Abstract

One third of humanity is without access to clean drinking water. In addition, over 90% of clean drinking water is contaminated with microplastics. 71% of the earth’s surface is water but we are without a cheap, efficient and versatile means of making water safe to drink. This study aims to design, build and test a highly efficient, solar powered and portable water purification method that will clean water of most contaminants, including microplastics, salt and pathogens, and can be used across the globe. In this study a water vaporization enthalpy decreasing chitosan and PVA hydrogel was synthesized via repeated freeze drying at -80°C to stimulate the expansion of pores within the hydrogel decreasing the vaporization of the water within the hydrogel from 2260Jg\(^{-1}\) to 1200 J g\(^{-1}\). Additionally, a solar tracking mylar coated nested paraboloidal solar collector has been designed to power a multistage of these hydrogels which increases the efficiency of the solar power for vaporization by ~450%. The unity of these industry leading concepts enables the proposed system to reliably function at not only a highly efficient rate but also a reduced energy cost. This design’s solar tracking ability collects up to 223.8W which, when partnered with its ability to float, makes it functional nearly anywhere there is water. This design is capable of sustaining a purification rate of 1.84L per hour and an evaporation rate of 180L hr\(^{-1}\) m\(^{-2}\) enabling it to purify water indefinitely.

Introduction

The United Nations has a goal to supply clean water and sanitation for all [1]. This goal originates from the fact that one in three people do not have access to safe drinking water [1]. Clean water is an essential resource for our survival, yet of the 3% of water on Earth that is fresh only 0.5% is drinkable [2]. As well as this, our already meager water resources are being threatened by climate change as weather patterns change and sea levels rise [3]. For example, San Diego’s water is supplied by the Colorado River but, due to a change in weather patterns, the water level is dropping resulting in a need to look elsewhere for clean water [4]. This lack of clean water will likely become more widespread and even amplified as our climate becomes less stable due to catastrophes, such as the deforestation of the Amazon[5].

To tackle water shortages desalination plants are being built. However, the process is inhibited by high operating costs. For example, plants spend 1,000 to 2,000 US dollars per acre-foot (of water), $10’s to $100’s of millions per year in maintenance, and billions in construction costs [4]. The cost of these plants make them simply out of the question for many impoverished developing countries. The most widely used methods of desalination are reverse osmosis and thermal evaporation [4]. Thermal desalination is typically not commercially viable due to its intensive energy requirement resulting in reverse osmosis plants becoming the favored design.
However, reverse osmosis plants have many consequences such as toxic waste pollution and killing of local wildlife [4]. Even our supposedly safe drinking water is at risk as microplastics have been found in over 90% of all drinkable water [6]. Microplastics have the potential to cause health problems such as cancer, weakened immune systems and reproductive problems [7]. The water industry is crucial to humanity’s survival, yet it has so much room for improvement.

Theory
This study aims to synthesize hydrogels that decrease the enthalpy of both saltwater and freshwater vaporization by about half [8]. The hydrogel reduces water vaporization enthalpy because of the hydrophilic bonds between both Chitosan & Polyvinyl Alcohol with water [8]. These hydrophilic bonds weaken the hydrogen bonds within the water, labeled in Figure 1 as “Intermediate water”, reducing their enthalpy of vaporization from 2260 J g\(^{-1}\) to 931 J g\(^{-1}\) as shown in Figure 2 [8]. Pores that work as crosslinks enable this type of bonding shown in Figure 1. These pores are generated by repeated freeze-drying of the hydrogel. Freeze-drying is effectively the freezing of water molecules within the hydrogel and the sublimation of these water molecules so that porous gaps are left within the hydrogel. The hydrogel utilized a Chitosan and Polyvinyl alcohol mixture of concentration 1.0:0.175 PVA/Chitosan, named h-LAH4 shown in Figure 2.

h-LAH 4 was chosen over h-LAH5 as the saturated water content of h-LAH5 hindered the evaporation enthalpy unpredictably. This was likely due to flooding which overwhelmed the bonding capability of the Chitosan & PVA crosslinks within the hydrogel.

In this study the hydrogel was frozen at a temperature of -80°C and dried in a 60°C hot bath in a beaker whereas in prior research the hydrogel was frozen in liquid nitrogen at -196°C and dried at 30°C [8]. Freeze-drying at -80°C has been proven in prior research to increase the pore sizes within Chitosan based hydrogels, as shown in Figure 3. The purpose of changing the pore size was to test if larger pores would decrease the evaporation enthalpy of water within the hydrogel further. 60°C was used instead of 30°C due to the fact that freeze-drying is based on sublimation, so a higher temperature is favored because a lower drying temperature increases the probability of water changing to its liquid phase after solid rather than sublimating.

