may produce between 5-10 gallons/day.

Referring to Figure 1, there are four main subsystems: primary heater, air circulation system, humidifier, and condenser. The subsystems will be discussed in-depth in the next section. The HDH process works similarly to the rain cycle. Saline water enters the system and is used to humidify air within the humidifier. Some systems heat the saline water to increase humidity (as seen in Figure 1) while others heat the air; some systems heat both fluids (known as a dual heater). After the air has been humidified, the water in the air is separated within the condenser and exits the system as freshwater. The saline water that was used to humidify the air exits the system through the humidifier as brine. For clarity, throughout the report "inlet water" and the "brine" are not the same though they are both salinated–refer to Figure A2 for more details.

An important design consideration is how each fluid will circulate through the HDH system. The team conducted research on closed-air/open-water (CAOW), open-air/closed-water (OACW), and open-air/open-water (OAOW) systems by studying the published studies presented in Mohamed et al. Research showed that both CAOW and OACW tend to have high performance and were relatively easy to implement but the team decided to use an CAOW system for their prototype. The decision was made primarily because CAOW systems have been researched more thoroughly than OACW systems. To this end, the team has built an HDH prototype with a packed bed humidifier, resembling Figure 1, to achieve the first project requirement.

To achieve requirements 2 through 6, the team placed temperature probes, water and air flow meters, and a humidity probe in the appropriate locations throughout the prototype during operation. Furthermore, the team used a Brix refractometer to determine the inlet and outlet water salinity. These measurements allowed the team to then calculate the efficiency of the prototype and estimate how much fresh water could be produced in a day. The completed prototype can be found in the appendix (Figure A2).

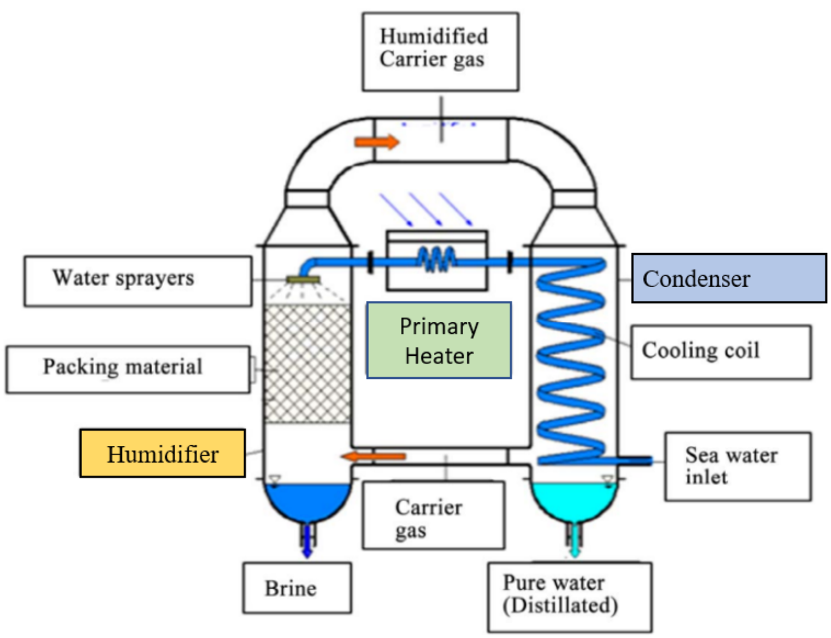

Figure 1. A simple humidification-dehumidification (HDH) process [Kabeel et al.]

II. Overview of Final Design

A. Primary Heater

The primary heater heats one or more fluids used in the HDH process to increase the freshwater output of the prototype. The primary heater increases the humidification capacity of the air in the system, thus larger volumes of freshwater can be condensed from it by the condenser. In Figure 1, the primary heater is shown in green. The team's research showed that existing HDH prototypes use water, air, or dual heaters, which heat both the water and air.

The following conclusions were drawn from the research. Using a water heater is more advantageous because water has a higher heat capacity than air. The lower heat capacity of air makes it difficult to maintain the operating temperature needed to produce fresh water. Therefore, operating an air heater takes more energy compared to a water heater which makes the air heater less efficient [Mohamed et al.]. Furthermore, water heaters are cheaper and more easily obtained than air heaters. Dual heaters, which is a system of heaters that heat both the air and water, have both the best and worst qualities of air and water heaters. With this information, the team decided to implement a water heater in the prototype. The water heater that the team used was provided to them by the sponsor, SwRI, and can heat water to up to 180℉. The specifications of the water heater are shown in Figure 2.

Figure 2. Additional water heater specifications

B. Air Circulation System

The air circulation system moves air through the humidifier and into the condenser to generate freshwater. By moving the hot humid air from the humidifier into the condenser, the hot humid air can cool and change phase into liquid fresh water. To identify the best air circulation system for the prototype, the team first researched convection processes and how they could be implemented within the HDH prototype.

Convection processes are classified as either natural or forced. When there is a fluid flow there is friction involved in the movement which causes head loss. In forced convection, the head loss is compensated for by pumps that do work on the fluid. Natural convection relies on buoyancy so this option limits the physical configuration to be vertical so that the buoyant motion of the air is not inhibited [Department of Energy]. With this in mind, the team had to choose between the two convection types for the air circulation system. The first option was to use natural convection processes and allow buoyancy effects to move air throughout the system and the second was to use an air pump and use forced convection to circulate the air. The air circulation system is not shown in Figure 1 but it is implied as the air must move between the humidifier and condenser.

The design choice for this subsystem was weighted primarily on the following decision criteria: cost, parts availability, performance, and compatibility with other subsystems. With these criteria in mind, the team decided to use a forced convection air circulation system for the prototype. The system used was an air compressor, a Commercial Air Pump 7 from Ecoair. The air compressor had an output of 3566 GPH, operated at a pressure of 6.96 psi, and utilized ½ inch inner diameter tubing.

C. Humidifier

The humidifier increases the humidity of the air within the system to the desired level determined through design and iteration. Increased air humidity increases the amount of fresh water that can be condensed later in the process. The primary decision criteria for the humidifier included cost, manufacturability, and performance. The secondary decision criteria include size, ease of repair, and durability. Cost, manufacturability, and performance were of the utmost importance due to the budget constraint and timeline of the project. The other criteria were not a necessity but helped improve the design. The humidifier is shown with the gold box in Figure 1.

The team's research indicated that the most commonly used humidifiers for HDH desalination prototypes are packed bed towers [Mohamed et al.]. Packed bed towers consist of a closed column with an inlet and outlet on both the top and bottom enclosures. Heated water sprayed from the top contacts air flowing from the bottom. Heat transfer occurs across the surface area of the packing material, humidifying the air. Humid air leaves the tower from the top and excess saline water exits at the bottom. Refer to Figure A4 for an image of a packed bed humidifier.

The column used in this prototype was schedule-80 6-inch diameter clear PVC and the packing material was ⅜ inch ceramic Raschig rings. The column was 4.5 feet tall and the packed bed was approximately 3.75 feet tall and 5-11/16 inches in diameter. Plastic flanges from McMaster-Carr were purchased to seal the ends of the column. A ½ inch showerhead served as the spray nozzle to reduce pressure buildup. The inlet and outlet connections made by drilling holes in the flanges were sealed with a combination of room-temperature-vulcanizing (RTV) silicone, aquarium sealant, caulk, and plumber's putty.

D. Condenser

The condenser subsystem is also known as the dehumidifier and it condenses water vapor from the humid air within the system into fresh water. The condenser prioritizes heat transfer efficiency to be able to produce as much fresh water as possible from a quantity of humid air. In Figure 1 the condenser is shown near the blue box. The primary decision criterion used to evaluate the condenser options was manufacturability. The secondary decision criteria included cost, size, performance, ease of repair, and durability. Manufacturability is of utmost importance due to the limited scope and timeline of the project. The other criteria are more of a luxury; they are important but not as important as the manufacturability criterion.

The team had initially planned to implement a second packed bed for the condenser based on these decision criteria. However, after learning of the complexities involved in designing and building a packed bed, the team decided to use a heat exchanger. In the lab where the team completed most of the construction and testing, a small refrigeration unit was found from a previous senior design project. After assistance from the University's facilities maintenance team, the condenser was able to run but could only cool water to about 39℉.

The team reviewed the remaining budget at this time and collaborated with the project sponsor to determine that the best use of resources was to simply use an ice bath for the condenser. A plastic 5-gallon bucket was used to house the ice water along with many coils of Santoprene tubing containing the humid airflow. The tubing entered the bucket from a hole in the lid and exited through a sealed hole at the bucket's base before entering the separator. An Automatic-Drain Compressed Air Separator was purchased from McMaster-Carr and placed after the condenser and before the air pump inlet. The separator drained the fresh water into a container while allowing the dehumidified air to pass through and be recirculated by the air compressor. The addition of the air separator allowed the team to efficiently collect the fresh water.

E. Construction of Prototype

The prototype was constructed using equipment available in the Trinity University Makerspace and electrical shop. Construction of the prototype included assembling the wooden scaffolding on which the prototype operates, assembling and sealing the packed bed humidifier, sealing the condenser, and building the supporting structures for the air separator and flowmeters. All construction involving wooden support structures was cut by either a circular saw, chop saw, or band saw. Drilling was completed with both electric hand drills and a drill press.

The humidifier column required inlet and outlet ports in the flanges to be drilled using a drill press and then sealed with PVC cement onto the tube section. The mesh floor was secured within the column using Rust-Oleum Leak Seal spray and RTV silicone. RTV silicone and aquarium sealant were used at the inlet and outlet connections within the flanges. Finally, wrenches and ratchets were used to tighten the bolts connecting the flanges.

Construction of the condenser became simplified after the team switched from using the small refrigerator unit to an ice bath. Building the ice bath involved cutting out a hole on the outer rim of the lid and a hole on the bottom of the side of a 5-gallon bucket. This is done so that as the tube exits the top of the humidifier, it coils within the bucket. After coiling the tube within the bucket, silicone aquarium sealant was used to prevent leaking from the hole in the side. Finally, the outside of the bucket was wrapped in double reflective insulation and the inside was filled with ice and water to keep the submerged tube cold enough to condense but not freeze the generated output freshwater.

Through the use of various adapters and tube sections, appropriate flow bypasses were made for the water pump, water heater, and air compressor. The electric shop provided an appropriate plug head for the water pump.

After the testing of the first iteration prototype concluded, the team decided to make some modifications to the prototype. The team lowered both levels of the plywood on the wooden scaffolding to make the equipment easier to access. Drills were used to back out the screws used to secure the two levels of plywood and then used to set them back at a lower position. The team decided to change all of the tubings that would have heated air or water within them because the freshwater produced by the first iteration prototype was very cloudy and appeared to have microplastics in it. The old tube sections were replaced to avoid leaching plastic from overheated tubes. Santoprene tubing was found to operate within the temperature range of our heated water and be relatively inexpensive. The Santoprene tubing was wrapped in foam pipe insulation for testing as well. Furthermore, the original water pump was replaced with a larger pump provided by the University. An additional bypass valve was added to the water heater in hopes that the water would be recirculated through the heater multiple times and get warmer. The final modification was implementing an Automatic-Drain Compressed Air Separator after the condenser. This involved creating wooden support for the separator to rest on so that beakers of various sizes could be placed underneath the separator to collect the output. Hand drills were used to create the wooden support brackets and metal L-brackets were used to secure the support onto the lower level of the scaffolding.

