Design of a Mobile Community Level Water Treatment System Based on Humidification Dehumidification Desalination

by

Jeffrey H. Huang

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2012

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ABSTRACT

In order to successfully deploy the mobile desalination technology being developed at the Rohsenhow Kendall Heat Transfer Laboratories, it is necessary to design a three dimensional, solid model of the technology. This Humidification Dehumidification (HDH) based technology aims to be applied at community level water supplies, bringing clean water to those countries with inadequate water infrastructure. The mobility provided by the model would allow the HDH based desalination setup to be moved to other communities with a higher demand for clean water at a moment's notice. The model described herein describes a preliminary plan on how to organize the components of the desalination system. Two systems were created for this purpose, a single-dehumidifier system (SDS) and a multiple-dehumidifier system (MDS). These systems maximize on the amount of accessible space while minimizing on used material. While the SDS assembly may need rearrangement due to a federal width limitation preventing its deployment in the US, the MDS assembly is more promising. Nonetheless, the SDS assembly may still be deployed in areas such as India or Africa, where regulations are not as stringent.

Thesis Supervisor: John H. Lienhard V
Title: Samuel C. Collins Professor of Mechanical Engineering

Acknowledgements

The project contained in this thesis would not have been possible without the support of Prakash Govindan, my guide and mentor. Even when things seemed tough, he would always provide a positive outlook and helpful hints. Secondly, I would like to thank Mohamad Hussein Mirhi. Although the scaling experiments never got data, working with you to design the experimental setup was very fun I really got a good feel for what the RK culture is like. Finally, I would like to thank Professor Lienhard and all those in the Lienhard Research group for their support and advice with my project.

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Nomenclature

A	Cross-sectional Area [m^2]
D_{small}	Diameter of Smaller Cross Sectional Area [m]
D_{net}	Diameter of Net Flow [m]
v	Velocity [m/s]
ΔH_{actual}	Actual Enthalpy Change [J]
ΔH_{max}	Maximum Enthalpy Change [J]
ε	Effectiveness [-]
ρ	Density [kg/m^3]

Acronyms

HDH	Humidifier Dehumidifier
MDS	Multiple Dehumidifier System
SDS	Single Dehumidifier System

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Chapter 1

Introduction

1.1 Project Motivation

The availability of clean water is quickly diminishing as the world population grows larger and larger. Furthermore, people of developing and underdeveloped countries lack the necessary clean water to maintain even the most impoverished lifestyle. Desalination can provide an answer to this. By making use of brackish or seawater, desalination technologies can provide new sources of clean water.

The Lienhard research group is currently working on creating an HDH based desalination system. While this technology aims to be installed at a community level, giving the desalination system mobility can quicken and ease the implementation of the technology. Furthermore, system mobility can allow the technology to be moved to other locations when the demand for water is decreased for a specific region due to rainfall.

1.2 The Need for Desalination

Earth has a majority of its surface covered by water, yet of the water available, only 3% of that is fresh water. Of that 3 percent, only 0.3% is water that is available on the surface, in the form of lakes, swamps, and rivers [1]. This is demonstrated in Figure 1-1 below.

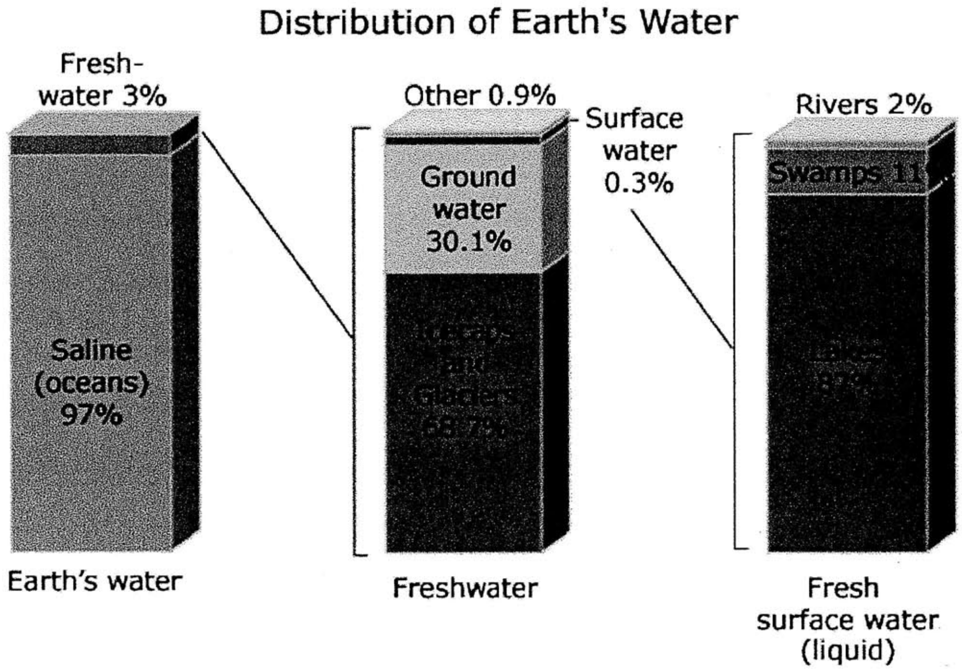

Figure 1- 1: Distribution of Earth's Water Sources [1]

As mankind continues on its path of technological innovation and developing countries begin to get more and more developed, we find ourselves consuming more and more water while our supplies quickly dwindle. As seen in Figure 1-2, developed countries consume more water per person than do countries that are not yet developed. Similarly, developing countries such as China and India consume more water than the under developed nations. In the future, the issue of a lack of fresh water will only be exacerbated with the expected development of the BRIC countries.

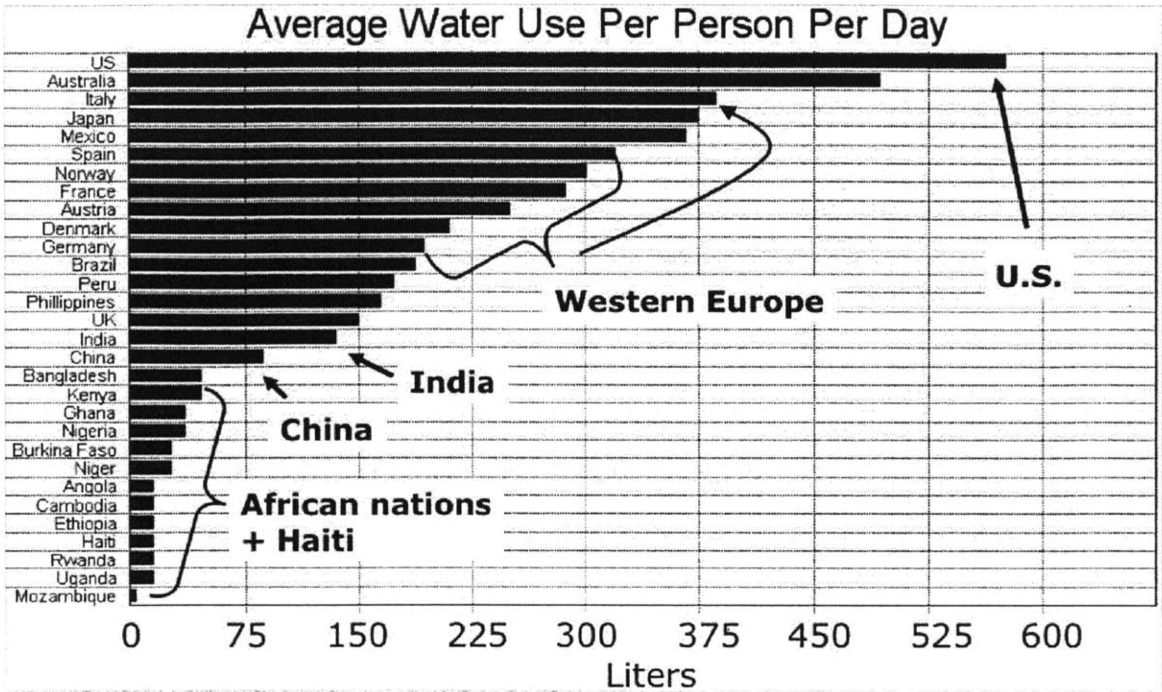

Figure 1- 2: Average water use per person per day by country [2]

Even now, though, water is scarce around the world. While some areas have a physically scarce water supply, other areas have an economically scarce water supply. The difference between these two terms is that physical water scarcity occurs when there is a lack of clean water in the area due to either its consumption or the pollution to it while economic scarcity occurs due to a lack of infrastructure to provide water to communities in need of them [3]. As seen in Figure 1-3, there are a large number of African countries with an economic scarcity while there are just as large a number of countries with physical scarcity.

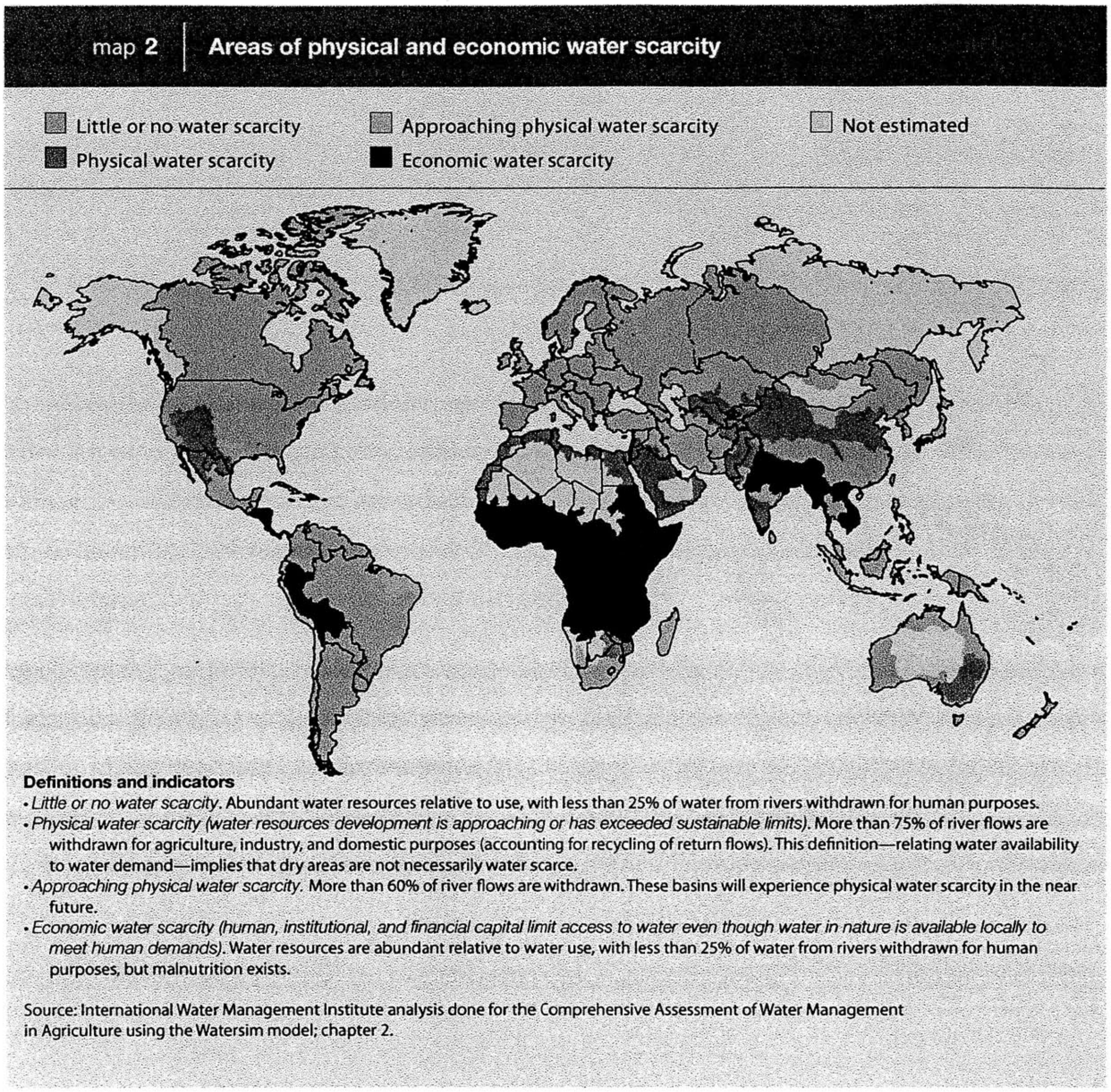

Figure 1- 3: Physical and Economic Water Scarcity Map [4]