Figure 1: Function of crosslink within Hydrogel

![Figure 1](image1.png)
The crosslink effectively induces low bond strength in the Intermediate water via the pull on the bound water. Source 8.

Figure 2: Effect of Concentrations of h-LAH

![Figure 2](image2.png)
h-LAH 4 with a concentration of 1.0:0.175 PVA: Chitosan was chosen for this study. Source 8.
Figure 3: Chitosan based Hydrogel freeze-dried at -80°C vs -196°C

The images above compare the pore distribution and size with differing temperatures of freeze drying, CST1 being -80°C & CST2 being -196°C. Source 9.

A multistage was included in the design to increase the efficiency of the system. Generally, in evaporative water purification, the steam generated by water vapor is collected and then condensed. However, the heat retained by the steam is rarely harnessed which wastes potential energy. So, instead of wasting energy, a second stage capable of capturing the heat within that steam and using it to power evaporation in the second stage would increase the efficiency of the energy put into the system. Adding a third stage would increase the efficiency further by utilizing the steam of the second stage. This can theoretically go on infinitely but for this project a total of 10 stages were used. Using prior research as reference, use of the multistage is projected to increase the heat efficiency of the system by 450% [10].

This study’s approach to the multistage is different to prior research in that instead of using a horizontal plane for the travel of water vapor a vertical plane was used as shown in Figure 4 and Figure 5. A vertical plane was used because heat rises and in prior research a core limitation was the loss of heat to the surrounding wall. Also, the insulation used in prior research was only used on the bottom aluminum plate of the multistage of this study due to the generally minimal surface area contact between the surrounding materials and the other plates. Additionally, the capillary wicks utilized in prior research were replaced with the enthalpy decreasing hydrogels which are described above.

Figure 4: Design and Function of MIT’s Multistage

A solar absorber insulated by silica gel heats the first stage of the multistage. The multistage then vaporizes the water drawn by the capillary wick which heats the next stage. Source 10.

Figure 5: Design and Function of this Study’s Multistage

The bottom aluminum plate is heated evaporating the water within the Hydrogel. Water vapor then passes through the GORE-TEX layer and condensates on the next aluminum plate heating it. The condensed water is then caught and funneled by the GORE-TEX into the corners for collection.

To power the multistage a solar tracker was added to the design. The nested paraboloid design was mathematically proven, as shown in Figure 6, to concentrate solar energy from a .55 meter diameter outer parabola into a 10 cm diameter. Beneath the diameter is a 150mm diameter lens with a focal length of 70 mm. The lens focuses the light onto a central absorber 2cm in diameter which is connected to the bottom stage of the multistage via thermal piping. An automated slider, as shown in Figure 7, sits below the nested paraboloids to avoid the system overheating. The solar collector is also automated to be
capable of solar tracking anywhere in the world. The collector is mounted on a pair of arms that are in turn mounted on a geared turntable allowing 90° of rotation combined with 360° of rotation for differing distances from the equator as shown in Figure 7. An Arduino determines location and necessary movement in relation to the sun through a photoresistor circuit in a constant feedback loop. The same Arduino also controls the motors connected to the arm, turntable, and slider.

Figure 6: Calculation and graphing of light trajectory within reflective Paraboloids

Tangent line, angle of incidence and equation of reflected ray were calculated showing the function of the reflective nested paraboloids. https://www.desmos.com/calculator/v1ce8e5fa7
Thanks to Dr. Bleckner for checking calculations.

Figure 7: Solar Tracker range of movement

The first image shows 90° of arm movement and the second shows 360° of turntable rotation. These were drawn using Onshape Cad.