III. Design Evaluation

The following section will describe and evaluate the functionality and performance of the HDH prototype against the six project requirements.

A. The prototype shall use the HDH process to desalinate saline water into potable water.

1. Associated Tests

This requirement was verified by the implementation and inspection of the prototype. The objective of the test was to verify that the prototype used the HDH method to desalinate water. This was a simple test as it was performed as the team researched design options and constructed the prototype. This section will only discuss the use of the HDH process;desalination results will be discussed in a later section. The only acceptance criterion was to use the HDH process as indicated by the necessary subsystems.

2. Test Results

Figure A2 shows a schematic of the final prototype. As discussed in the preceding sections, HDH systems have the four main subsystems shown in Figure 1 (primary heater, air circulation system, humidifier, and condenser). To summarize, the team built a prototype with a water heater, an air pump, a packed bed humidifier, and an ice bath with an air separator for the condenser.

In addition, the team used a water pump to circulate the water through the packed bed humidifier. A water pump is not essential for an HDH system but it improves performance as it can move water at a faster flow rate than gravity could and it allows for more flexibility in system configuration.

3. Evaluation

The test results show that the project requirement was successfully met because the HDH process was used. As the inlet water was itself potable and the team took precautions to ensure that the materials within the prototype would not contaminate the flow, it can be assumed that the freshwater was potable as well. The fresh water was somewhat cloudy but did not contain any large particles or have a concerning smell (see Figure A1). During the test in which the sample in Figure A1 was taken, all Santoprene tubing was used in the post-heater subsystems. This indicates that the cloudiness is likely due to residue from the Raschig rings, not microplastics from the tubing. The team sent a sample of freshwater to be purity tested through a service offered at The Home Depot but is unsure when the results will be available. When available, the water purity results will be shared with the sponsor.

B. The prototype should operate within ±20% error of design parameters, including operating temperature, humidity at inlet and outlet, and outlet salt content.

1. Associated Tests

The design parameters of the prototype are defined as the operating conditions that allow the prototype to produce at least 5 gallons of freshwater per day. This project requirement was initially created for the HDH model the team planned to create. However, after learning that the needed modeling software was unavailable, it became too time-consuming to model the entire system and the design parameters could not be chosen this way. Instead, the team chose to determine the mode parameters via experimentation of the physical prototype. The requirement's meaning has been adapted to account for the stability of the prototype operation as there was not enough time to revise the proposal to remove this requirement. Stability refers to how far from the set-point the prototype varies while in operation.

This requirement was verified by the complete prototype tests of the final iteration. The objective of the complete prototype tests was to evaluate the performance of the overall desalination prototype.

These tests served to satisfy all of the project requirements as temperature, flow rates, humidity, inlet, and outlet salt content were all measured with respect to time. This project requirement focuses on the stability of operation.

The salt content of the brine, inlet saline water, and fresh water was measured using a Brix refractometer provided by the sponsor. This refractometer is calibrated to measure sugar content in water and a conversion chart provided by the sponsor was necessary to calculate the salt content (Figure 3). These tests assumed that the prototype was operating at steady-state, optimal conditions, therefore the flow rate and salt content were uniform within the container (inlet saline water bucket or graduated cylinder) from which the sample was collected.

Salt g/100g	Refractive Index	Brix %
0	1.3330	0
1	1.3348	1.3
2	1.3366	2.5
3	1.3383	3.7
4	1.3400	4.8
5	1.3418	6.0
6	1.3435	7.2
7	1.3453	8.4
8	1.3470	9.5
9	1.3488	10.6

Figure 3. Conversion chart for Brix % to percent salinity (provided by sponsor)

The temperatures were measured at five locations throughout the HDH system. Thermometers were placed to measure the temperature of the water entering and exiting the water heater, the inlet air into the humidifier, the outlet from the humidifier, and the outlet air from the condenser. Four of the temperatures were measured using calibrated meat thermometers except for the temperature of outlet air of the humidifier which was measured using the humidity probe. An Extech RH390 Digital Psychrometer with a published accuracy of ±3% relative humidity at 90%+ relative humidity was used to measure the temperature and humidity of the ambient air and outlet air of the humidifier. The complete test setup can be found in the appendix (Figure A2 & A3).

Acceptable results include data that has a relative standard deviation of less than 20% for humidity and temperature measurements and the difference in measured salinity of the inlet water and fresh water should be at least 20%.

2. Test Results

The complete prototype tests were completed at a variety of water heater setpoint temperatures and flow rates to better understand its desalination capabilities. Artificially salinated water was used as the inlet water. The inlet water was made from a reverse osmosis water supply (quality of about 0.5 MΩ/cm^2) mixed with water softener salt pellets rated to be 99% pure sodium chloride. The inlet water was salinated to 3.4-3.7g salt/100g water to mimic the salinity of the ocean [NOAA]. During testing, the salinity of the brine exiting the humidifier was measured and the team found that it was not significantly different from the salinity of the inlet water. Therefore, the brine was recycled through the system to conserve resources.

The summary of salinity results of the complete prototype tests can be found in Table 1. A more detailed data set can be found in the appendix in Table A1. Table 1 shows that the prototype was able to decrease the salinity of water by 93%.

Table 1. Summarized salinity results of complete prototype tests

Water Heater Setting [℉]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Avg. Inlet Water Salinity [g/100g]	Freshwater Salinity [g/100g]	Percent Salinity Decrease [%]
150	0.60	3.49	Not measurable	Not measurable
165 (high flow)	0.60	3.51	0.23	93.4
180	0.39	3.49	0.15	95.7
165 (low flow)	0.37	3.27	0.15	95.4
150 (long test)	0.15	3.36	0.10	97.0

As the tables below show, the relative standard deviation (RSD) of humidity and all five temperatures was low except for the humidity data from the long test. This indicates that when the prototype was set to run at a specific operating condition it was generally very stable. The higher RSD value of the relative humidity during the long test was likely because the team was not able to collect many data points. The relative humidity of the humidifier outlet air became too high and began to saturate the humidity probe. To protect the device from permanent damage, the probe was removed after only nine data points could be collected. Furthermore, the team was still determining the best water heater setpoint temperature and humidifier inlet water flow rate to preserve the tubing integrity for the duration of the test which would also affect the relative humidity measurements.

The results presented in the following tables were collected over a series of tests that spanned from 21-30 minutes with data taken at 3-minute intervals. The complete prototype tests were conducted at a series of water heater setpoint temperatures and flow rates and are listed within the tables in the order in which they were performed. The test called “165℉ low flow” corresponds to the test with an average flow rate of 0.37 GPM and “165℉ high flow” denotes the test with an average flow rate of 0.6 GPM (see Table 1). The humidifier inlet air measurements had the highest RSD values overall. This was because the air temperature increased while the air pump was turned on; the temperatures steadily rose with air pump operation time. However, increased air temperatures help the air become more humid,so the increased temperatures were not viewed as a flaw.

Table 2. RSD calculations of relative humidity measurements of humidifier outlet air

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Relative Humidity Measurements [%]	Standard Deviation	RSD
150	0.60	9	93.74	0.07	0.08%
165 (high flow)	0.60	7	93.71	0.11	0.11%
180	0.39	10	94.44	0.23	0.25%
165 (low flow)	0.37	10	93.93	0.18	0.19%
150 (long test)	0.15	9	79.81	21.2	26.59%

Table 3. RSD calculations of temperature measurements of pre-heater water

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Pre-Heater Water Temps [°F]	Standard Deviation	RSD
150	0.60	9	67.54	0.30	0.45%
165 (high flow)	0.60	7	70.86	1.06	1.49%
180	0.39	10	67.46	0.67	0.99%
165 (low flow)	0.37	10	75.71	2.02	2.66%
150 (long test)	0.15	25	66.38	1.05	1.58%

Table 4. RSD calculations of temperature measurements of post-heater water

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Post-Heater Water Temps [°F]	Standard Deviation	RSD
150	0.60	9	76.42	1.14	1.50%
165 (high flow)	0.60	7	82.90	0.77	0.93%
180	0.39	10	84.08	3.26	3.87%
165 (low flow)	0.37	10	82.90	0.77	0.93%
150 (long test)	0.15	25	102.41	6.66	6.50%

Table 5. RSD calculations of temperature measurements of humidifier inlet air

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Humidifier Inlet Air Temps [°F]	Standard Deviation	RSD
150	0.60	9	97.11	3.80	3.92%
165 (high flow)	0.60	7	95.29	4.83	5.07%
180	0.39	10	95.58	6.58	6.89%
165 (low flow)	0.37	10	103.73	5.80	5.59%
150 (long test)	0.15	25	113.10	8.97	7.93%

Table 6. RSD calculations of temperature measurements of post-condenser air

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Post-Condenser Air Temps [°F]	Standard Deviation	RSD
150	0.60	9	58.81	0.88	1.49%
165 (high flow)	0.60	7	56.34	0.57	1.02%
180	0.39	10	55.89	0.86	1.53%
165 (low flow)	0.37	10	61.79	2.75	4.45%
150 (long test)	0.15	25	79.16	8.68	10.96%

Table 7. RSD calculations of temperature measurements of humidifier outlet air

Water Heater Setting [°F]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Number of Measurements in Test	Mean Humidifier Outlet Air Temps [°F]	Standard Deviation	RSD
150	0.60	9	79.12	0.41	0.52%
165 (high flow)	0.60	7	87.97	0.66	0.74%
180	0.39	10	89.03	2.83	3.18%
165 (low flow)	0.37	10	98.21	3.40	3.47%
150 (long test)	0.15	9	114.16	11.07	9.70%

3. Evaluation

The results presented in Tables 1-7 show that our prototype partially met the above project requirement. The prototype was able to decrease the salt content of the inlet saline water by over 93% while the goal was to reduce it by at least 20%. Except for the relative humidity measurement during the long test, the relative standard deviation of each parameter in each test was far less than 20%. It can then be concluded that the prototype can operate steadily under operating conditions chosen by the user.

However, the team was not able to determine optimal operating conditions to be considered as design parameters. The Santoprene tubing that the team implemented in the prototype was not able to withstand the water pressure imposed by the water pump. For safety, the water flow had to be decreased which then decreased the volume of fresh water produced (discussed later). The operating conditions that produced the desired amount of fresh water would be considered ideal but could not be determined from the current iteration of the prototype.

C. The prototype shall allow the operating temperature, humidity at inlet and outlet, and outlet salt content to be measured.

1. Associated Tests

To confirm that the prototype can measure operating temperature, the humidity of the inlet and outlet air, and the outlet salt content, the team performed complete prototype tests.

The complete prototype tests, along with the long test, measured multiple parameters of the HDH prototype which include: measuring outlet salt content of the fresh water, calculating gained-output ratio (GOR), recovery ratio (RR), and performing temperature, and humidity tests.

The temperature data collected during the complete prototype tests was measured at five locations throughout the HDH system. The locations were the inlet water into the water heater, the heated water from the water heater, the inlet air into the humidifier, the outlet air from the humidifier, and the outlet air from the condenser. This test allowed the team to measure the operating temperatures of the prototype.

The humidity data was collected at two locations: the ambient air humidity and the outlet air humidity of the humidifier. The humidity test allowed the team to measure the humidity of the inlet and outlet air of the prototype. When performing this test, it was assumed that the condenser in the prototype did not have a significant effect on the inlet humidity of the humidifier and the outlet humidity of the humidifier.