With widespread water scarcity as an impetus, many have looked to the worlds' largest stores of water – the ocean. While naturally non-potable due to its high salinity, there is such a vast resource of water off any coast such that succeeding technologies could play a large difference in the available water resource. Purifying only 0.01% of the worlds' oceans would provide the entire US population with water for the next two millennia [1,2,5]. However, this is a lot easier said than done.

Currently, there are many processes available for water desalination. One of the main forms of desalination makes use of a semi-permeable membrane driven by a pressure difference. This is seen in reverse osmosis technologies. Another form of desalination is through a thermal distillation, such as Mutli-effect distillation (MED). This thesis focuses on a new form of carrier-gas based desalination (which is the subject of a lot of research at the Lienhard research lab at MIT), known as the Humidifier-Dehumidifier (HDH) desalination system.

1.3 The Focus on Community Level Water Supply (for the low income market)

When considering the chances of success of a desalination system in the low income communities and markets, there are a couple of key factors to take into account. As shown in Figure 1-3 below, the two factors that account for the success of a desalination technology, disregarding any socio-political factors, are the scalability and the implementability of the technology.

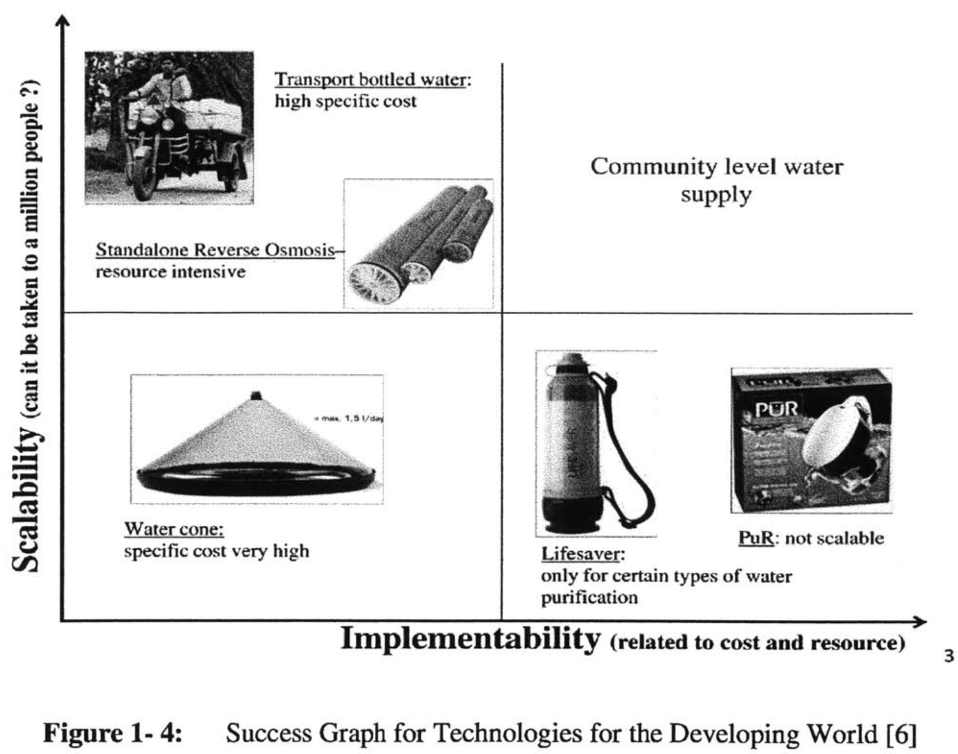

Figure 1- 4: Success Graph for Technologies for the Developing World [6]

Technological scalability refers to ability of a technology to continue working at the same level of efficiency and reliability, even if the technology is expected to accommodate for a larger group of people. While certain technologies may seem promising in the laboratory or in a single family household, it may not be so effective when it is repurposed to support a city of 60,000 people. The Lifesaver and PuR technologies are such examples, which can hardly provide for 10 people, let alone a city's worth.

Technological implementability refers to the cost of the technology in terms of either capital or resource. Technologies with poor implementability, therefore are highly expensive or resource intensive. This high capital cost or the high resource intensity of the technology really prevents it from adoption into a community. Under developed countries, for example, would not be able to afford technologies that have such a high cost and resource.

If a desalination technology can be made with relatively good implementability, with low costs and resource intensity, and it can scale well to larger populations, the technology would be most likely to succeed. As such, the Lienhard Research group has looked toward technologies affecting community level water supplies. Any cost and resource effective technology that can apply to the community based water supply would be highly successful.

1.4 The Market for Community Level Water Supply

Due to the water scarcity situation in Figure 1-3, there is a large market for water in places with economic scarcity as well as in places with physical scarcity. We can get a basic idea of how well this HDH technology will fare in the underdeveloped countries by looking at the potential customers.

The target customer for the HDH-based desalination is among the lower income people of under developed countries. Places in poverty tend to have higher costs of water. The cost of fresh water in the slums of Dharavi, in Mumbai, for example, exceeds the cost of water in Warden Road, home to Mumbai's affluent class by 37 times. Figure 1-5 below indicates that there is a large market potential within the lower classes for clean water.

Cost	Dharavi	Warden Road	Poverty premium
Credit (annual interest)	600 percent-1,000 percent	12 percent-18 percent	53X
municipal-grade water (per cubic meter)	$1.12	$0.03	>37X
phone call (per minute)	$0.04-$0.05	$0.025	1.8X

Ref: CK Prahlad & Al Hammond, HBR

Figure 1- 5: The poverty premiums for water, among other things [7]

When taken into context around the world, this is still true. According to Hammond et al. in "The Next 4 Billion: Market Size and Business Strategy at the Base of the Pyramid", there is a $20.1 billion dollar market for water among the lower classes of the underdeveloped countries [8]. As shown in Figure 1-6, this is spread out rather evenly through Africa, Asia, Eastern Europe, and Latin America, with a heavier emphasis on the underdeveloped Asian countries.

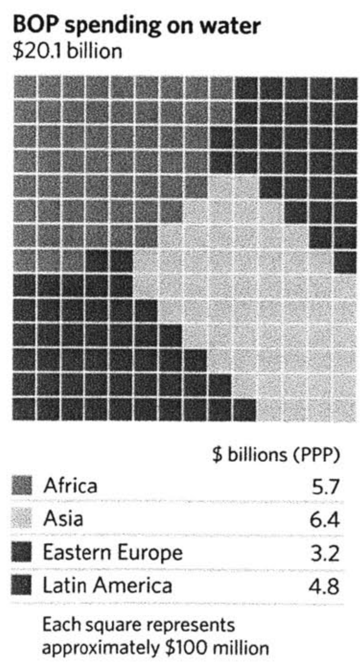

Figure 1- 6: The Market for Water in Base of Economic Pyramid Populations [7]

Within these countries, there is a bottom heavy spending pattern, which concerns those families living on an income of $1500 US dollars equivalent or less a year. To provide an example of the bottom heaviness of spending, India's spending pattern for those with income less than $3000 US equivalent is reproduced below in Figure 1-7. In the figure, BOP means "Bottom of Pyramid," referring to those at the bottom of the economic pyramid. The number following this term is the annual income of that group. The spending patterns for other underdeveloped nations can be found in Hammond's paper [8].

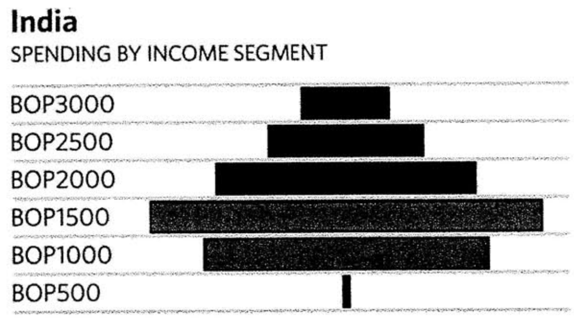

Figure 1- 7: India's Spending Pattern [8]

1.5 Conventional Desalination Technologies

Many forms of desalination have or are already currently under research. These forms generally fall within three categories. These are thermal distillation, membrane filtration, and chemical interaction. The first of these requires the use of a heat source to heat the water and cause it to change into a vapor phase, at which point the water can distill from the originally brackish or otherwise non-potable solution. In membrane filtration, pumps are used to create a driving pressure to ensure a constant one-way flow of a solution across a membrane. Chemical approaches are more varied, including such approaches as ion exchange and liquid-liquid extraction [2].

Unfortunately, one problem with these technologies is that they are generally large in size. As a result, they are typically placed near large urban areas and lack mobility. Downsizing the technology for use in smaller villages is difficult because there is a lower limit for the technology to be economically and technically feasible. The alternative, transporting water from the urban center to a less centralized village, can be also very costly. More often than not, the smaller, more isolated villages have a greater need for clean water due to a lack of infrastructure.

Another issue with current technologies is that they often require a large amount of energy to function. A majority of those which do are fossil-fuel driven, contributing negatively to the environment. These technologies, by virtue of being fossil-fuel driven, will have a dependency on fossil fuels, and may have prices that follow the price volatility of the corresponding fossil fuels [2].

Chapter 2

HDH Background

2.1 System Overview

In general, the HDH system can be classified as a thermal desalination technology. Like other thermal distillation technologies, it evaporates the liquid and then condenses it out. It also requires the use of a heater to bring the brackish or sea water at a temperature high enough such that the water can vaporize in the presence of a large percentage of air (at a low partial pressure for the water vapor).