Methods, Testing & Results

On 03/12/2020 using the h-LAH4 concentration, 850mg of PVA, 150mg of Chitosan, 10ml of deionized water and 1 ml of 1.2M Hydrochloric acid were added to a beaker and the solution was then sonicated for approximately 24 hours for thorough dissolution. On 04/12/2020 ~50 μL of glutaraldehyde was added to 4ml of h-LAH4 solution to strengthen the bonds between the Chitosan/PVA crosslinks. The solution was then left to gelate for 5 days. On 09/12/2020 the pre-freeze-dried sample was photographed at 40x zoom under a microscope and hydrated before being frozen at a temperature of -80°C for over 48 hours. The hydrogel was then reheated at 60°C in a water bath for 30 minutes. The process of freezing at -80°C for 48 hours and heating at 60°C for 30 minutes was repeated for a total of 10 freeze-dries. However, due to restricted lab access the repeated freeze-drying took a total of 30 days from 09/12/2020 until 08/01/2021 with varying time at which the hydrogel spent in the freezer at -80°C. The full calendar can be seen in Table 1. Microscopic images of the polymer of 40x strength were taken every other freeze dry to monitor the progress of the pore expansion. The results of the freeze-drying process are shown in Figure 8. The predicted outcome that the pores within the hydrogel would be greater in size and less evenly distributed appear to be accurate when comparing the final image from Figure 8 and Figure 9.

Figure 8: 40x Images taken throughout Freeze-Drying at -80°C process of Hydrogel

Pre-Freeze Dry

2nd Freeze Dry

4th Freeze Dry

6th Freeze Dry
These images show the growth in distribution and size of the pores throughout the Hydrogel during the Freeze-Drying process.

Figure 9: Porous Hydrogel Freeze Dried 10 times in Liquid Nitrogen

This is an image of h-LAH4 after 10 freeze-dries at -196°C. Source 6.

Table 1: Freeze-drying Data

<table>
<thead>
<tr>
<th>Date</th>
<th>60°C for 30mins</th>
<th>40x images</th>
<th>Frozen at -80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/12/2020</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>11/12/2020</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>24/12/2020</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>27/12/2020</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>30/12/2020</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>20/1/2021</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Between each date the hydrogel was left in the -80°C freezer.

The hydrogels also went through testing after the freeze-drying to determine the change in water evaporation enthalpy within the hydrogel and the hydrogels heat of deformation. The hydrogel was first hydrated and weighed before being put on the weighted hotplate shown in Figure 10. The peltier plate was wired to a controlled power source so that the energy absorbed by the hydrogel could be monitored and controlled. The hotplate was mounted on a scale so that the change of weight due to evaporation of water could be recorded throughout the experiment. The energy cost of evaporating water from 25°C was calculated to be approximately 1,200 J g⁻¹ based on the data in Table 2. Comparing this to prior study’s vaporization enthalpy of 931 J g⁻¹ it is clear that a more even distribution of pores is favoured.

The correlation between the hydrogel evaporation rate and surface area of Hydrogel was also tested using the experimental setup in Figure 10. Using the data in Table 3 the evaporation rates can be calculated as 8.9 x 10⁻⁴, 4.4 x 10⁻⁴ and 3.9 x 10⁻⁴ for 178 mm², 87.5 mm² and 66 mm² respectively. The ratios calculated using the data from Table 3 for the evaporation rates of the hydrogels and the surface area of the hydrogels are 8.9 x 10⁻⁴ : 4.4 x 10⁻⁴ : 3.9 x 10⁻⁴ for 178 mm², 87.5 mm² and 66 mm² respectively. The ratios of the evaporation rate and the respective surface areas are approximately equivalent given the margin of error meaning that the evaporation rate and the surface area are strongly correlated. This information will enable the calculation of the final design’s production rate as the final design uses larger
hydrogels with much greater surface area.

The hydrogel was also heated to a temperature of 200°C, just below the melting point of the thermally resistant resin used as the surrounding structure material, and didn’t deform. The evaporation rate of the hydrogel was tested at 200°C by placing the hydrated hydrogel on an aluminum plate on top of the hot plate, as shown in Figure 11, and recording its mass every 30 seconds using a scale. Using the data recorded, as shown in Table 4, the evaporation rate is approximately 0.004 g of water per second. Using the surface area of the hydrogel used in the experiment (~359.46 mm²) the evaporation rate per surface area is calculated as 1.11x10⁻⁵ g s⁻¹ mm⁻².

Table 2: Testing Evaporation Enthalpy within Hydrogel

<table>
<thead>
<tr>
<th>Time</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 min</td>
<td>1.69</td>
<td>1.79</td>
<td>1.7</td>
</tr>
<tr>
<td>1 min</td>
<td>1.61</td>
<td>1.75</td>
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<td>1.56</td>
<td>1.42</td>
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<tr>
<td>4 min</td>
<td>1.18</td>
<td>1.45</td>
<td>1.33</td>
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<tr>
<td>5 min</td>
<td>1.12</td>
<td>1.23</td>
<td>1.26</td>
</tr>
<tr>
<td>6 min</td>
<td>1.05</td>
<td>1.25</td>
<td>1.22</td>
</tr>
</tbody>
</table>

The peltier plate was powered by 1.89 W for 6 minutes and the reduction in the hydrogels’s hydration weight was recorded in grams.