2. Test Results

As mentioned in §A of the Design Evaluations, Table 1 shows comparisons of inlet saline water content and fresh water salt content. The table displays the salt content of both the inlet salinated water and the outlet fresh water. When the water heater was set to 150°F, the prototype did not generate a measurable volume of fresh water. However, when the water heater was set to 165°F, 180°F, and 150°F for the long test, the salinity of the fresh water was reduced by over 90%.

The plots of the temperature tests can be found in Figures 4-7. Figure 4 displays the temperature test for when the water heater was set to 150°F. The plot displays a visible difference in temperature between the water before going through the heater and the water after it has passed through the heater. As previously stated, when the water heater was set to 165°F during the complete prototype tests, the prototype experienced technical issues and the team had to split the data into two sets to account for the gap in elapsed time. The first set of data, with the water heater set at 165°F and an average humidifier inlet water flow rate of 0.60 GPM, had an average water temperature difference of 12.1°F. The team then performed tests at 180°F with the water inlet flow rate lowered to an average of 0.39 GPM. The team decided to retake the 165°F water heater setpoint measurements to get a complete set of data. Similar to the 180°F water setting, the team lowered the average humidifier inlet water flow rate to an average of 0.37 GPM to further prevent the tubing from swelling.

After the complete prototype tests, the team performed a long test with the water heater set at 150°F. The 1 inch water heater tubing connections and ½ inch humidifier inlet water connection were replaced with vinyl and braided tubing, respectively to prevent swelling and bursting of the tubing. The vinyl tubing did not have the temperature specifications required, so to further prevent swelling the team also decreased the inlet water flow rate to an average of 0.15 GPM. By reducing the flow rate to 0.15 GPM the inlet water had more time in the water heater to be heated and significantly increased the outlet water temperature from the heater. It was found after performing the complete prototype tests and the long test that the water temperature after the heater was unable to achieve the setpoint temperature.

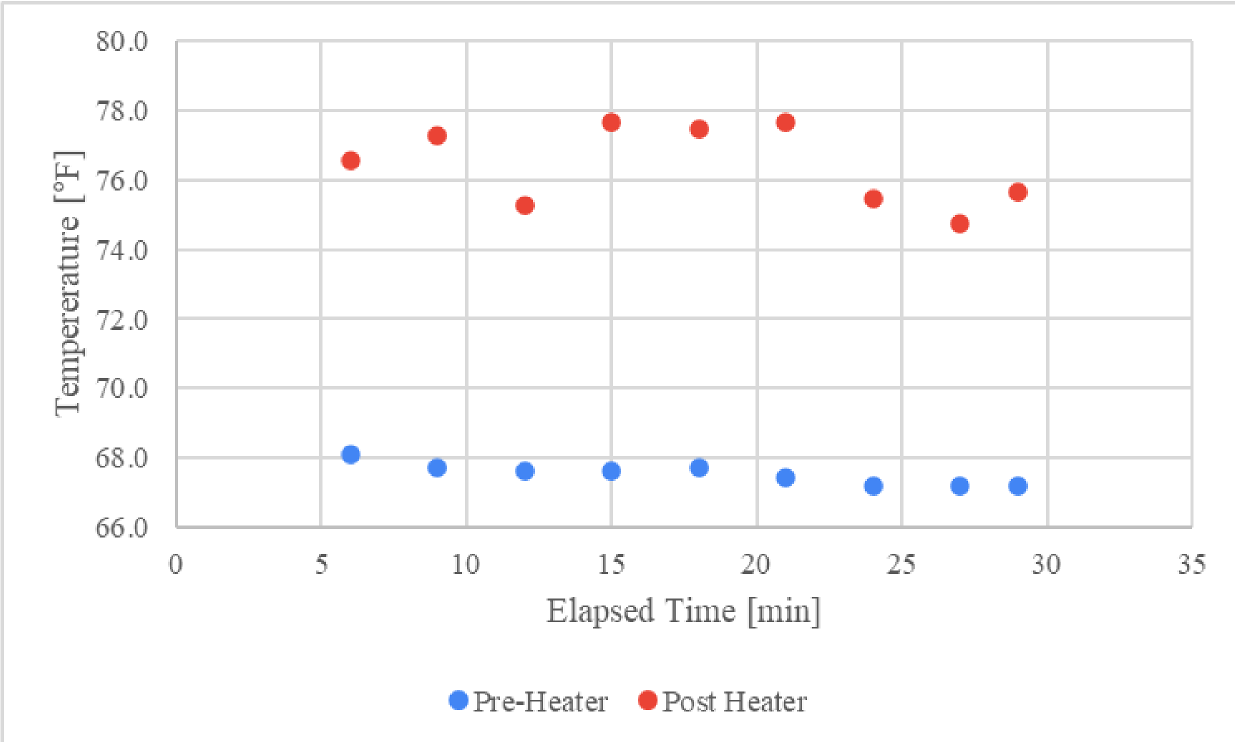

Figure 4. Temperature comparison between the inlet water heater and the outlet water heater with respect to elapsed time. The water heater setting for this set of data was set to 150°F and the average water inlet flow rate was 0.60 GPM.

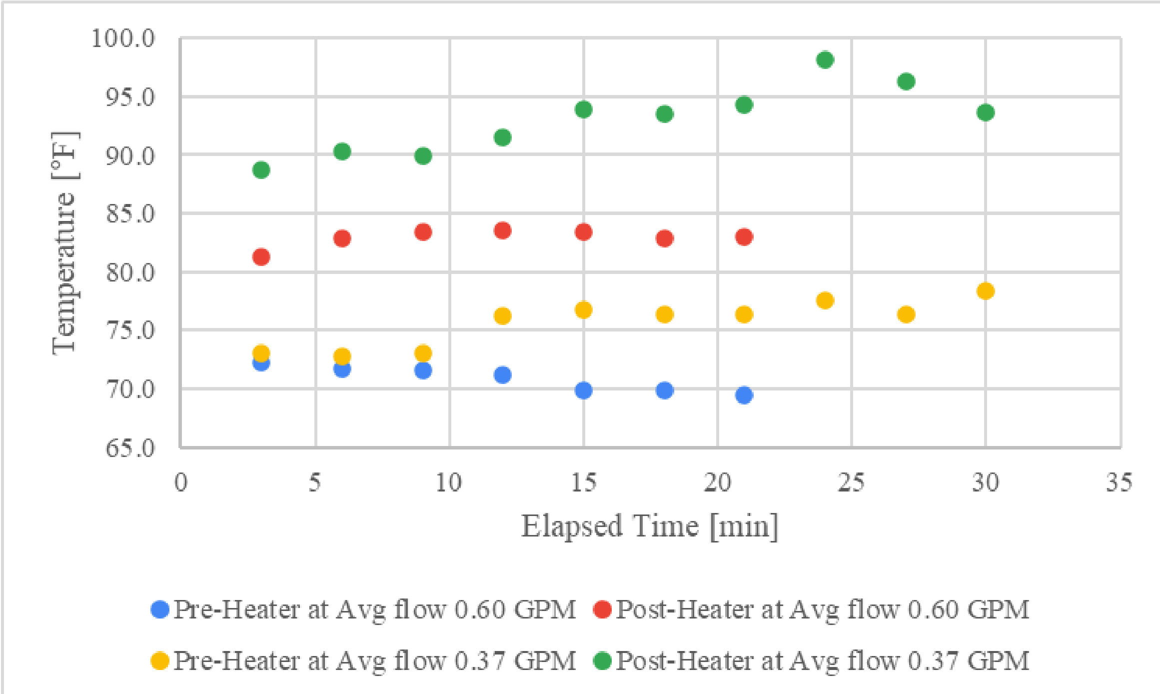

Figure 5. Temperature comparison between the inlet water heater and the outlet water heater with respect to elapsed time. The water heater setpoint for this data was 165°F.

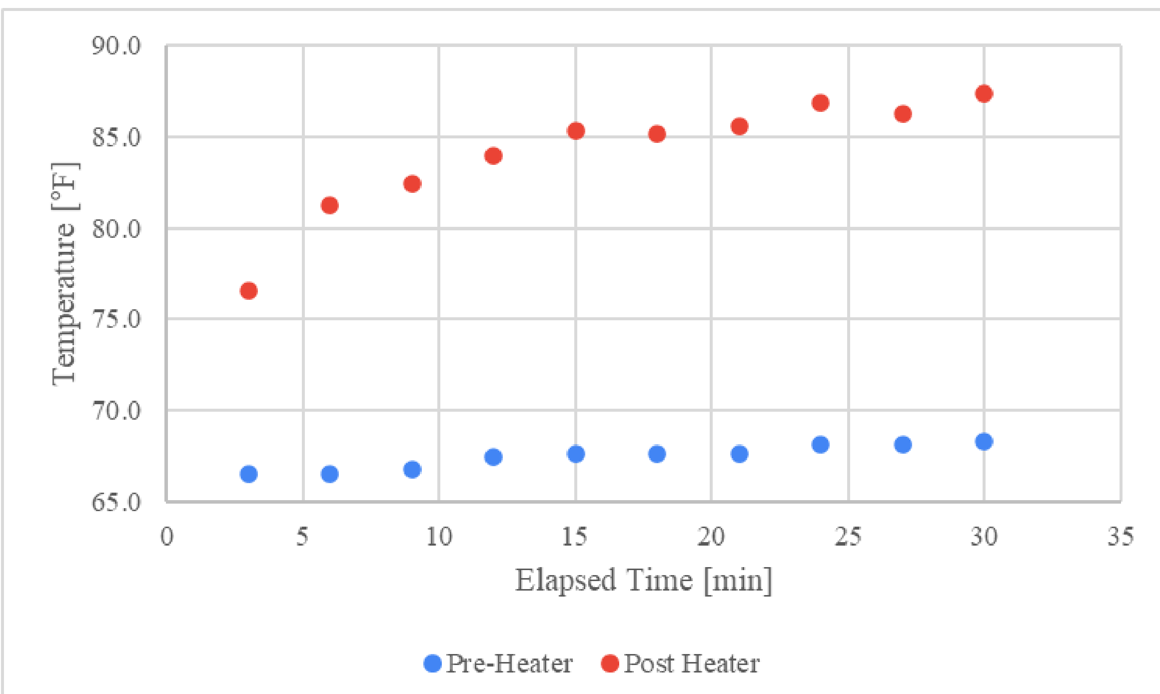

Figure 6. Temperature comparison between the inlet water heater temperature and the outlet water heater temperature with respect to elapsed time. The water heater setting for this set of data was set to 180°F and the water inlet flow rate average was 0.4 GPM.