The typical HDH system can be seen in Figure 2-1. Sea water enters from a source at the bottom entrance to the dehumidifier. As it travels up the dehumidifier, it cools the humidified carrier gas. The sea water is heated up to a point to a sufficiently warm temperature before it is sprayed out of a nozzle in the humidifier. As the heated seawater falls to gravity, it encounters the packing material in the humidifier and slides down across the packing material. A carrier gas flows in beneath the humidifier and runs up along the packing material as well. As the carrier gas and seawater slide along the packing material, the liquid from the seawater is picked up by the carrier gas, leaving a more saline solution than before. The carrier gas continues rising up and out of the humidifier. This carrier gas, by this point, has become fully humidified. As it rises, it is forced into the dehumidifier. While in the dehumidifier, the carrier gas encounters the piping from the cool seawater rushing into the dehumidifier. The humidified carrier gas condenses around the piping and slowly, pure water forms. This water is captured at the bottom of the dehumidifier.

The remaining brine solution and the air can both be recirculated. In the case of the brine, it can only be recirculated until a certain point when the salinity of the water is too high. If so, there is a sensor installed at the exit of the brine solution to determine the salinity of the water. If the water is too salinated, it must be discarded.

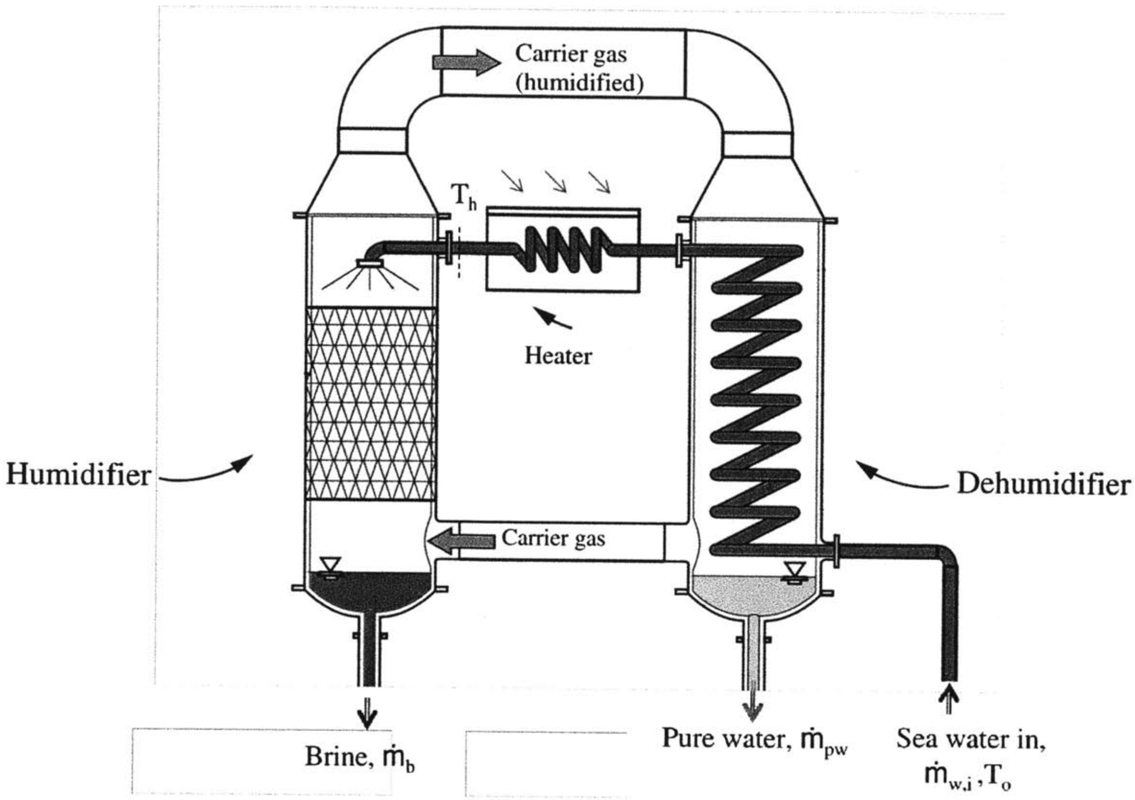

Figure 2- 1: HDH System [6]

In this thesis, two versions of the HDH based dehumidification system are modeled on top of a trailer base. The difference between the two versions is the number of dehumidifiers. The first version, referred to as the Single Dehumidifier System (SDS), has one dehumidifier connected to five humidifiers. The outputs of brine and humid air of the humidifiers are connected together to provide one flow of water and air into the lone dehumidifier. Similarly, the inputs of saline water and dry carrier gas are split between the humidifiers.

The second version, the Multiple Dehumidifier System (MDS), has equal number of dehumidifiers to humidifiers. Humid air from the humidifiers goes directly into the corresponding dehumidifier. The brine that leaves the humidifier and the saline water that enters the dehumidifier come together before being checked for oversalination or before being heated. Likewise the carrier gas that is input into the humidifier is supplied by one blower. As a result, it must be split before reaching the humidifiers. The dehumidified air, though, which can be very humid, is not returned to the blower, creating an open air system. Rather, it is thrown into the atmosphere.

To power both the SDS and MDS assemblies, diesel will be used as the major source of power. One part that will use this diesel is the heater, which will heat the water leaving the dehumidifier(s) before entering the humidifiers. This heating will come directly from burning diesel. The other parts that require power will require electricity, which arise from the pumps, the blower, and the detection gauges for the oversalinated water. This will be provided by electricity coming from a diesel generator. However, these aspects are not modeled in this thesis because this thesis focuses on the placement and organization of the two systems. It is also noted that the system can be alternatively run using solar power or some form of waste heat.

2.2 Humidifier

A humidifier is the device in the system where the vapor from the saline water is evaporated into the air stream. This is also known as a cooling tower, which is a heat rejection device. In a cooling tower, there is a packed bed which is called "fill." This fill consists of a large number of slanted wetted surfaces on which water will spread thinly on [9]. This packed bed in the humidifier is there to increase the amount of water that air entering the system will hold. When a carrier gas that has not yet reached saturation is brought into contact with water, water will be diffused into the gas until saturation is reached. There are many ways to do this, including using spray towers, bubble columns, wetted wall columns, and packed bed towers [10].

The method being implemented in the HDH system is the spray tower. In it, a water stream is cooled by a moving air stream. The heat from the liquid warms up the air. As it warms, the air's relative humidity rises and so the air picks up moisture from the warm liquid. In the humidifier, preheated saline water enters from another component and is sprayed into the humidifier through a nozzle. The nozzle evenly disperses water onto a cross-sectional projection 12 inches below the nozzle height, called the rain zone. This even distribution ensures that the water runs evenly down the packing material.

Below the nozzle is packing material. Here the material provides a counter-flow method for cooling the warm water. Water rushes down the material as a cooler carrier gas flows up the packing material. However, the water rushing down the packing material cannot transfer all of its heat to the carrier gas by the time it reaches the bottom. In order to increase this cooling rate, the physical design and shape of the packing must maximize the surface area on which water and carrier gas may interact. In comparison to six other geometric organizations, a mixed fluted plates with a corrugated pattern ('g' of Figure 2-2) should be use in order to maximize pressure losses and heat transfer. This maximizes on the highest volumetric heat transfer coefficient [11].

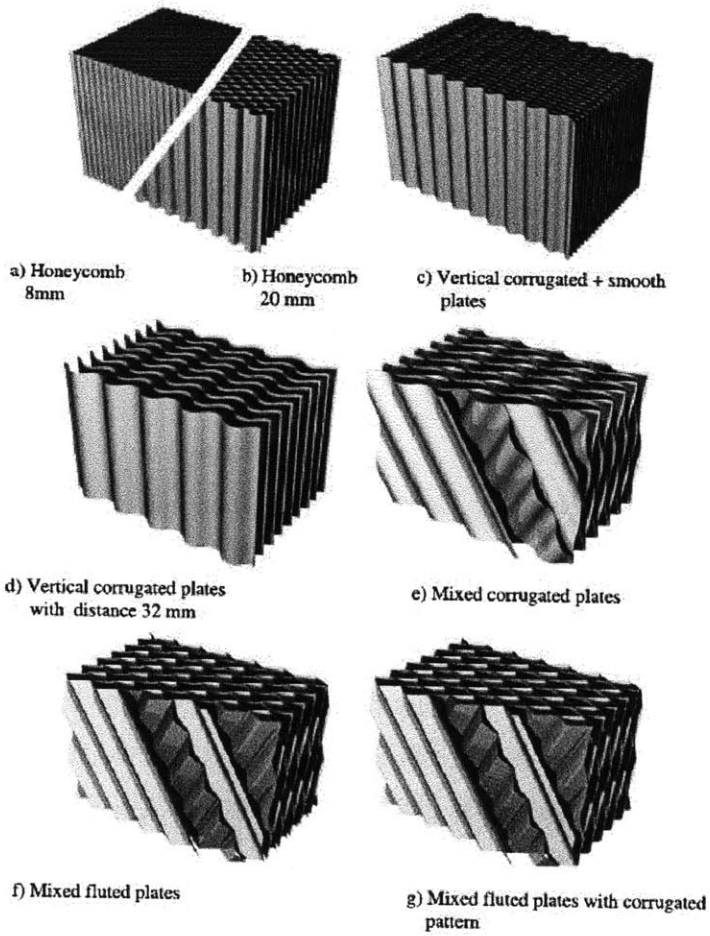

Figure 2- 2: Filling Geometries [11]

In addition to packing geometry, the material that maximizes economically feasibility with effectiveness of heat transfer is also important. This experiment was performed in Liburd et al, which determined that the best performing materials between locally available materials in Haiti and various other economically feasible materials was PVC CF-1200 Brentwood film packing [2]. Because of the simplicity in drafting up a solid model, the packing material that was selected for design was polyvinyl chloride (PVC) CF-1200 Brentwood film packing, as shown in Figure 2-3.

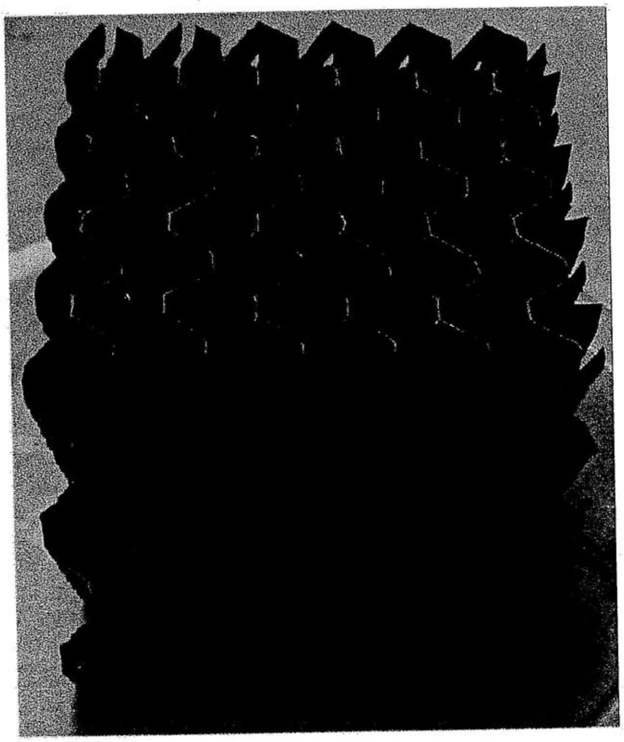

Figure 2- 3: PVC CF-1200 Packing [2]

Beneath the packing section, a basin is necessary to contain the falling brine. This is particularly important to prevent any brine from entering the blower piping or the blower. This basin needs to easily catch the water that is falling from the packing section and safely divert it away to be either removed from the system or recirculated.

2.3 Dehumidifier

The humid carrier gas that leaves the humidifier enters the dehumidifier to be cooled down. Unlike Figure 2-1, however, the dehumidifier being designed in the Lienhard Research groups makes use of a bubble column dehumidifier (Figure 2-4) [12]. Using the bubble column dehumidifier, warm, humid carrier gas can be directly injected into a pool of water to be cooled down. Inside the pool of water is also a cooling coil through which the brackish or saline water is run through. This helps to cool down both the liquid and the carrier gas while slightly preheating the saline water before it reaches the heater. As the carrier gas' temperature falls, its specific humidity also falls. This releases moisture that was carried to the dehumidifier by the carrier gas.

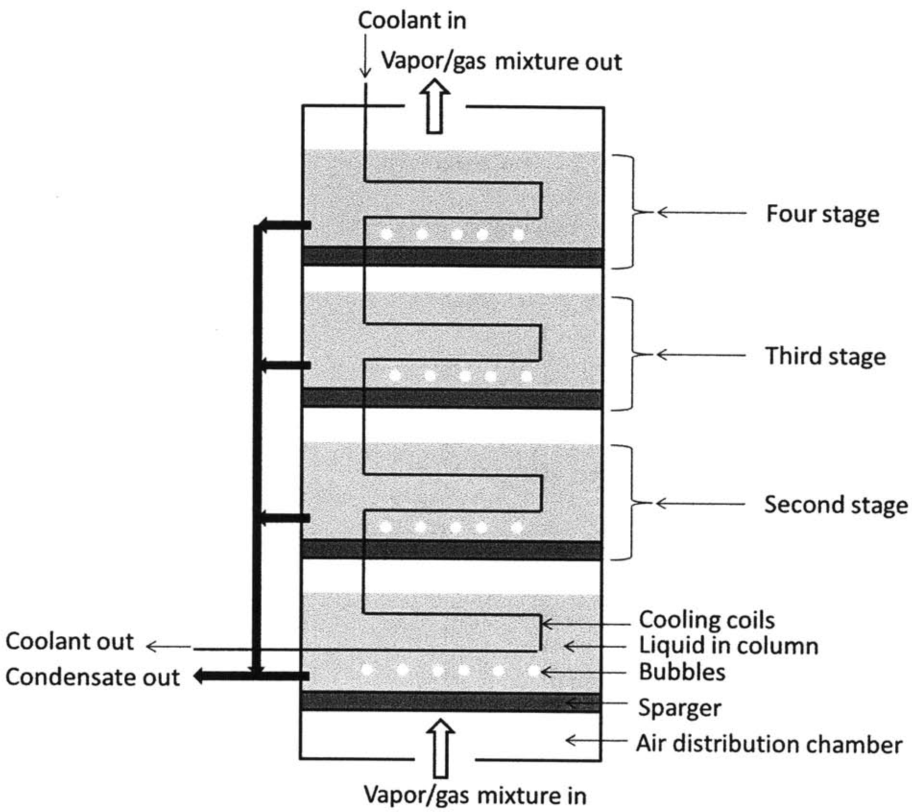

Figure 2- 4: Bubble Column Dehumidifier [6]

As seen in Figure 2-4, the bubble column dehumidifier is a four stage dehumidifier. Each stage is separated by a bubble column. Due to the small diameters of the bubbles and the velocity of the air rushing through, water does not seep down through the column. The implementation of the four stages allows for the full extraction of water from the carrier gas. As the Figure 2-5 shows, the more stages a dehumidifier has, the better its effectiveness for extraction will be. Here, effectiveness is defined in Equation 1 below:

$$\epsilon = \frac{\Delta\dot{H}_{actual}}{\Delta\dot{H}_{max}} \tag{1}$$

With a higher effectiveness, more heat will be extracted from the air [6].

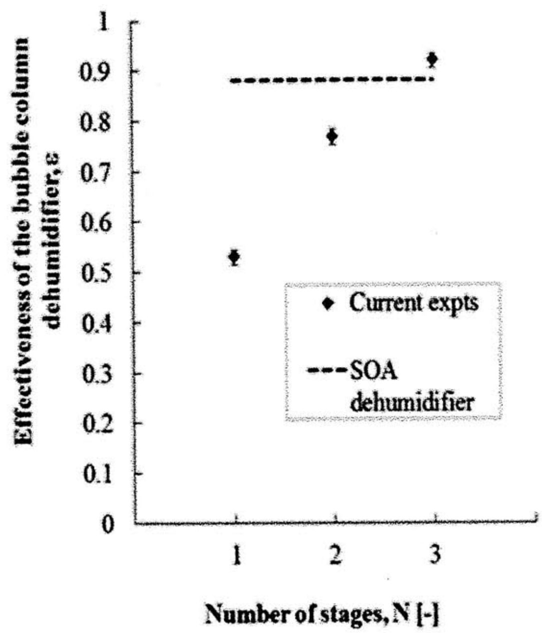

Figure 2- 5: Effectiveness of Bubble Column Dehumidifier vs Stages [6]

2.4 Connections and Other Parts

The saline water and carrier gas inlet and outlets of both the dehumidifier and humidifier are connected by tubing and ducts. The tubing needs to be flexible and must have a small diameter. The flexibility of the tube will allow it to fit into cramped spaces and allow it to bend to the form of the humidifier and dehumidifier. Furthermore, using flexible tubing in place of hard elbows prevents the forces that arise at elbows when the water in the system is emptied. The smaller diameter reduces not only the space that the tubing will take up, but also the surface area on which the heated liquid can lose heat from. However, the limit on the tubing size is based on the expected flow rate of the saline water that travels through the tubing. This flow rate must be 10 cubic meters per day.

The carrier gas ducts must also be flexible. This flexibility of the ducting does not only help to minimize the space taken but allow for easy displacement should the ducting need to be temporarily moved.

Chapter 3

Component Modeling in SolidWorks

3.1 Size Constraints

The HDH system is to be placed on a trailer for ease of mobility between periods of operation. As such, the humidifier and dehumidifier must fit within the confines of the trailer. Using an open trailer system, where the trailer is open to the atmosphere, the height of the humidifier and dehumidifier were not taken into account. Thus, the only limitations are the requirements based on the net volume flow rate for the different components and the maximum size of the trailer. Based on a preliminary investigation, the average width of various trailers was found to be on the order of 10 feet and the average maximum length of various trailers was found to be on the order of 40 feet. These accuracy estimations are discussed further in Chapter 4.2. Nonetheless, the below was designed with these trailer dimensions in mind.

3.2 Humidifier

Figure 3-1 shows the solid model of the Humidifier that the Lienhard Research group intends to implement in their desalination technology. The humidifier spans a height of 13 feet and 9.5 inches. The inner cylindrical tower has a diameter of 3 feet, with a thickness of 1 inch. The cylindrical shell is separated at various parts with a flat surface. These mid-sections are 1 inch thick and are equally thick throughout the model.

At the top of the humidifier is a 1.5 inch diameter hole attached to which is the saline water inlet. This is attached to a nozzle which sprays out the water evenly into the space below. 1 foot below the bottom of the nozzle lays the packing material. The packing material is split into two parts, each a height of 4 feet. They are separated by a foot. This space is left out in order to give the option of extraction air from the humidifier to incorporate thermodynamic balancing [13]. Beneath the packing material lays the basin for the unevaporated brine water.

This brine water drains into tubing that has an inner diameter of 0.9 inches and this water is drained out the bottom of the humidifier. The basin itself has a slightly larger diameter than the cylindrical tower, of 3 feet and 4 inches. As a result, this puts the basin outer shell at 3 feet 8 inches. The whole assembly is mounted on threaded screws, one inch in diameter. These threaded screws keep the humidifier stable by mimicking a tripod. If four threaded rods were used instead, a slight variation in one of the lengths would cause the system to rest solely on two points, the tallest and the smallest threaded rods. Because three points define a plane, using three threaded rods instead of two would provide much better stability. In addition to this though, there are mounting boards to provide extra stability.

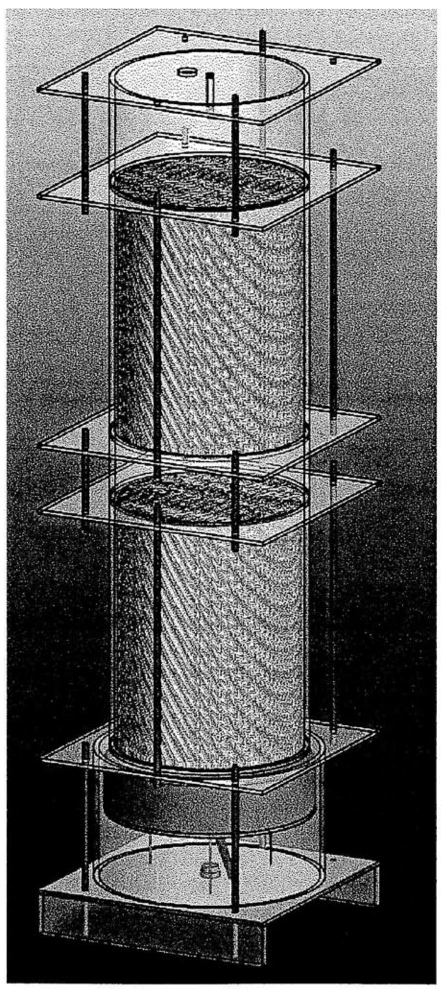

Figure 3- 1: Humidifier Assembly for both SDS and MDS

3.2.1 Packing Design

The packing in the humidifier spans four feet in height and is cut to fit inside the humidifier assembly. The material used for this, as described in Chapter 2, was based on PE CF-1200. However, for higher temperatures, PP CF-1200 was used because of its better resistance to heat. Figure 3-2 shows an extra layer of material that encases the packing material. This material was used solely for the purpose of creating the necessary mates to keep the packing in its place. However, in reality, this should not be included. The extra material would, in a sense, eliminate packing space as it eliminates a rather significant portion of the surface area on which the saline water and carrier gas can interact. Figure 3-3 shows a single sheet of the packing material, which is the building block for the packing in Figure 3-2.