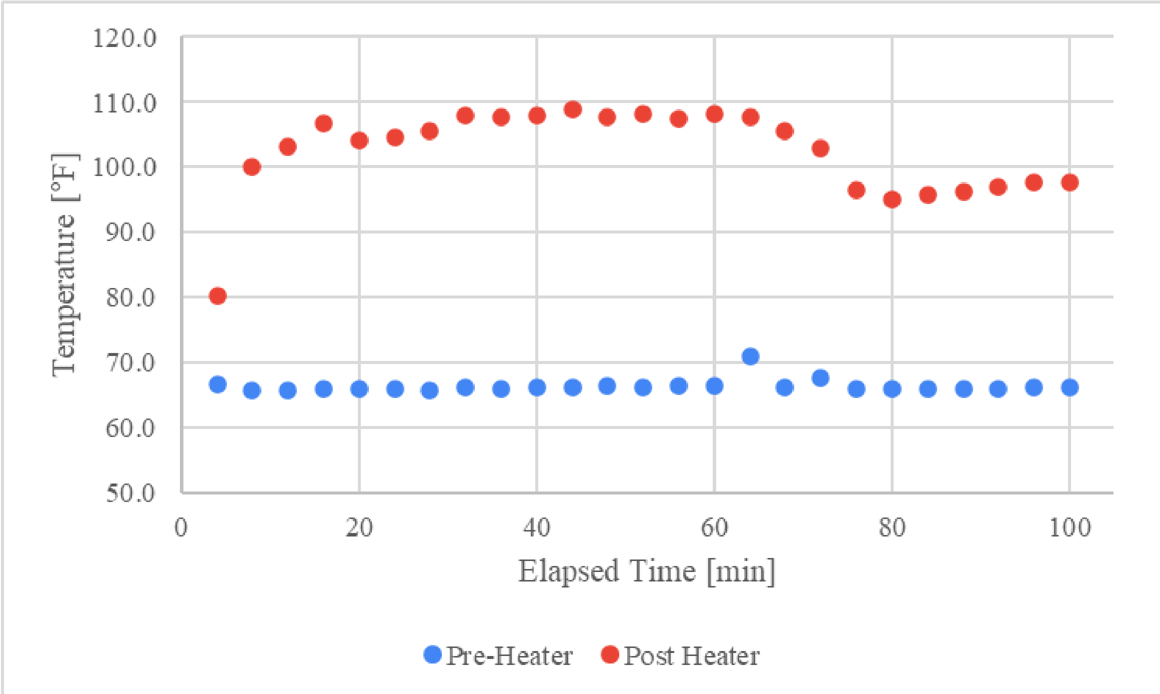

Figure 7. Comparison of the inlet water heater temperatures and the outlet water heater temperatures with respect to elapsed time. This plot represents data from the long test with a water heater setpoint of 150°F and average water inlet flow rate of 0.15 GPM.

The plots related to the humidity data can be found in Figures 8-12. For all four sets of complete prototype test data, the average relative humidity of the air leaving the humidifier was higher than 93.0%. The data set with the largest average relative humidity was when the water heater was set to 180°F, which had an average relative humidity of 94.4%. Performing the humidity test indicated that the relative humidity of the outlet air of the humidifier was approximately 28 percent higher than the relative humidity of the ambient air.

When the team performed the long test, only nine points of relative humidity data were taken. The team believes that this was due to the oversaturation of the humidity probe. To prevent damaging the device, the team decided to not measure the relative humidity for the long test any longer. Before the humidity probe became oversaturated, the relative humidity ranged from 75.1 to 94.6% humidity. The outlet air temperature ranged from 85.7-123.0°F and had an average of 114.2°F.

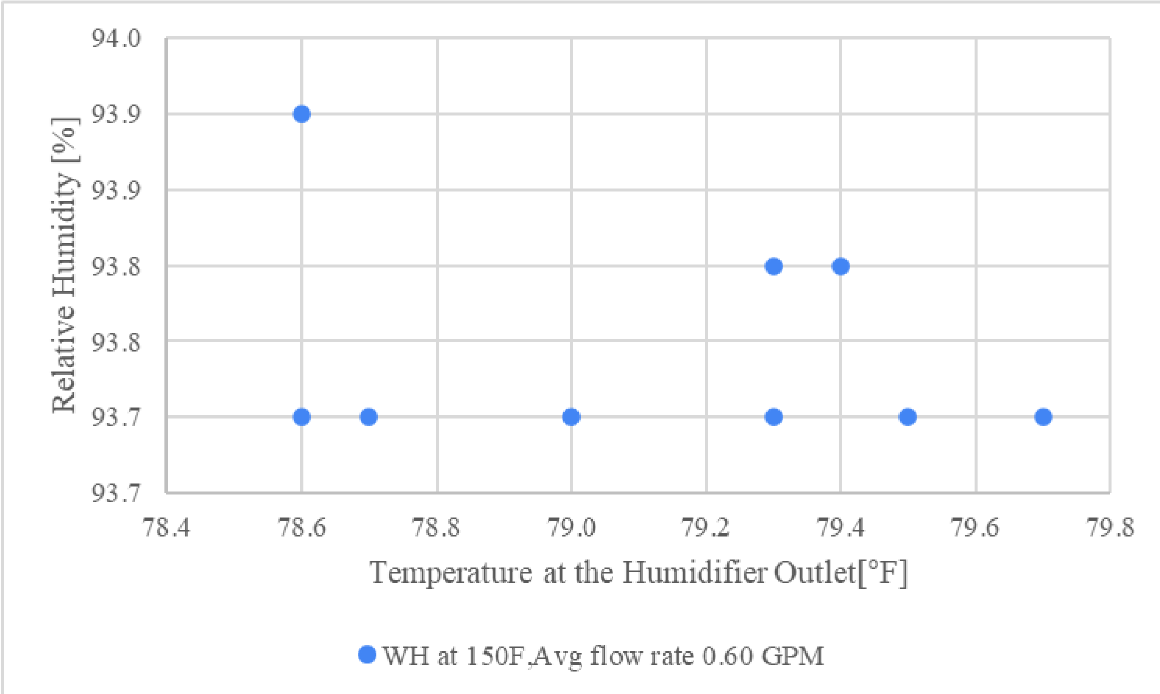

Figure 8. The relative humidity of the outlet air of the humidifier with respect to humidifier outlet air temperature. The water heater setting for this plot was set at 150°F with an average water inlet flow rate of 0.60 GPM

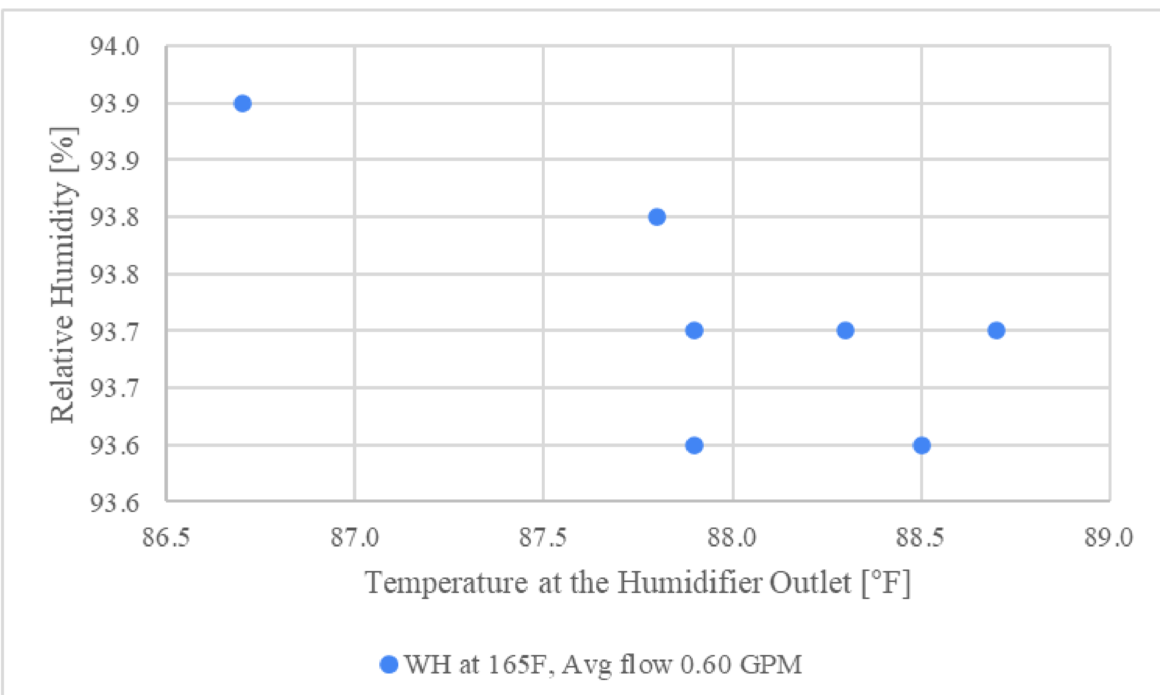

Figure 9. The relative humidity of the outlet air of the humidifier with respect to humidifier outlet air temperature. The water heater setting for this plot was set at 165°F with an average water inlet flow rate of 0.60 GPM.

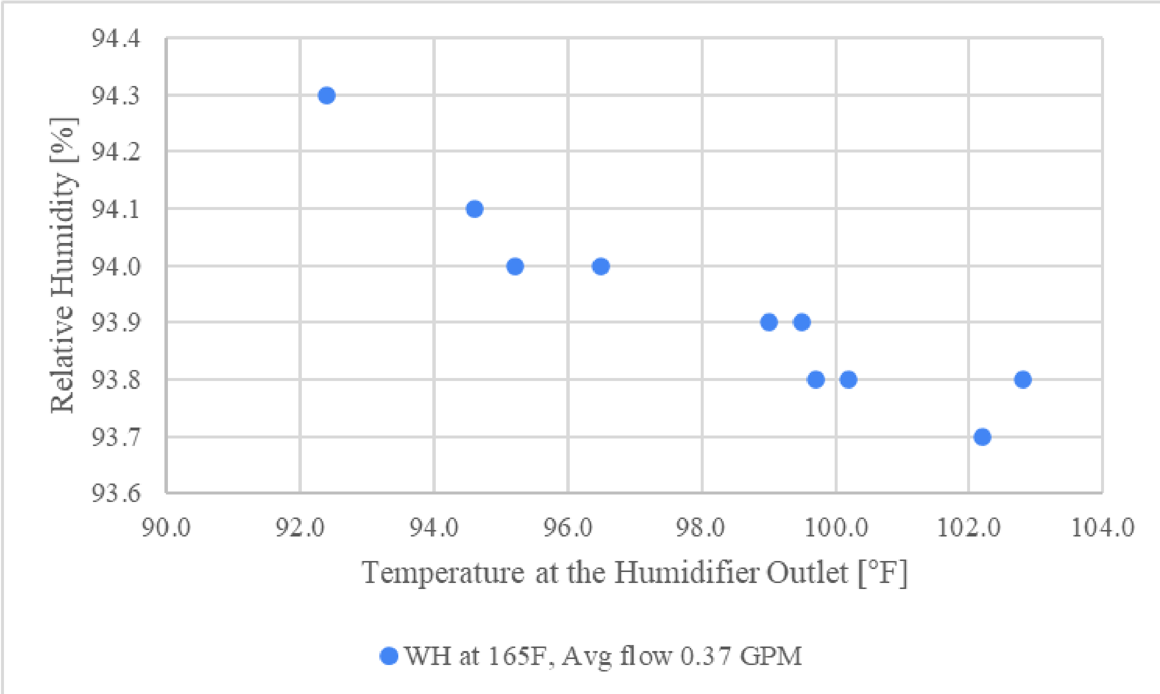

Figure 10. The relative humidity of the outlet air of the humidifier with respect to humidifier outlet air temperature. The water heater setting for this plot was set at 165°F with an average water inlet flow rate of 0.37 GPM.