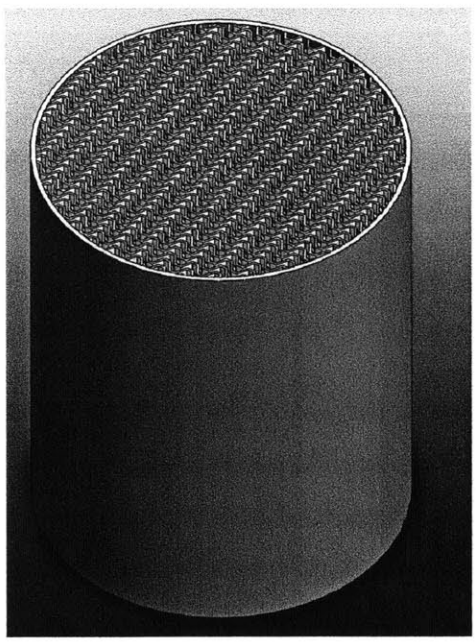

Figure 3- 2: Packing Assembly

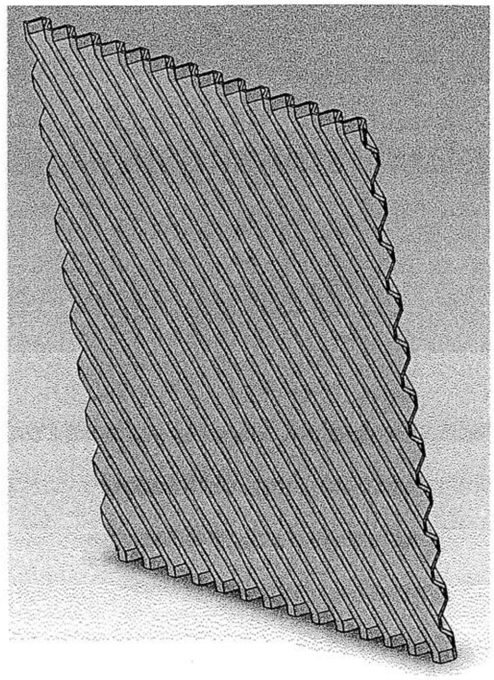

Figure 3- 3: Single Sheet of Packing Material

3.2.2 Basin Assembly

The basin assembly has a slightly larger diameter than the diameter of the cylindrical shell of the tower in order to ensure the full catching of the dropping water exiting the packing section. In the model of the basin assembly (Figure 3-4), the outer rim is made of copper. This is attached to a piece of CPVC through which is drilled a hole for flexible water tubing. This water drains through the bottom surface, out of the humidifier, and back to the produced water tanks before it is recirculated back into the HDH system. Brine recirculation is important for HDH systems to attain a high recovery.

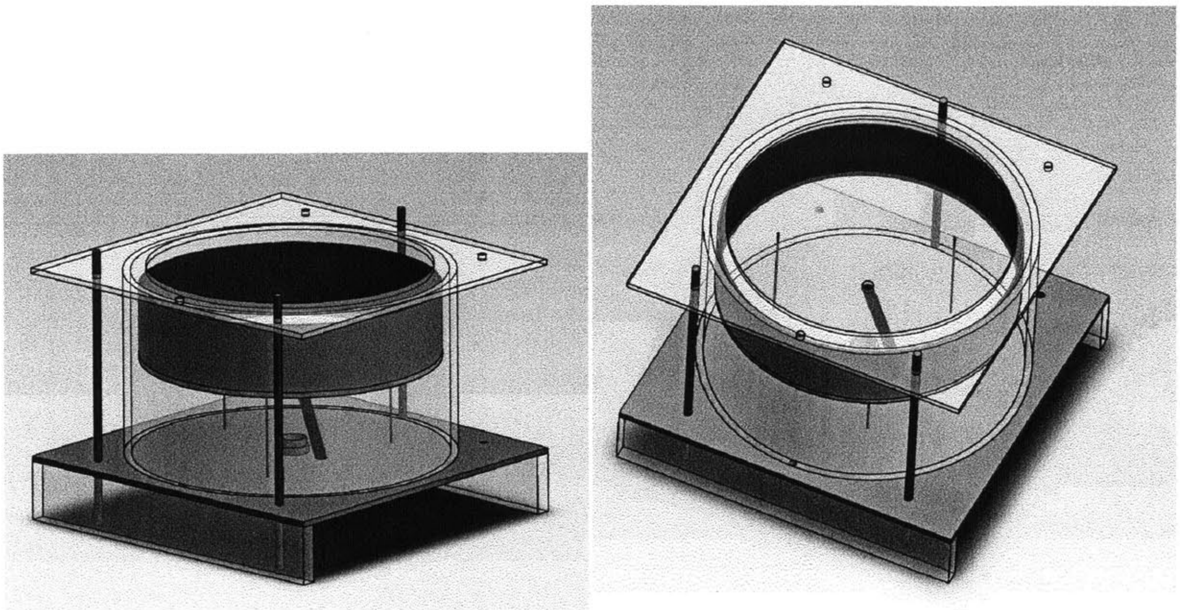

Figure 3- 4: Basin Assembly and Humidifier Bottom

3.3 Dehumidifier

3.3.2 MDS Bubble Column Dehumidifier

The bubble column dehumidifier assembly (Figure 3-5), is the MDS' four stage dehumidifier. Each stage is separated with a 4 inch piece of CPVC. At the top of the dehumidifier is a 3 inch hole to allow for the escape of dehumidified air back into the atmosphere. Alternatively, in a closed air system, this can also be recycled.

At each stage, a hole is drilled through the cylindrical shell allowing for the passage of the cooling loop. These holes are 1 inch thick and should be just enough to support the cooling loop's exit. Because the cooling loop is under water, special attention should be paid to this section when creating a water tight seal.

At the bottom of the dehumidifier, a hole is drilled to provide an entrance hole for the moist air to enter from the humidification tower. The hole is designed at 3 inches such that a constant velocity is maintained as the carrier gas enters the dehumidifier. If the diameter of the hole is a different size, the gas will lose less kinetic energy as it travels around the bend.

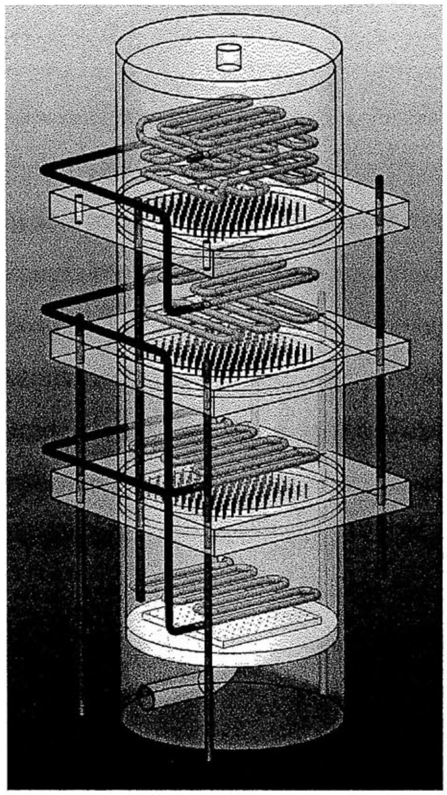

Figure 3- 5: MDS – Bubble Column Dehumidifier

The CPVC sparger plate (Figure 3-6) has a cylindrical bore 3 feet in diameter and 1 inch deep, so that the cylindrical shell for that stage can be deep set into the CPVC piece and so a better watertight seal can be made with good stability. This deep set hole is cut into both sides of the CPVC stage separator. On the stage separator are drilled a set of 1/16 inch holes going through the piece, acting as bubble columns. These holes allow for air passage between stages.

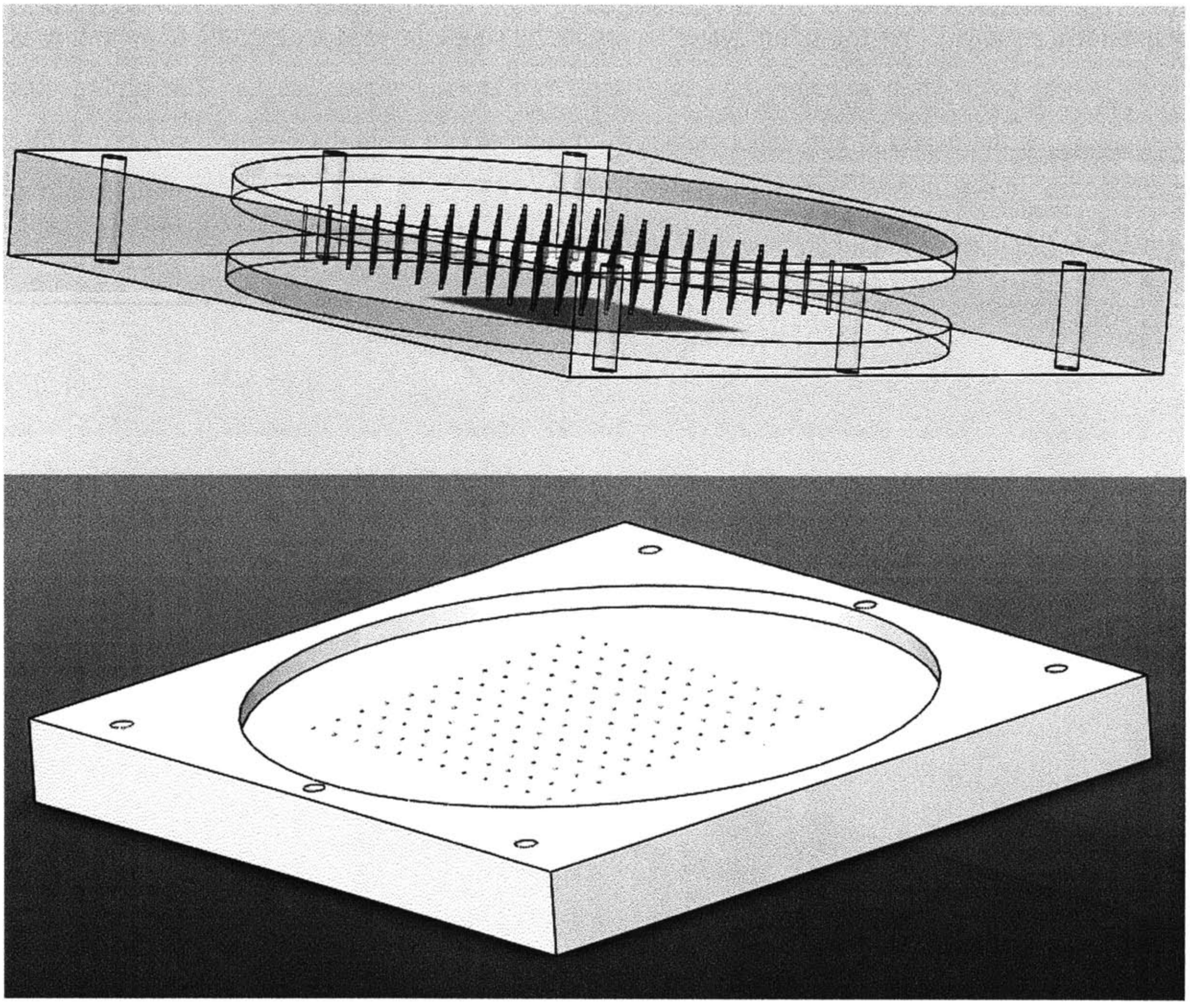

Figure 3- 6: MDS Sparger Plate

At each stage is also a cooling loop of a copper alloy known as copper nickel. This material was chosen because of its natural resistance to seawater corrosion and as a result, its common adoption in seawater piping systems [14]. Additionally, using a metal rather than a plastic was particularly useful because the bubble column itself has a very low resistance to heat transfer and it is not desirable to increase it. The cooling loops, summed over the four stages, have a net surface area 22.11 square feet. The cooling loops are, however, staggered in surface area as one goes down the dehumidifier. The upper most piping is the four-layered piping with a surface area of 10.1 square feet. The piping second stage from the top is a two-layered piping with a surface area of 5.6 square feet. The bottom two stages have a single-layered piping each with a surface area of 3.3 square feet. This staggering allows for a higher energy effectiveness in dehumidification [6]. As the saline water enters in the single-layered piping, the temperature is much cooler than when it enters and two- and four-layered piping stages. The piping was designed such that water would enter from one corner and exit from the opposite corner. While the stability of this is untested, the separation to the corners, at least, should provide minimal movement in the upward and downward directions.