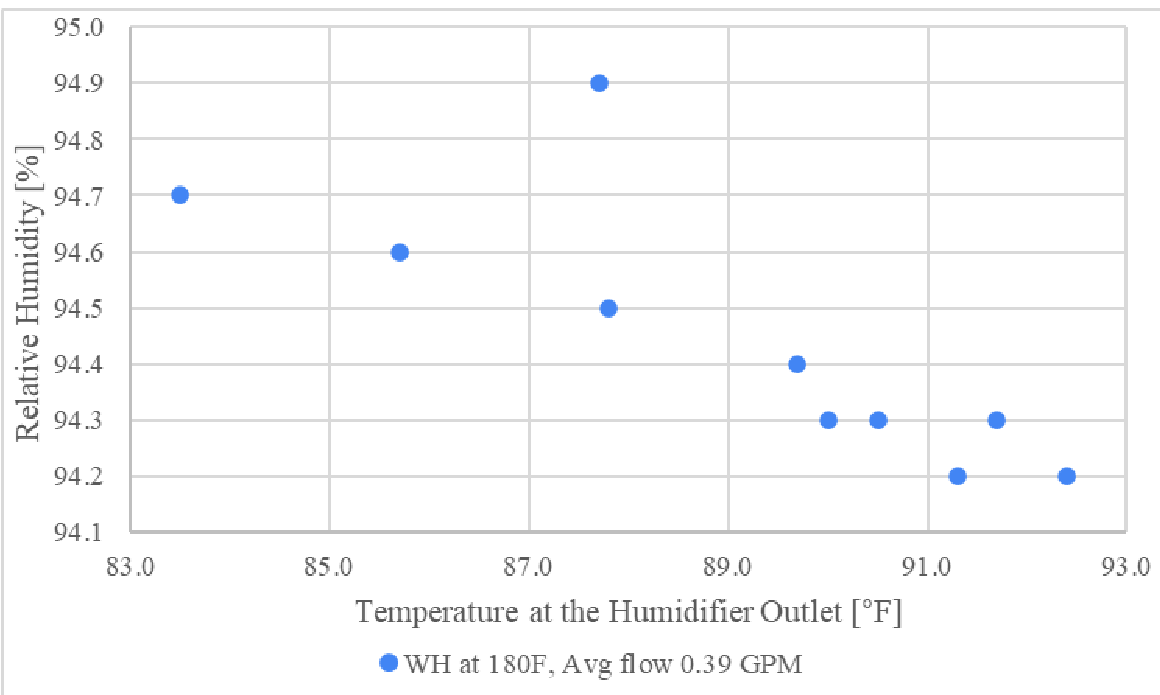

Figure 11. The relative humidity of the outlet air of the humidifier with respect to humidifier outlet air temperature. The water heater setting for this plot was set at 180°F with an average water inlet flow rate of 0.39 GPM.

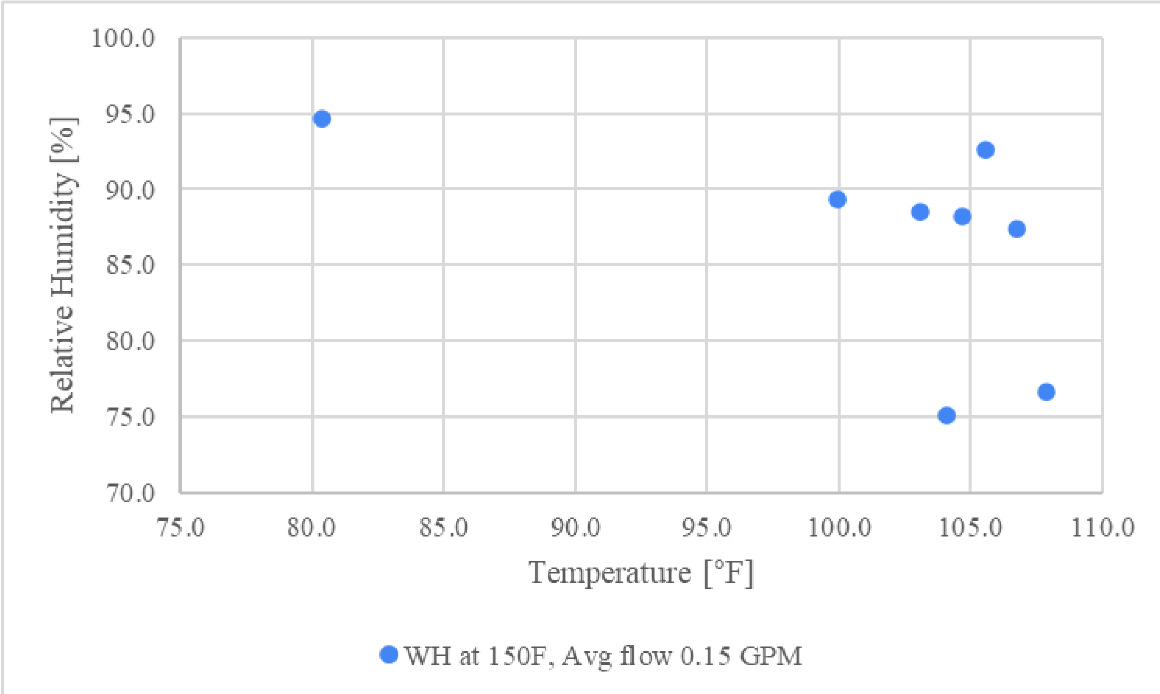

Figure 12. The relative humidity of the outlet air of the humidifier with respect to humidifier outlet air temperature. This plot represents the long test and the water heater setting was set at 150°F with an average water inlet flow rate of 0.15 GPM.

3. Evaluation

The results presented in Table 1 of section A of the Design Evaluations as well as Figures 4-12 show that the team met this requirement. To measure temperature, meat thermometer probes were placed in the proper locations (see Figure A2). To measure the saltwater content, a Brix Refractometer was used by placing a few drops of saltwater on the lens. Finally, to measure the humidity an Extech RH390 Digital Psychrometer was placed at the outlet air of the humidifier. As previously stated, when the salt content of the inlet water was compared to the salt content of the freshwater at the outlet, the prototype was able to remove over 90% of the salt.

The temperature measurements showed there was a significant increase in temperature between the inlet water and the outlet water from the heater. The lowest average water temperature difference occured when the water heater was set to 150°F (average humidifier inlet water flow rate of 0.60 GPM) which produced a temperature difference of 7.4°F. The highest average temperature difference occured when the water heater was set to 165°F (average humidifier inlet water flow rate of 0.37 GPM) which produced a temperature difference of 17.3°F. The highest average temperature difference was expected to come from the 180°F water heater setpoint with an average water inlet flow rate of 0.39 GPM. The team believes the 165°F setting was the highest average temperature difference because this test was conducted after the 180°F test. Because of this, the water heater did not have enough time to fully cool down.

The humidity measurements showed that there was a significant increase in relative humidity when comparing the outlet air of the humidifier and ambient air. The average difference in relative humidity between the outlet air of the humidifier and ambient air was approximately 28% relative humidity. The moisture carrying capacity of the air is dependent on temperature, and relative humidity is a measure of this relationship. Figures 9-12 show a trend that as temperature increases the relative humidity decreases. While relative humidity is only decreasing slightly, the temperature of the air is still increasing, therefore the air may be holding more water than it would at lower temperatures. Additional measurements would be required to verify this assumption, including pressure.

The long test was performed to observe the long-term behavior of the prototype. It was observed that by lowering the flow rate, the post-heater water temperature increased significantly, possibly because the water spent more time in the heater. As previously stated, the team was only able to measure nine points of humidity data because the outlet air was too humid and oversaturated the humidity probe. As a result the probe was unable to provide readable data, and the team decided to stop the measurement of humidity at the outlet air of the humidifier.

The complete prototype and long test both met the project requirement of measuring operating temperature, humidity at the inlet and outlet of the humidifier, and outlet salt content. The long test appeared to have performed slightly better than the shorter, complete prototype tests because the water heater had longer to warm up. The long test had a higher average temperature difference between the post and pre-heater, higher average temperature at the outlet air of the humidifier, and the salt content in the freshwater decreased to 0.10 g/100g compared to the 0.15 g/100g seen in the results of the complete prototype tests. This may have occurred because the water inlet flow rate was reduced and allowed the water to be heated to a higher temperature. The significant increase in temperature may have also affected the amount of salt removed from the fresh water.

D. The prototype should allow efficiency to be measured and compared to current desalination processes via gained-output-ratio (GOR), recovery ratio (RR), or other efficiency measures.

1. Associated Tests

No extra tests were required to measure efficiency. Instead, data from the complete tests were used to calculate the GOR and RR. The GOR is defined as the ratio of latent heat of generated freshwater to the input heat, as seen in Equation 1, where $\dot{m}_{FW}$ is the mass flow rate of fresh water and $\dot{Q}_{in}$ is the total heat added to the system. The RR is defined as the ratio of fresh water flow rate to saline water flow rate.

$$GOR = \frac{\dot{m}_{FW}\lambda}{\dot{Q}_{in}} \tag{1}$$

The increase in temperature generated by the water heater and air compressor serves as the basis for the input heat, using Equation 2 to calculate the heat transfer rate along a tube length. Meat thermometers measuring water temperature before and after the water heater were used to calculate the water temperature difference and meat thermometers measuring air temperature before and after the air compressor were used to calculate the air temperature difference. The flowmeters provide the volume flow rate, which is then transformed into the mass flow rate using the density of water and unit conversion. The heat capacities of water and air were assumed to be approximately 4.18 kJ/kg-K and 1.006 kJ/kg-K respectively and the densities of water and air were assumed to be approximately 1000 kg/m^3 and 1.1 kg/m^3, respectively.

$$q = \dot{m} \cdot c_p \cdot \left(T_{m,o} - T_{m,i}\right) \tag{2}$$

A key assumption for the calculation is atmospheric pressure. Because no pressure probes were implemented with the system, it is difficult to know if either the water or air flows were at atmospheric pressure. Based on the response of the Santoprene tubing carrying water flows (extreme swelling), this assumption may not be valid. Still, density does not vary greatly with pressure for water, saline or not, meaning this assumption likely does not introduce a great deal of error in calculations.

These two measurements of efficiency are slightly different. The GOR is more focused on the total energy input required to generate a unit of freshwater and will increase when energy or heat losses are reduced and system efficiency is increased. The RR is simply a measure of the extraction efficiency and does not account for the amount of energy put into the system. The RR will, of course, increase with increased heat energy input and reduced energy loss. For both measures of efficiency, a high value is desirable.

As long as a value can be calculated for GOR and RR, this requirement is met.

2. Test Results

Both the GOR and RR calculated were very low compared to typical systems; however, this was expected due to the relatively low temperatures and flow rates. The system also had minimal insulation, meaning significant heat losses during operation. The results are tabulated in Table 8. For comparison, a simple solar still has a GOR of approximately unity [Kabeel et al.]. HDH systems built in the 1980s had RR values of around 25%, and modern systems can reach 45% or even 60% with a second stage [Mohamed et al.].

Table 8. GOR and RR calculated from prototype iteration testing

Water Heater Setting [℉]	Avg. Humidifier Inlet Water Flow Rate [GPM]	GOR [-]	RR [-]	RR [%]
165 (high flow)	0.60	0.02033	0.00185	0.185
180	0.39	0.01004	0.00181	0.181
165 (low flow)	0.37	0.01234	0.00231	0.231
150 (long test)	0.15	0.00692	0.00676	0.676

3. Evaluation

There were some assumptions required to calculate the total input heat, including the stability of water and air densities with pressure and accuracy of meat thermometers. However, the rest of the data measured allowed for the calculation of GOR and RR, meaning that the prototype design meets the requirement.

E. The prototype should allow outlet water samples to be collected and tested by instruments provided by SwRI.

1. Associated Tests

This requirement was verified first by the complete prototype tests of the previous iteration. Then the same complete prototype tests were conducted on the final iteration, which retained the ability to collect and test water samples. The objective of the complete prototype tests was to evaluate the performance of the overall desalination prototype by the ability to collect fresh water samples.

The complete prototype tests served to satisfy all of the project requirements as temperature, flow rates, humidity, inlet, and freshwater salt content were all measured with respect to time. This section focuses on the ability to collect and measure the volume of fresh water samples from the outlet of the prototype. The main features of this test are the ability to desalinate water and the compatibility of subsystems to produce the final output. The fulfillment of this project requirement was the ability to collect enough volume of fresh water such that tests can be performed using SwRI instruments.

2. Test Results

The complete prototype tests were conducted on both the previous and final iterations of the prototype. This requirement emphasizes obtaining the minimum production of fresh water from the system for measurement whereas the next requirement is about obtaining the maximum volume of freshwater. This distinction is presented as the previous iteration's complete prototype tests and the final iteration's prototype tests respectively.

Complete prototype tests of the previous iteration of the prototype were conducted at a variety of water heater temperatures and flow rates to better understand its desalination capabilities. The tests were completed in two sets. The first was completed with the water heater set to 165℉ and the other with the water heater set to 180°F. Each test was performed over a period of 30 minutes, with data collected at 3-minute intervals. The first test produced about 19 mL of fresh water from the condenser. The second test produced around 39 mL. The values were then converted into gallons and extrapolated to find daily output, assuming production rates remain consistent. These results can be seen in Table 9. The team did not feel that salinity measurement would be accurate for the previous iteration's complete prototype tests because saline water was not used, but it is also not needed to fulfill this specific requirement. However, the results obtained from this test indicate that increasing the water heater temperature results in a greater volume of fresh water. This is logical, as hotter water will decrease the reduction in inlet air temperature. Ideally, the water would not cause any reduction in air inlet temperature. With the air remaining at a higher temperature, its moisture carrying capacity increases, resulting in a larger fresh water output when condensed.

Table 9. Volume of fresh water produced after 30 minutes from the complete prototype tests on the previous iteration

Water Heater Setting [℉]	Volume of Fresh Water [mL]	Volume of Fresh Water [gal]	Extrapolated Daily Output [gal]
165	19	0.005	0.241
180	39	0.010	0.494

3. Evaluation

The results presented in Table 9 show that the team successfully met this requirement. The prototype allows for fresh water samples to be collected and tested by instruments provided by SwRI. The instrument provided by SwRI to test the salinity of the fresh water was a Brix refractometer, and a beaker was used at the water outlet to measure volume. To make use of the Brix refractometer an unspecified amount of water is needed to coat the lens for viewing. The team was able to collect data from the Brix refractometer using samples of water less than 5 mL, as only a few drops are needed. This is the effective minimum volume needed to measure the output. Observing the water collected in a graduated cylinder with a resolution of 1 mL indicates the requirement was fulfilled. While this project requirement was fulfilled, in anticipation of the next project requirement the team decided that the next iteration would have better water and air separation after the condenser to achieve a larger volume of fresh water. The current volume of water produced is not close to the final project requirement target. As such, the final iteration focused on increasing the volume of the freshwater knowing that the prototype has the ability to allow for collection and measurement of the freshwater.

F. The prototype may produce between 5-10 gallons/day.

1. Associated Tests

This requirement was evaluated using the results of the complete prototype tests and the long test of the final iteration. The objective of the complete prototype tests was to evaluate the performance of the overall desalination prototype. The complete prototype tests served to satisfy all of the project requirements as temperature, flow rates, humidity, inlet, and outlet salt content were all measured with respect to time. This section focuses on the ability to produce water at the desired rate of 5-10 gallons per day. The main features of this test are the ability to desalinate water and the compatibility of subsystems to produce the final output.

The objective of the long prototype test was to evaluate the performance of the prototype while it was continuously running for more than 30 minutes. The long prototype test also satisfied all of the project requirements as temperature, flow rates, humidity, inlet and outlet salt content were all measured under continuous operation. The long test differs from the complete prototype tests because it focuses on the ability to produce water without stopping for a test period of 100 minutes, with a set flow rate and water heater temperature. The main feature of this test is the ability to desalinate water continuously. The fulfillment of this project requirement involves the ability to collect enough volume of fresh water such that the extrapolated daily volume production is 5-10 gallons.

2. Test Results

The complete prototype tests for the final iteration of the prototype were conducted at a variety of water heater temperatures and water flow rates to better understand its desalination capabilities. The water output of the 27-minute-long test at 150℉ was not large enough to be measured. Another test was conducted at 165℉ at an average flow rate of 0.37 GPM after the test at 180℉ because the first test at 165℉ was not completed. The team noted that the average inlet water and air temperatures were increased during the test conducted at 165℉ and an average flow rate of 0.37 GPM because both the water heater and the air pump did not have sufficient time to cool down between tests. This accounts for the larger volume of water collected during the low-flow 165℉ than the 180℉ setpoint test, despite the water heater being set to a lower temperature.

The data collected in Table 10 shows that increasing the water temperature does not directly correlate with increased water production. However, the team reasoned that the inconsistency in the data stems from unpredictable water heater performance. When running the tests with high inlet saline water temperatures a higher volume of fresh water is measured. However, the water heater setting and the temperature of the humidifier inlet water flow are separate values.

Table 10. Volume of fresh water produced after 30 minutes from the complete prototype tests on the final iteration

Water Heater Setting [℉]	Avg. Humidifier Inlet Water Flow Rate [GPM]	Volume of Fresh Water [mL]	Volume of Fresh Water [gal]	Extrapolated Daily Output [gal]
150	0.60	Not measurable	Not measurable	Not measurable
165	0.60	88	0.023	1.113
180	0.39	82	0.021	1.036
165	0.37	105	0.027	1.329

The long prototype test for the final iteration of the prototype was conducted with the water heater set to 150℉ and a decreased flow rate to reduce pressure build-up within the tubes. Table 11 shows how the temperature changed with respect to time as well as the cumulative volume of freshwater obtained during the long test. The team discovered that the air separator doesn't drain into the collection beaker while the air is flowing through the separator. While the system is running the separator holds the condensed water, and to measure the volume collected the prototype had to be momentarily turned off to let the water drain. This caused decreases in post-heater water temperature following the measurement of fresh water volume. After just over an hour, the prototype produced 110 mL of fresh water when drained from the separator. However, it is seen in Table 11 that while the operating temperature was lower, the final iteration of the prototype was able to produce more volume due to the longer operation time and general improvements to the system.

Table 11. Volume of fresh water produced after 100 minutes from the long prototype test on the final iteration

Time Elapsed [min]	Humidifier Inlet Water Flow Rate [GPM]	Post-Heater Water Temperature [℉]	Humidifier Air Inlet Temperature [℉]	Cumulative Water Collected [mL]	Cumulative Water Collected [gal]	Extrapolated Daily Output [gal]
4	0.20	80.36	87.62	-	-	-
8	0.19	99.96	94.32	-	-	-
12	0.17	103.06	99.02	-	-	-
16	0.18	106.76	102.92	-	-	-
20	0.16	104.06	107.32	-	-	-
24	0.15	104.66	110.32	-	-	-
28	0.13	105.56	113.42	-	-	-
32	0.10	107.86	115.52	-	-	-
36	0.11	107.66	117.02	-	-	-
40	0.10	107.86	118.82	-	-	-
44	0.10	108.96	118.82	-	-	-
48	0.12	107.66	119.72	-	-	-
52	0.10	108.26	119.92	-	-	-
56	0.12	107.36	120.62	-	-	-
60	0.13	108.26	120.92	-	-	-
64	0.13	107.66	104.22	110	0.0291	0.6548
68	0.16	105.56	118.12	-	-	-
72	0.2	102.86	111.92	225	0.0594	1.1880
76	0.2	96.56	118.42	-	-	-
80	0.2	95.06	119.12	260	0.0687	1.2366
84	0.18	95.66	115.52	-	-	-
88	0.17	96.16	118.12	-	-	-
92	0.15	97.06	118.62	-	-	-
96	0.15	97.66	118.82	-	-	-
100	0.15	97.76	118.22	384	0.1014	1.4602

3. Evaluation

The results presented in Table 10 show that the prototype was unable to produce an amount of fresh water that would extrapolate to 5-10 gallons of water per day. However, this project requirement was less important than the others as the prototype will be used by the sponsor to further their own research into the process. Comparing Tables 9 and 10 shows that the team successfully more than doubled the initial volume of water produced in 30 minutes after only one iteration of the design. The results from Table 11 confirm that the final iteration produces more the longer the system runs.

The prototype has the potential to reach the project requirement given some improvements to the prototype. With an increased budget the team could purchase a more powerful water heating subsystem to heat the water more effectively. To further increase fresh water production, the team would also need to purchase a higher capacity air compressor, higher pressure rated tubes, and a more effective condenser system. It is likely that after these improvements are made, the prototype could produce 5-10 gallons of fresh water per day.

IV. Conclusions

The final prototype meets all design objectives and most project requirements. The prototype successfully used the HDH process to desalinate water, operated with a relative standard deviation of less than ±20% from setpoints, allowed operating temperature, humidity at inlet and outlet, and outlet salt content to be measured, allowed efficiency to be calculated and compared to current desalination processes via GOR and RR, and allowed freshwater samples to be collected and tested by instruments provided by SwRI.

The first objective that remains unfulfilled is determining the optimal design parameters. A final, optimal set of input conditions was not found to achieve maximal results. This is because the system as constructed was not able to handle the full range of inputs provided by the pumps and heater.

The second objective that remains unfulfilled is the total output of the system. According to the tests performed so far, the prototype is capable of producing upwards of 100 mL of fresh water in a 30-minute period, which is about 25% of the necessary output to see a daily output of 5 gallons. This can be attributed to two major factors. First, the flow rates of both air and water were far too low. The airflow rate was limited by the capacity of our compressor, and the water flow rate was limited by the pressure rating of our heat-resistant tubing. Second, the water was not heated enough to make humidification effectively and efficiently achievable. A bypass was added to the heater in an attempt to increase the circulation of water through the heater, and the heater provided up to a 42℉ increase in water temperature, a noticeable difference from the heater's capabilities without a bypass. However, the tubing used could not withstand the temperature combined with pressure from reasonable flow rates and was not insulated well. Thus the heater was not able to be used to its full potential and the humidification was not able to be maximized.Achieving this project objective requires a serious investment in higher capacity pumps for both the air and water, as well as better tubing.

The prototype was also completed while adhering to most of the constraints. The team did request $100 in extra funds beyond the $1,200 budget, but otherwise the prototype fit within a 1000 ft^3 space and was manufactured using parts either provided by the sponsor or university, easily accessed online, or purchased at local hardware stores. The prototype was also tested using artificially salinated water by measuring the salinity of the water before and after processing.