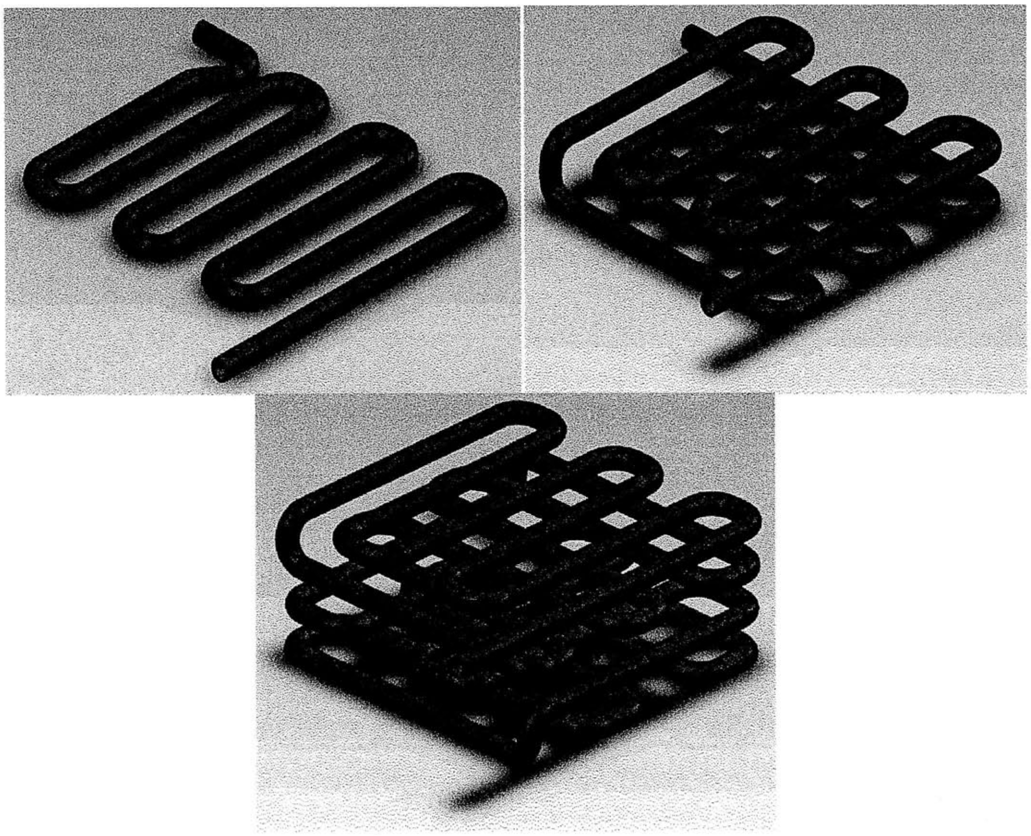

Figure 3- 7: Copper Nickel Alloy Dehumidifier Tubing for MDS

3.3.2 SDS Bubble Column Dehumidifier

Figure 3-8 shows the bubble column dehumidifier for the SDS. This dehumidifier spans a height of 8 feet, 10.75 inches and is 6 feet in length and width. The dehumidifier tower shell is larger in diameter when compared to the MDS dehumidifier, measuring at 5 feet, with a wall thickness of 1 inch. Because the SDS uses only one dehumidifier whereas the MDS uses five, the carrier gas and saline water tubing holes for the SDS version must be the constructed to handle the net flow of the five MDS humidifiers. For the water, the pipes are sized at 2 inches inner diameter with a thickness of 0.25". This was calculated using a conservation of mass (Equation 2), with given desired velocities.

$$\rho A_{MDS} v_{MDS} = \rho A_{SDS} v_{SDS} \tag{2}$$

The entrance and exit holes for the carrier gas are sized at 4" inner diameter with a thickness of 0.25" as well. The bubble column diameter does not change from the MDS version to the SDS version since bubble fluid dynamics still govern in the same way. The net surface area of the water piping within the dehumidifier is 110.6 square feet. This is approximately equal to the net surface area across the five MDS dehumidifiers.

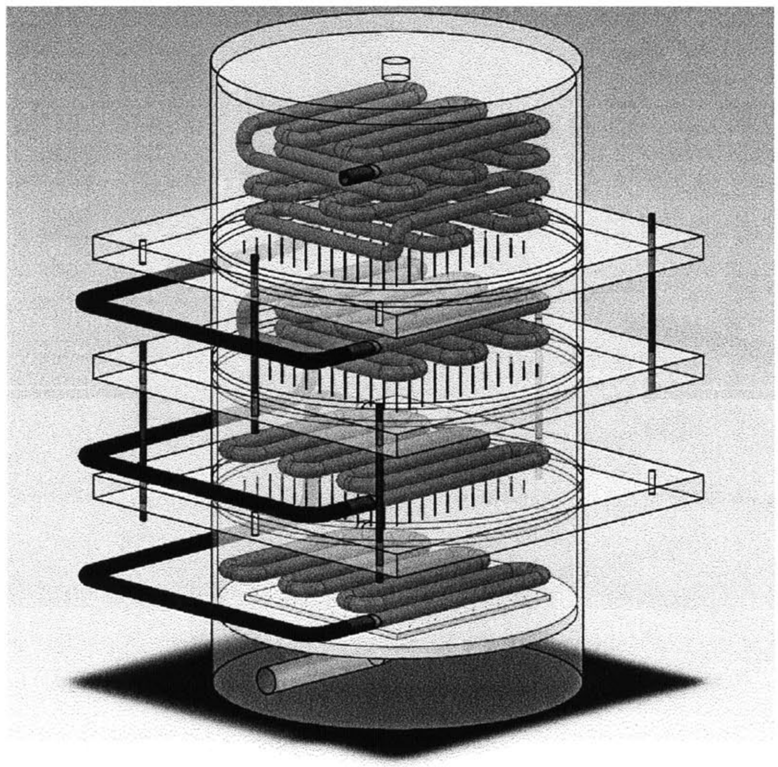

Figure 3- 8: SDS – Bubble Column Dehumidifier

Because of the larger diameter of the cylindrical shell of the SDS Dehumidifier, the corresponding CPVC sparger plates are also larger. Those shown in Figure 3-9 measure 6 feet in length and 6 feet in width. The thickness of the separation is 4 inches. Similar to the MSD sparger plate, the SDS sparger plate has a one inch bore on both surfaces to provide added stability and sealing capabilities. Into the separation, there are drilled a series of 1 inch holes to allow the threaded screws to pass through. There are also small, 1/8" holes drilled into the CPVC piece, to provide the bubble between the stages.

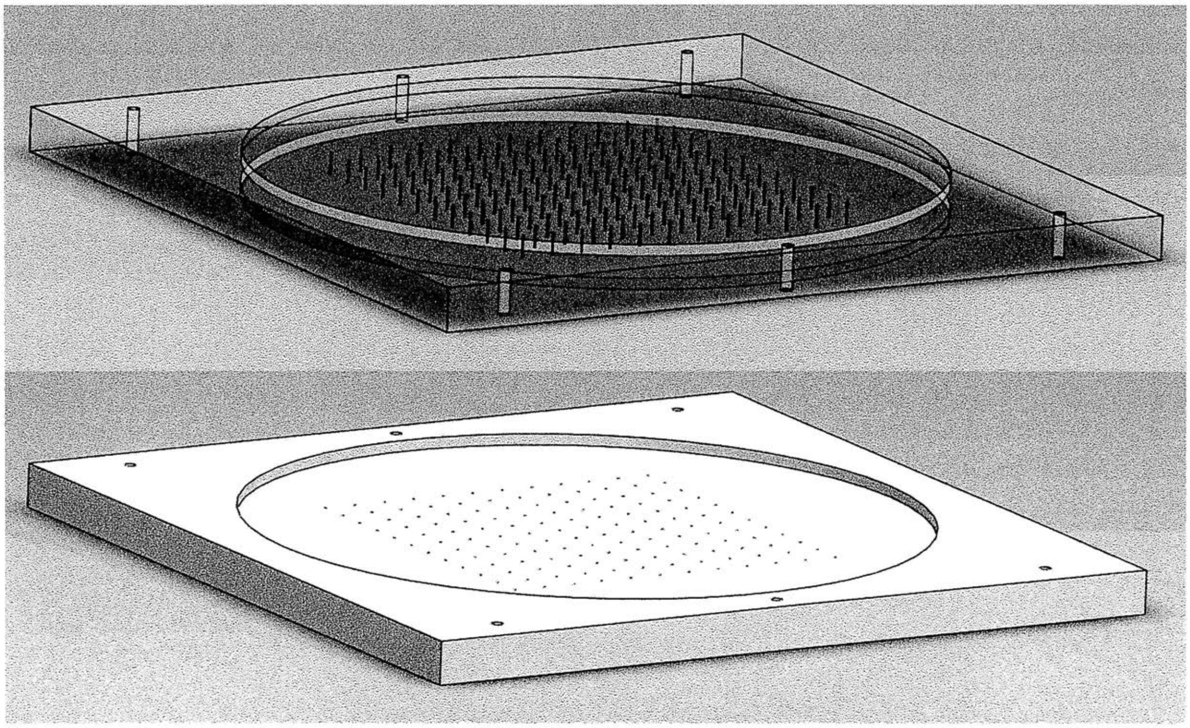

Figure 3- 9: SDS Sparger Plate

The water tubing for the SDS dehumidifier is very similar to those of the MDS dehumidifier. The only difference between the two is the increase in the diameter. As is the case for the MDS, the SDS stages have a staggered number of layers for piping. The top stage of the dehumidifier has a 4-layer piping. The second from the top has a 2-layer piping. The bottom layer has single layer piping. The tube material is the same as the MDS assembly, making use of the Copper Nickel alloy.