V. Appendices

A. Set-up/Operating Instructions

The HDH Desalination prototype follows a distinct set of instructions to operate. To set up the system the team followed the steps below:

1. Check the tubing and clamps to make sure there won't be any leaks
2. Check to make sure the temperature probes, flowmeters, and humidity probes all work
3. Place brine bucket beneath the humidifier with outlet brine tube going into the bucket to prevent spills
4. Set the water heater to the desired temperature
5. Fill the inlet container with salinated water
6. Prime inlet to the water pump with salinated water to prevent air bubbles and running water heater dry
7. Fill the condenser with an ice bath
8. Plug in the water heater, water pump, and air compressor into the power strip
9. Once all the steps are complete and proper PPE is worn then the power strip can be turned on along with the cooling fan
10. Allow any air bubbles in the water flow to exit
11. The experiment can begin

After the prototype is set up and ready to go there are steps to follow as the prototype is running to ensure the group members are safe and that the prototype does not experience any issues.

1. Monitor the tubing and flow rates to ensure water is flowing through the system and that the tubing does not swell or leak
2. Monitor temperatures probes, air, and water flow meters, and humidity probe to ensure the system is within desired operating levels
3. Change water and air flow rates by adjusting the respective bypass valves
4. Periodically check the brine outlet to ensure it does not overfill the container used
5. Ensure that the condenser and humidifier do not leak excessively (see troubleshooting)
6. Monitor the inlet saltwater container and fill it up with more salinated water once the volume of the water is too low to prevent the pump from intaking air

   a. When refilling the inlet salinated container measure the saltwater content

7. Periodically check the water separator for freshwater entering the beaker

8. Once the system is done running the power strip can be switched off

B. Troubleshooting Tips

The main concerns when operating the prototype are leaks and maintaining pipe integrity. The condenser is prone to leaking from the hole in which the tubing exits the bucket. The team has attempted to seal it with a variety of products but many are fragile. It is recommended that the bucket be placed on top of a drip tray when full of ice water and periodically resealed. Furthermore, the Santoprene tubing used is rated for a maximum pressure of 5 psi at 72℉. The team recommends replacing the tubing with another material able to withstand the temperatures and pressures encountered during operation. However, if this is not possible, monitor the tubing during operation to ensure they have not swelled excessively; reduce the flow rate if the tubes are at risk of bursting. Lastly, the Santoprene tubing is prone to pinching when turning corners or changing directions. Check periodically that the tubing is not pinched so that the flow can move freely through the tubing. Some small pinches/bends can be fixed with several layers of tape to provide additional support.

C. Safety Considerations

The water can achieve very high temperatures that could cause burns if exposed to skin;heat resistant gloves and outerwear are recommended.

The air and water flows are under moderate pressure. Safety glasses should be worn at all times in case of tubing burst.

Water leaks may pose a slip hazard. It is recommended to have a towel/mop nearby as well as a wet floor sign. Users should wear closed-toe, slip resistant shoes and be aware of any water on the floor.

D. Tables

Table A1. Results of packed bed flow tests on new humidifier- note that the pump was unable to flood the new packed bed

Flooding Condition	Water Inlet Flow (digital) [GPM]	Pre-Heater Water Flow (analog) [GPM]	Post-Heater Water Flow (analog) [GPM]	Humidifier Air Inlet [SCFM]	Humidifier Air inlet [GPM]	Time	Notes
none	0.57	0.61	0.60	4.2	31.42	2:10 PM	maximum water flow
none	0.54	0.59	0.58	4.3	32.16	2:11 PM	
none	0.5	0.56	0.54	4.3	32.16	2:12 PM	
none	0.44	0.5	0.5	4.2	31.42	2:14 PM	
none	0.36	0.45	0.45	4.2	31.42	2:15 PM	inaccurate digital readings now
none	0.30	0.41	0.40	4.2	31.42	2:16 PM	inaccurate digital readings now
none	0.12	0.36	0.36	4.4	32.91	2:17 PM	inaccurate digital readings now
none	0	0.33	0.32	4.4	32.91	2:19 PM	refilled inlet bucket
none	0	0.30	0.29	4.4	32.91	2:20 PM	
none	0	0.29	0.27	4.4	32.91	2:22 PM	pump is very warm to the touch
none	0.50	0.57	0.55	4.4	32.91	2:37 PM	
none	0.38	0.48	0.47	4.3	32.16	2:39 PM	
none	0.30	0.42	0.41	4.3	32.16	2:40 PM	
none	0.12	0.39	0.37	4.4	32.91	2:40 PM	
none	0	0.34	0.33	4.4	32.91	2:41 PM	
none	0	0.28	0.26	4.3	32.16	2:42 PM	
none	0	0.25	0.24	4.3	32.16	2:43 PM	
none	0	0.23	0.21	4.4	32.91	2:44 PM	
none	0.44	0.51	0.50	4.4	32.91	2:45 PM	refilled inlet bucket
none	0.57	0.62	0.60	4.3	32.16	2:46 PM	maximum flow

Table A2. Temperature results of 150℉ setpoint (average humidifier inlet flow rate of 0.60 GPM) complete prototype tests

Water Heater Setting [℉]	Inlet Water Salinity [g/100 g]	Time Elapsed [min]	Pre-Heater Water Temp [℉]	Post-Heater Water Temp [℉]	Humidifier Inlet Air Temp [℉]	Post-Condenser Air Temp [℉]	Humidifier Outlet Air Temp [℉]
150	3.64	6	68.1	76.56	89.42	58.08	78.6
150	3.36	9	67.7	77.26	93.62	57.68	78.6
150	3.36	12	67.6	75.26	95.72	57.88	79.3
150	3.36	15	67.6	77.66	96.52	58.48	79.4
150	3.55	18	67.7	77.46	97.72	58.58	79.5
150	3.55	21	67.4	77.66	99.02	59.18	79.7
150	3.55	24	67.2	75.46	100.22	59.48	79.3
150	3.55	27	67.2	74.76	100.62	59.88	79.0
150	3.55	29	67.2	75.66	101.12	60.08	78.7

Table A3. Temperature results of 165℉ setpoint (average humidifier inlet flow rate of 0.60 GPM) complete prototype tests

Water Heater Setting [℉]	Inlet Water Salinity [g/100 g]	Time Elapsed [min]	Pre-Heater Water Temp [℉]	Post-Heater Water Temp [℉]	Humidifier Inlet Air Temp [℉]	Post-Condenser Air Temp [℉]	Humidifier Outlet Air Temp [℉]
165	3.45	3	72.22	81.26	86.42	56.08	86.7
165	3.55	6	71.72	82.86	92.02	55.58	87.8
165	3.55	9	71.52	83.36	94.72	55.78	88.3
165	3.55	12	71.22	83.56	96.32	56.28	88.7
165	3.36	15	69.92	83.36	97.92	56.68	88.5
165	3.55	18	69.92	82.86	99.02	56.78	87.9
165	3.55	21	69.52	83.06	100.62	57.18	87.9

Table A4. Temperature results of 180℉ setpoint (average humidifier inlet flow rate of 0.39 GPM) complete prototype tests

Water Heater Setting [℉]	Inlet Water Salinity [g/100 g]	Time Elapsed [min]	Pre-Heater Water Temp [℉]	Post-Heater Water Temp [℉]	Humidifier Inlet Air Temp [℉]	Post-Condenser Air Temp [℉]	Humidifier Outlet Air Temp [℉]
180	3.36	3	66.52	76.56	82.82	56.08	87.7
180	3.36	6	66.52	81.26	88.02	54.88	83.5
180	3.36	9	66.72	82.46	91.82	54.88	85.7
180	3.55	12	67.42	83.96	93.92	54.88	87.8
180	3.55	15	67.62	85.36	95.92	55.38	89.7
180	3.55	18	67.62	85.16	97.52	55.88	90.0
180	3.55	21	67.62	85.56	99.02	56.28	90.5
180	3.55	24	68.12	86.86	101.02	56.68	91.7
180	3.55	27	68.12	86.26	102.02	56.78	91.3
180	3.55	30	68.32	87.36	103.72	57.18	92.4

Table A5. Temperature results of 165℉ setpoint (average humidifier inlet flow rate of 0.37 GPM) complete prototype tests

Water Heater Setting [℉]	Inlet Water Salinity [g/100 g]	Time Elapsed [min]	Pre-Heater Water Temp [℉]	Post-Heater Water Temp [℉]	Humidifier Inlet Air Temp [℉]	Post-Condenser Air Temp [℉]	Humidifier Outlet Air Temp [℉]
165	3.09	3	73.02	88.76	91.42	58.08	92.4
165	3.09	6	72.82	90.26	97.92	58.58	94.6
165	3.09	9	73.02	89.86	100.62	59.48	95.2
165	3.36	12	76.22	91.46	102.42	60.28	96.5
165	3.36	15	76.72	93.86	104.02	60.98	99.0
165	3.36	18	76.42	93.46	106.02	62.08	99.5
165	3.36	21	76.42	94.36	107.82	63.08	100.2
165	3.36	24	77.62	98.16	108.72	64.38	102.8
165	3.36	27	76.42	96.36	109.12	65.28	102.2
165	3.27	30	78.42	93.66	109.22	65.68	99.7

Table A6. Temperature results of 150℉ setpoint long prototype test

Water Heater Setting [℉]	Inlet Water Salinity [g/100 g]	Time Elapsed [min]	Pre-Heater Water Temp [℉]	Post-Heater Water Temp [℉]	Humidifier Inlet Air Temp [℉]	Post-Condenser Air Temp [℉]	Humidifier Outlet Air Temp [℉]
180	3.09	4	66.7	80.36	87.62	58.5	85.7
180	3.09	8	65.8	99.96	94.32	64.0	111.9
165	3.09	12	65.8	103.06	99.02	78.4	115.7
150	3.09	16	65.9	106.76	102.92	85.8	123.0
150	3.09	20	65.9	104.06	107.32	91.0	117.1
150	3.27	24	65.9	104.66	110.32	90.7	119.0
150	3.27	28	65.8	105.56	113.42	91.4	118.5
150	3.27	32	66.1	107.86	115.52	88.9	118.8
150	3.27	36	65.9	107.66	117.02	90.1	117.7
150	3.27	40	66.3	107.86	118.82	85.6	-
150	3.27	44	66.3	108.96	118.82	82.4	-
150	3.27	48	66.5	107.66	119.72	82.4	-
150	3.27	52	66.3	108.26	119.92	83.8	-
150	3.27	56	66.5	107.36	120.62	82.4	-
150	3.27	60	66.5	108.26	120.92	79.0	-
150	3.27	64	71.0	107.66	104.22	73.0	-
150	3.27	68	66.3	105.56	118.12	80.2	-
150	3.55	72	67.7	102.86	111.92	77.2	-
150	3.55	76	65.9	96.56	118.42	76.3	-
150	3.55	80	65.9	95.06	119.12	76.1	-
150	3.55	84	65.9	95.66	115.52	75.0	-
150	3.55	88	65.9	96.16	118.12	76.3	-
150	3.55	92	65.9	97.06	118.62	76.1	-
150	3.55	96	66.1	97.66	118.82	69.3	-
150	3.55	100	66.3	97.76	118.22	65.7	-

Table A7. Desalination results of complete prototype tests at various water heater temperatures and flow rates (see Table 11 for long test results)