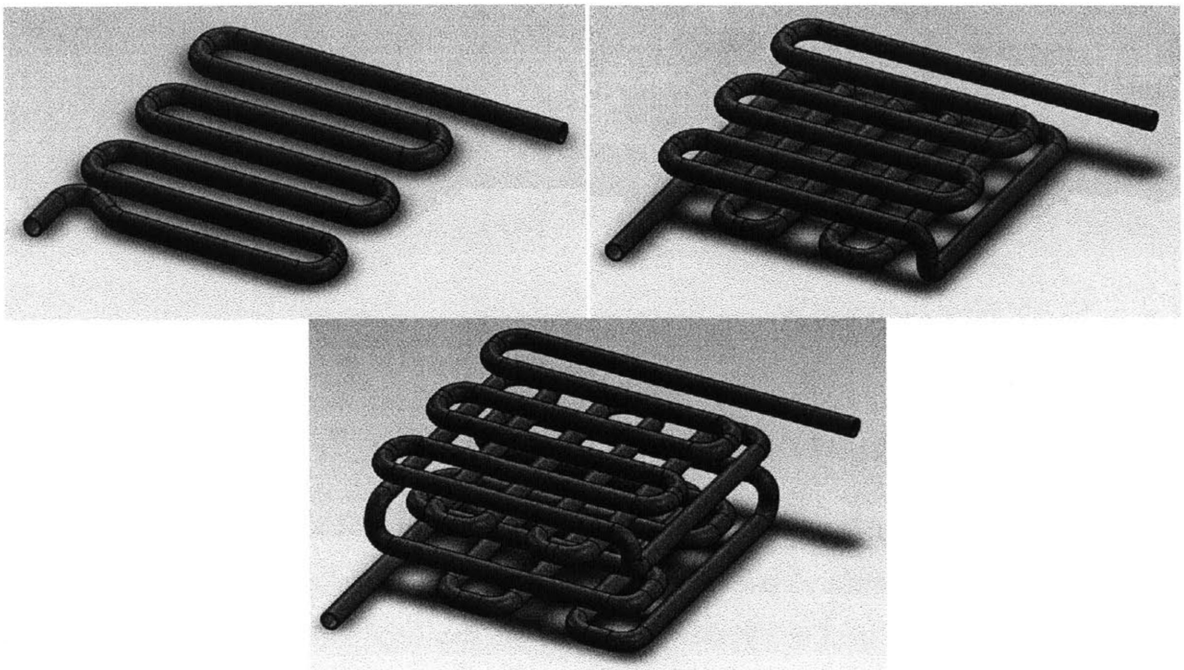

Figure 3- 10: Copper Nickel Dehumidifier Tubing for SDS

Chapter 4

System Modeling

4.1 System Overview

4.1.1 MDS Solid Model Assembly

The MDS process flow diagram, as described in Chapter 2, is shown in Figure 4-1. The green lines are representative of the air ducting. Air starts from outside the system and is taken in by the blower. The blower then blows the air out into the five humidifiers. As the air becomes moist in the humidifier, the air is pushed through directly into the corresponding dehumidifier where it drops off the carried water. After dehumidification, the air is then ejected into the atmosphere.

The blue lines are representative of the water tubing. The water is pumped in from an outside source and is fed into a dehumidifier where it cools the humidified gas to lower the specific humidity of the gas. The water leaving the dehumidifier is pumped into a heater (a red square) and then fed through the top of a humidifier. The water that leaves the humidifier is checked for oversalination and then, if the salinity of the fluid is too high, the liquid is pumped out and replaced with fresh seawater.

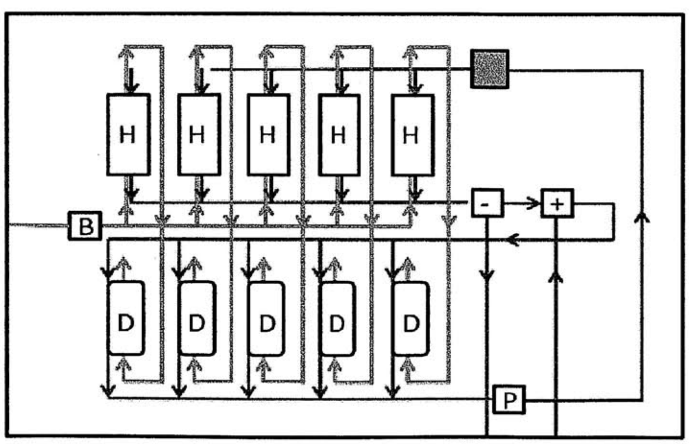

Figure 4- 1: MDS process flow diagram

The full model of the MDS solid model assembly is shown in Figures 4-2, 4-3, and 4-4. There is intended to be a pathway in between the humidifier and dehumidifier of 2 feet to allow for access for maintenance, if necessary. If possible, the humidifier and dehumidifier should be lined up against opposite walls with perhaps two inches of clearance. The distance between the dehumidifiers and humidifiers should be, again, 2 feet in order to allow maintenance to individual systems. The solid model does not quite accurately represent this because the flexible tubing and ducting is expected to be able to bend around extra spaces, so as not to interfere with the lining up of the parts. Because the focus on this assembly is on the layout of the piping and the ordering of the system parts (humidifier and dehumidifier), the pumps, blowers, and heaters are approximated. In the drawing, the humidifier and the dehumidifier are shown to be 1 foot apart on a trailer that is 10 feet in width.

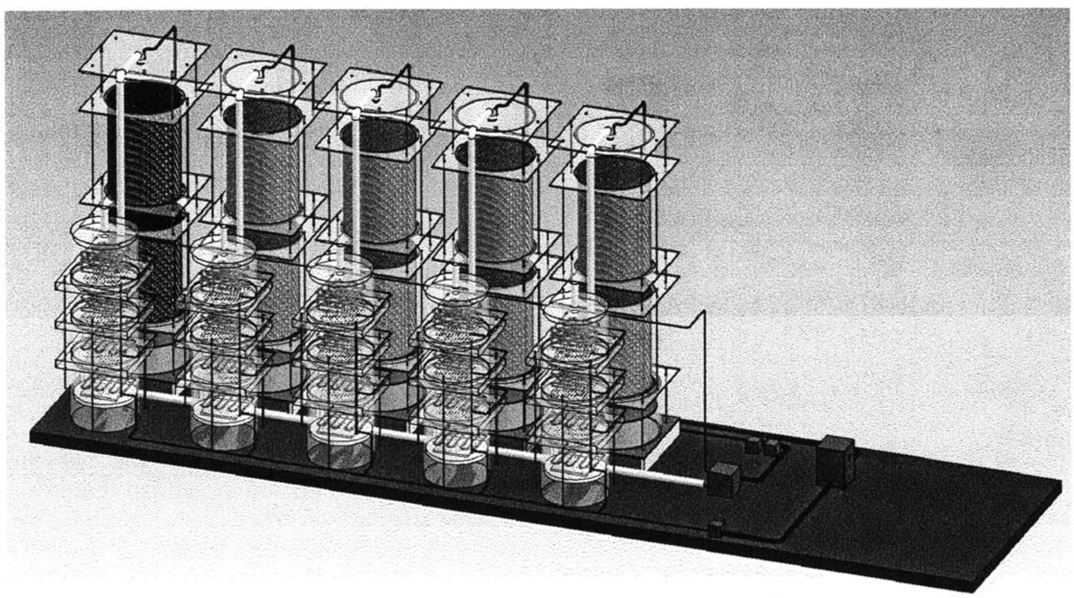

Figure 4- 2: Full MDS Solid Model Assembly – Isometric View

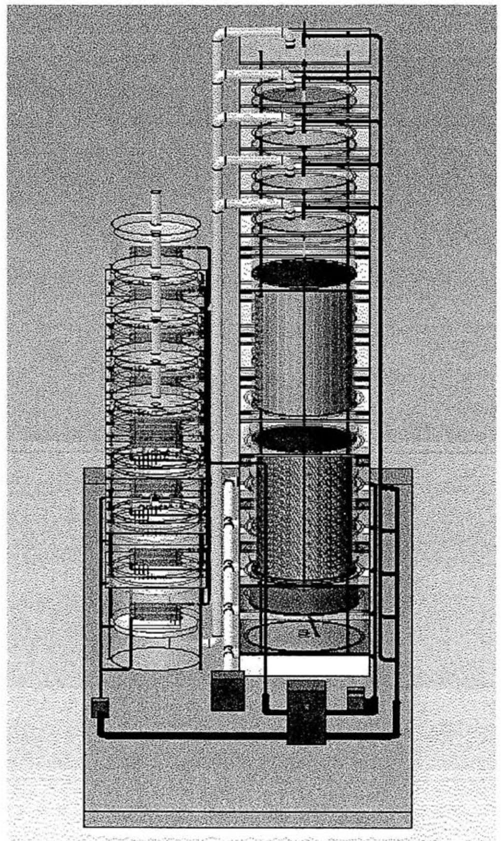

Figure 4- 3: Full MDS Solid Model Assembly – Front View

4.1.2 SDS Solid Model Assembly

The process flow diagram of SDS, detailing the flow of both air and liquid within the system, is shown in Figure 4-1. As the diagram shows, dry air is taken in from outside the system and blown into the humidifiers with a blower. The dry air becomes humid in the humidifier, after which it is deposited in the dehumidifier. The dehumidifier removes the carried water and then ejects the remaining air into the atmosphere.

The water follows a similar path as it did in the MDS process. Salt water is taken in from outside the system, pumped through the cooling loops of the dehumidifier. Afterward, another pump helps to push it into a heater and into the dehumidifiers where it makes contact with dry air. The resulting brine solution will be recirculated unless the salinity of the solution is in excess of the maximum allowable salinity.

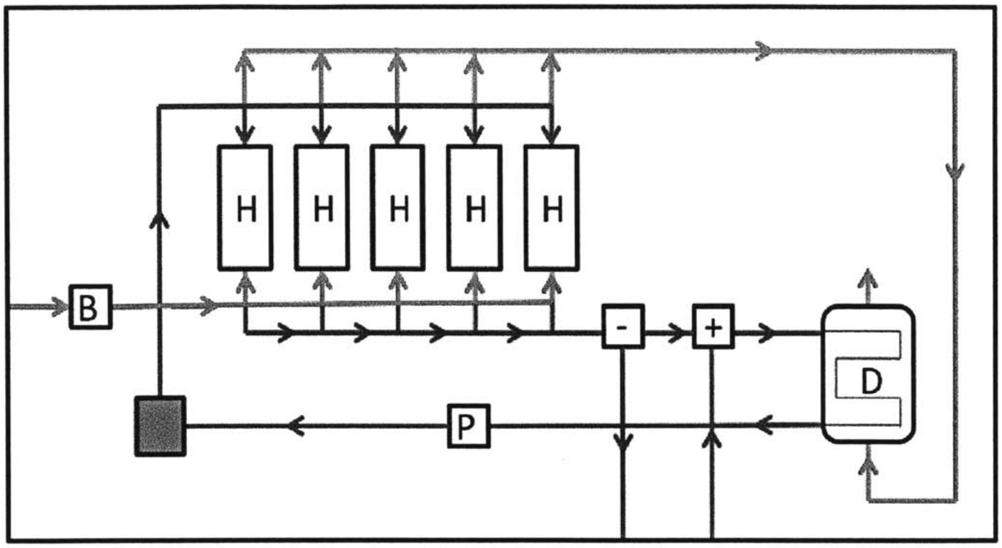

Figure 4- 4: SDS process flow diagram

The full solid model of the SDS is presented below. Here, the humidifiers are each separated by a distance of one foot and are centered along the center of the truck, allowing access by maintenance from both sides of the humidifier. The dehumidifier is placed at the end of the truck because it is the largest part and so it will limit access to the remainder of the system if placed in the front.