Water Heater Setting [℉]	Inlet Water Salinity [g/100g]	Inlet Water Flow Rate (post-heater) [GPM]	Collected Fresh Water Volume [mL]	Fresh Water Salinity [g/100g]
150	3.64	0.62	Not measurable	Not measurable
	3.36	0.62		
	3.36	0.62		
	3.36	0.62		
	3.55	0.62		
	3.55	0.62		
	3.55	0.62		
	3.55	0.62		
165 (high flow)	3.45	0.60	88 ± 5%	0.23
	3.55	0.60		
	3.55	0.60		
	3.55	0.60		
	3.36	0.60		
	3.55	0.59		
	3.55	0.59		
165 (low flow)	3.09	0.42	105± 5%	0.15
	3.09	0.42		
	3.09	0.43		
	3.36	0.42		
	3.36	0.42		
	3.36	0.42		
	3.36	0.42		
	3.36	0.2		
	3.36	0.27		
	3.27	0.3		
180	3.36	0.39	82± 5%	0.15
	3.36	0.40		
	3.36	0.40		
	3.55	0.40		
	3.55	0.40		
	3.55	0.39		
	3.55	0.39		
	3.55	0.39		
	3.55	0.38		
	3.55	0.37		

Table A8. Humidity results of 150℉ setpoint (average humidifier inlet flow rate of 0.60 GPM) complete prototype tests

Water Heater Setting [℉]	Time Elapsed [min]	Relative Humidity [%]	Humidifier Outlet Air Temp [℉]	Dew Pt Temp Humidifier Outlet Air [℉]	Wet Bulb Temp Humidifier Outlet Air [℉]
150	6	93.9	78.6	75.9	78.0
150	9	93.7	78.6	75.9	77.8
150	12	93.8	79.3	76.6	77.8
150	15	93.8	79.4	76.6	78.7
150	18	93.7	79.5	77.3	78.7
150	21	93.7	79.7	77.3	78.7
150	24	93.7	79.3	76.6	78.8
150	27	93.7	79.0	76.6	77.8
150	29	93.7	78.7	76.6	78.7

Table A9. Humidity results of 165℉ setpoint (average humidifier inlet flow rate of 0.60 GPM) complete prototype tests

Water Heater Setting [℉]	Time Elapsed [min]	Relative Humidity [%]	Humidifier Outlet Air Temp [℉]	Dew Pt Temp Humidifier Outlet Air [℉]	Wet Bulb Temp Humidifier Outlet Air [℉]
165	3	93.9	86.7	83.7	85.6
165	6	93.8	87.8	85.1	86.3
165	9	93.7	88.3	85.8	87.1
165	12	93.7	88.7	85.8	87.1
165	15	93.6	88.5	85.8	87.1
165	18	93.6	87.9	85.1	86.2
165	21	93.7	87.9	85.1	86.2

Table A10. Humidity results of 180℉ setpoint (average humidifier inlet flow rate of 0.39 GPM) complete prototype tests

Water Heater Setting [℉]	Time Elapsed [min]	Relative Humidity [%]	Humidifier Outlet Air Temp [℉]	Dew Pt Temp Humidifier Outlet Air [℉]	Wet Bulb Temp Humidifier Outlet Air [℉]
180	3	94.9	87.7	76.6	76.3
180	6	94.7	83.5	80.8	84
180	9	94.6	85.7	82.9	85.6
180	12	94.5	87.8	85.1	87.2
180	15	94.4	89.7	87.3	88.8
180	18	94.3	90.0	87.3	88.8
180	21	94.3	90.5	88.0	89.5
180	24	94.3	91.7	88.7	90.3
180	27	94.2	91.3	88.7	90.3
180	30	94.2	92.4	90.2	91.1

Table A11. Humidity results of 165℉ setpoint (average humidifier inlet flow rate of 0.37 GPM) complete prototype tests

Water Heater Setting [℉]	Time Elapsed [min]	Relative Humidity [%]	Humidifier Outlet Air Temp [℉]	Dew Pt Temp Humidifier Outlet Air [℉]	Wet Bulb Temp Humidifier Outlet Air [℉]
165	3	94.3	92.4	90.2	91.1
165	6	94.1	94.6	91.7	93.4
165	9	94.0	95.2	92.4	93.3
165	12	94.0	96.5	93.9	94.9
165	15	93.9	99.0	96.1	97.2
165	18	93.9	99.5	96.9	97.2
165	21	93.8	100.2	97.7	97.8
165	24	93.8	102.8	99.9	100.2
165	27	93.7	102.2	99.2	99.2
165	30	93.8	99.7	96.9	97.2

Table A12. Humidity results of 150℉ setpoint long prototype test

Water Heater Setting [℉]	Time Elapsed [min]	Relative Humidity [%]	Humidifier Outlet Air Temp [℉]	Dew Pt Temp Humidifier Outlet Air [℉]	Wet Bulb Temp Humidifier Outlet Air [℉]
180	4	94.6	85.7	84.4	87.2
180	8	89.3	111.9	107.7	109.4
165	12	88.5	115.7	110.1	109.8
150	16	87.4	123.0	118.2	118.4
150	20	75.1	117.1	106.9	109
150	24	88.2	119.0	112.5	116.2
150	28	92.6	118.5	114.9	117.3
150	32	76.6	118.8	108.5	108.4
150	36	26	117.7	65.7	78.5

E. Figures

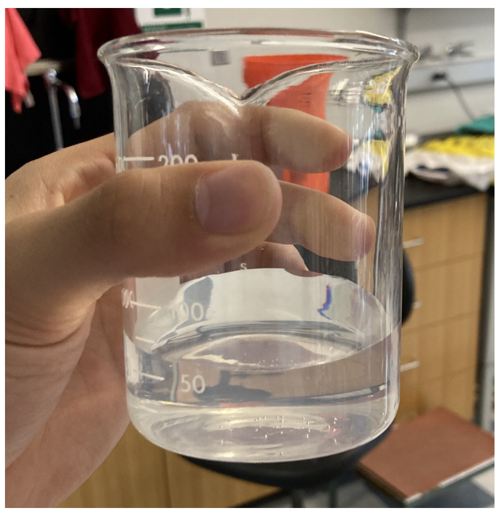

Figure A1. One of the water samples collected during testing–notice slight cloudiness

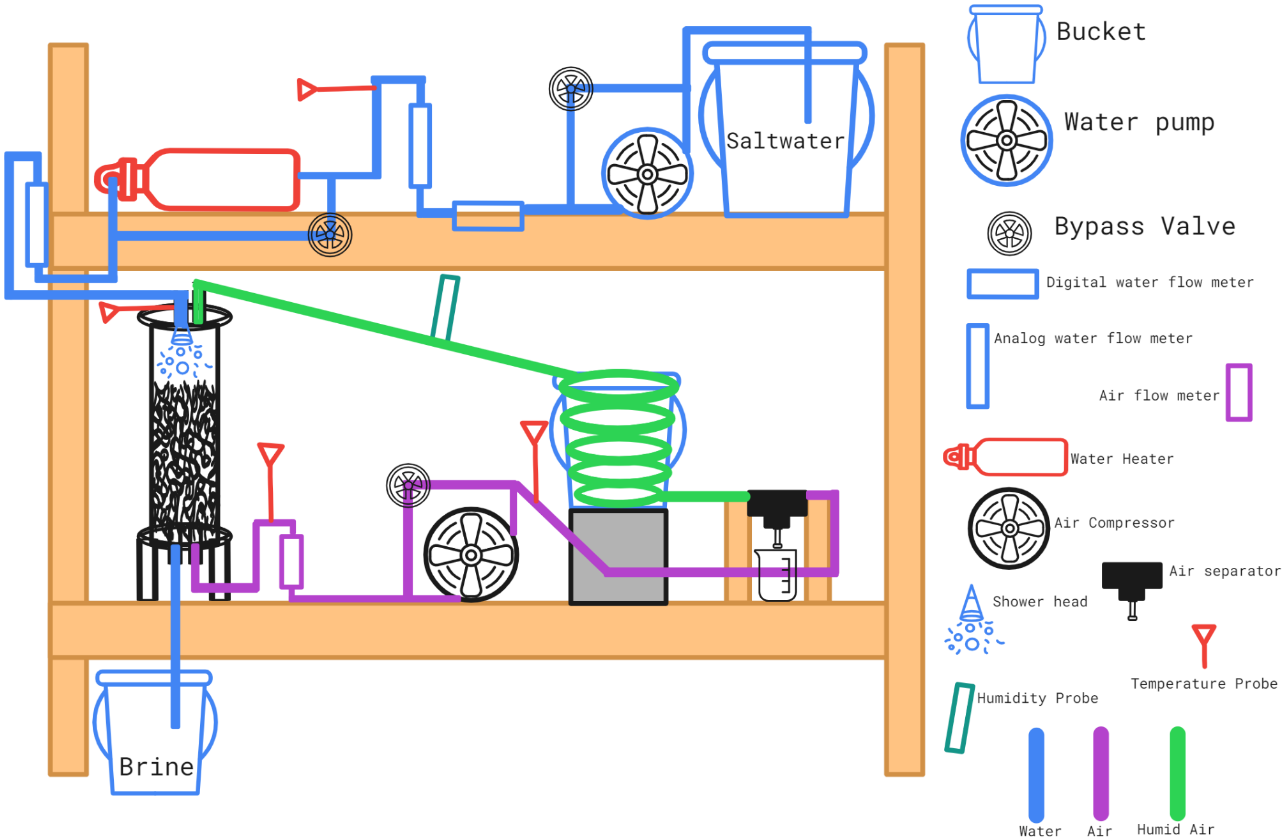

Figure A2. Prototype test set-up (use if system needs to be reassembled)

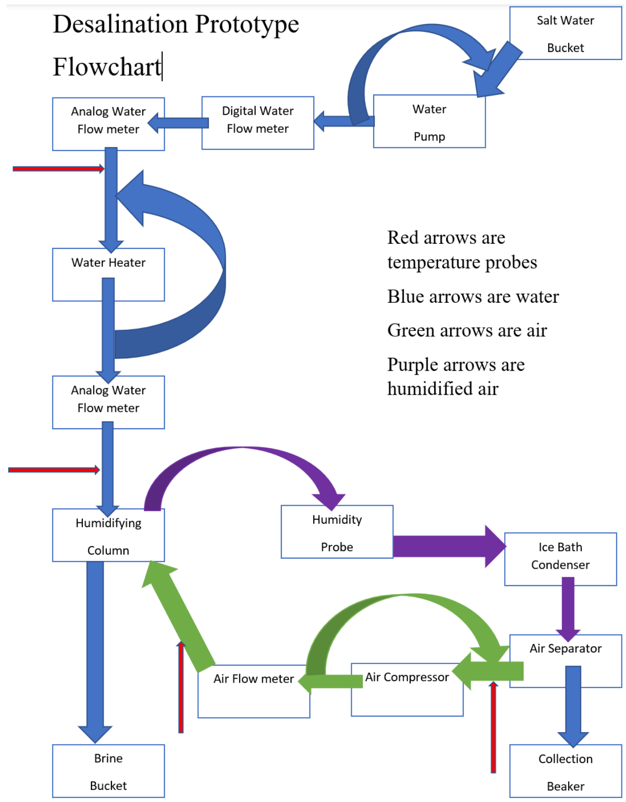

Figure A3. Prototype flowchart

Figure A4. Second iteration of packed bed humidifier

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