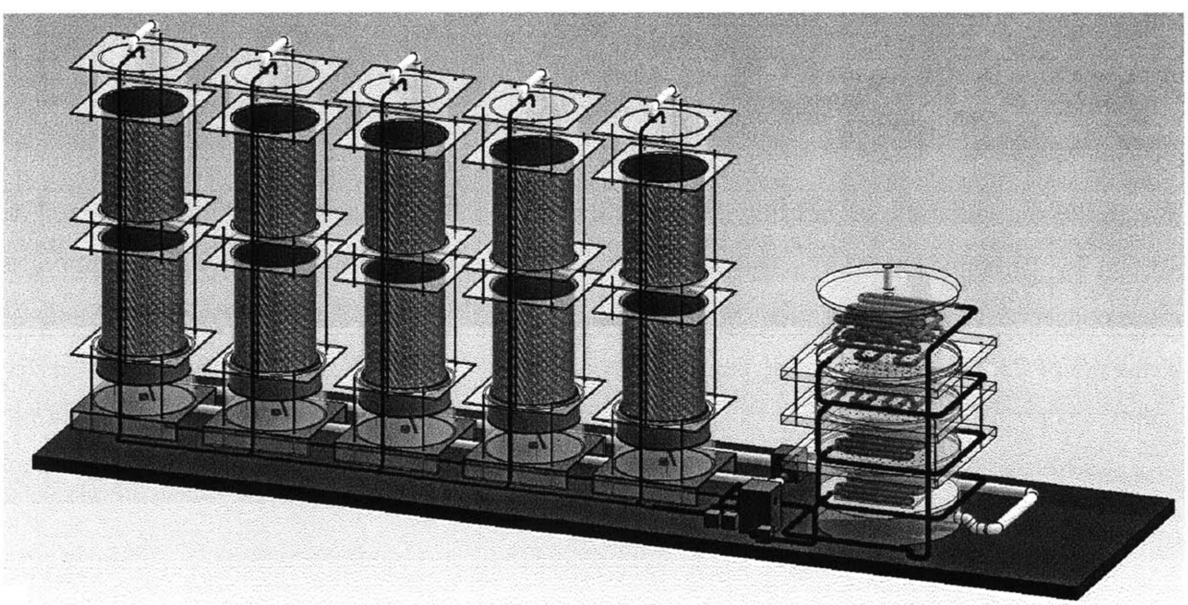

Figure 4- 5: Full SDS Solid Model Assembly – Isometric View

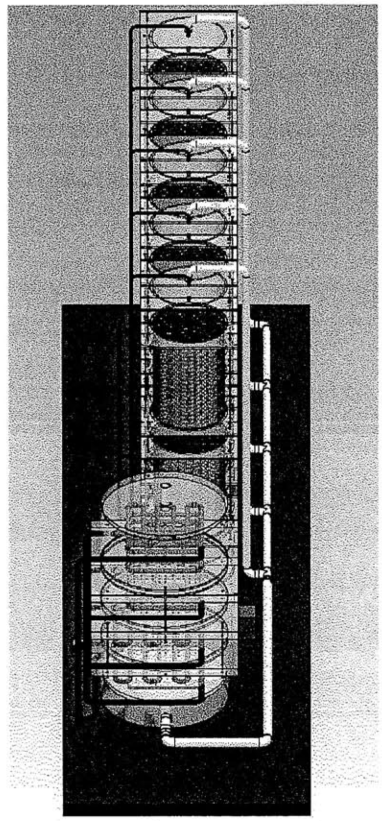

Figure 4- 6: Full SDS Solid Model Assembly – Back View

4.2 Trailer Sizing

The trailer on which the humidifier, dehumidifier, pumps, blower, and heater all rest is sized at 40 feet by 10 feet. This sizing was a preliminary estimate but on a secondary examination, a more conservative width of 8 feet should be used instead. This newer conservative estimate is based off of the US Department of Transportation Federal Highway Administration limits for the width of a truck, which is 102 inches (8.5 feet). The length of the trailer, however, was a more reasonable conservative estimate. The upper limits on length are 48-53 feet, varying by state [15].

In addition to this, another factor which should be considered is the height of the trailer. While an open trailer would technically allow for any height of humidifier or dehumidifier, bridges and other low clearances are designed with a certain height of trucks in mind. If the height from the bottom of the wheel to the top of the humidifier exceeds 14 feet, the truck containing the HDH system would not be gain access to a lot of different areas. In the United States, the height limit varies by state. This can result in heights of anywhere from 13.5 feet to 14 feet [15]. As such, the humidifier should be redesigned with this in mind to allow for the deployment of the HDH system to any section of the United States. While this system has the potential to be transported by train or rail, it is designed to allow for quick deployment to necessary locations with minimal setup. For regions such as India or Africa which lack a thorough rail infrastructure, using a trailer system is preferable. However, in such areas, a larger concern is the poor road maintenance.

4.3 Tubing Layout and Sizing

The goal of the tubing layout design was to minimize the amount of space taken up by the entire system. This resulted in a selection of tubing running underneath the humidifiers and dehumidifiers (Figures 4-7). In conserving the amount of tubing, a secondary goal was also accomplished, which was minimizing the amount of tubing that was necessary to connect the model together.

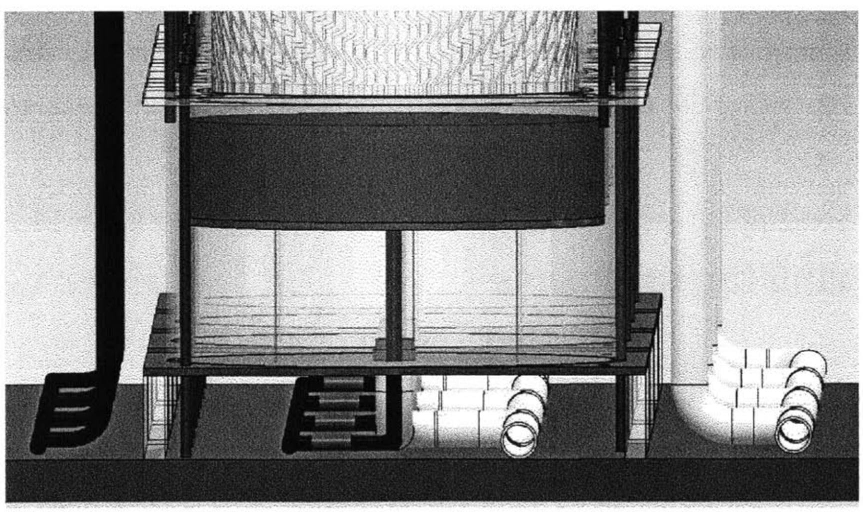

Figure 4- 7: SDS – Tube Connections at Humidifier Bottom

In the net water flow, the water runs through tubing of 2 inches inner diameter. When the water reaches the individual humidifiers, in order to conserve the velocity speed, the cross sectional area must be reduced in diameter. The reason the velocity was selected to be constant across the whole system is to prevent the cropping up of multiple velocities when determining heat transferred, the pressures in the system, etc. Rewriting equation 2 and including the fact that the water will be split into 5 dehumidifiers, the new diameter can be determined:

$$D_{small} = \frac{1}{\sqrt{5}} D_{net} \tag{3}$$

This yields an inner tubing diameter of 0.9 inches.

4.4 Air Duct Layout and Sizing

The air duct, like the tubing layout was optimized for both space and quantity. The air ducting layout beneath the humidifier for the SDS assembly can be seen in Figure 4-7. However, unlike the tubing, it is much harder to keep the air flow constant especially since the air is compressible. As such, changes in velocities were allowed. However, air flow in the dehumidifier should be fast in order to prevent water from flowing down the bubble column. As such, it was safer to select a diameter that would produce a higher velocity in the dehumidifier. Assuming instantaneous incompressibility and starting from a individual humidifier air duct of 3 inches, a diameter minimum can be determined which smaller values of the diameter would produce a faster flow. This comes out to be 6.7 inches. Using this as the upper bound, a diameter of 4 inches was chosen.

4.5 Potential Improvements

The model presented in this chapter does not account for the issues detailed in 4.2 related to trailer sizing and thermal management of the mechanical system. For the trailer sizing issue, a recommendation would be to allow for travel on US roads by reducing the height of the dehumidifier beneath 8 feet. 8 feet is the minimum cargo height that would be allowed on various types of cargo sections of trailers [16]. For the thermal management issue, creating a closable top which would still allow the air leaving the dehumidifier to escape into the atmosphere would be ideal.

As a result of the width of the trailer in the MDS model being larger than what was allowed through federal recommendations, the MDS assembly should also be changed to allow for easy access to all items. It is worthwhile to note though, that for areas which lack a developed infrastructure, such as India or Africa, these areas also lack strict regulations for trailer size limits. These designs can still be implemented as designed for those countries. However, for these areas also lack proper road maintenance and as such, the MDS and SDS support structures should be reconsidered for large vibrations.

Another factor that has not been accounted for is the internal thermal management of the mechanical equipment. Because of the fact that the trailer is open to the atmosphere, the interior section will need to be managed thermally, requiring cooling on hot summer days, and heating in the cold winter nights. With an open trailer, this is hard to account for because of the inability of the system to contain or exclude heat. To account for the thermal integrity of the mechanical equipment, it would be recommended to create a closeable top to this container through a reduction of equipment height. By enclosing the equipment, residual heat from the heater and the HDH system can help to heat the rest of the equipment during the cold winter nights. If this is not enough, additional heating can be supplied. During hot summer days, a cooling apparatus can be installed to maintain the temperature inside the trailer. However, while including for these thermal management factors, the dehumidifier should still expel its air stream back into the atmosphere. This is best accomplished by connecting the dehumidifier air outputs together using connectors and providing one exit hole for this net air flow.

Chapter 5

Conclusion

The models created through this project could be used to make a preliminary plan for how to organize the items within the mobile unit. While the SDS design needs some rearrangement due to the width limitation, the MDS design is more promising. The components of the HDH system are organized in an accessible fashion and optimize for the amount of material used and the space taken.

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