Table 3: Testing Correlation between Evaporation Rate and Surface Area

<table>
<thead>
<tr>
<th>Time</th>
<th>178 mm²</th>
<th>87.5 mm²</th>
<th>66 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 min</td>
<td>0.45</td>
<td>0.26</td>
<td>0.19</td>
</tr>
<tr>
<td>1 min</td>
<td>0.36</td>
<td>0.23</td>
<td>0.17</td>
</tr>
<tr>
<td>2 min</td>
<td>0.34</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>3 min</td>
<td>0.29</td>
<td>0.18</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Three hydrogels of differing surface areas were hydrated and placed on the peltier plate to measure their evaporation rate in grams per second.

Table 4: Testing Evaporation Rate at 200°C

<table>
<thead>
<tr>
<th>Time</th>
<th>1.83</th>
<th>1.72</th>
<th>1.73</th>
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<tr>
<td>0 min</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.30 min</td>
<td>1.71</td>
<td>1.62</td>
<td>1.64</td>
</tr>
<tr>
<td>1.00 min</td>
<td>1.62</td>
<td>1.46</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Hydrogel was hydrated and placed on a hotplate at 200°C, evaporation rate was recorded in grams per second.

The multistage was constructed using a variety of
materials. Aluminum plates were used as a conductive intermediate to avoid the hydrogels situated above absorbing the condensed water vapor of the previous stage while still efficiently conducting the energy retained by the water vapor. A GORE-TEX sheet was placed between the Hydrogel and the Aluminum plate to facilitate the funneling of the clean condensed water to the corner funnels while also allowing the water vapor to pass through unobstructed. This design avoids the possibility of the Hydrogel reabsorbing clean water which would be counterproductive. The surrounding material was prototyped using 3D printed PLA, but the final product will likely be 3D printed with highly thermal resistant resin capable of withstanding 238°C. The 3D printed encasing structure also has entryways on the side to allow salt water or polluted water to be absorbed by the hydrogel. The schematic of this design can be seen in Figure 11.

A prototype single stage was made by 3D printing the surroundings in PLA. An aluminum plate was mounted on the heated peltier plate and the hydrogel was placed on the aluminum plate. The plastic surrounds were then added and a laser cut GORE-TEX layer was placed above the hydrogel. Finally a second aluminum plate was placed in the structure above the GORE-TEX layer as shown in Figure 12. This stage went through testing to determine if the GORE-TEX was capable of passing the water vapor while also stopping the condensed water from passing through. This was proven as the top aluminum plate had condensation after the heating of the hydrogel and the GORE-TEX is hydrophobic as shown in Figure 13.

The Solar tracker was constructed by 3D printing multiple pieces of the primary paraboloid and then using a 3D print pen to weld them together. The slider and gear headed stepper motor were connected to the underside of the primary parabola. The secondary paraboloid was also 3D printed and suspended at the focal point of the primary paraboloid using HDPE plastic that was laser cut. Both the primary and secondary paraboloid were coated in Mylar using a heat gun and mylar sheets which offer ~97% reflectivity. The primary paraboloid was screwed
into 80-20 10cm aluminum one of which was mounted to a stepper motor and the other was mounted to a pillow block mount. The stepper motor and pillow blocks were bolted to a HDPE turntable top approximately 40cm in diameter. The turntable also supported the Arduino, 3 tic t500s, a thermal absorber and a secondary stepper motor for controlling rotation upon the turntable. The turntable was connected to the underside of the mount and the topside of the geared base with which the turntable top’s secondary motor rotated about using a gear head. The geared base was also connected to a floating stabilizer that has four arms connected to pool noodles enabling the multistage to be submerged while keeping the solar concentrator above water. A photoresistor circuit was positioned on the secondary paraboloid allowing detection of the sun in relation to the primary paraboloid’s focus. Using triangulation, the Arduino can determine and execute movement of the stepper motors to orient the paraboloid at the position of optimal solar collection. The Arduino also controls the slider and uses it to manage the heat of the system which it detects via a thermometer connected to the thermal absorber. The solar collection capability of this design is 223.8W as shown by the calculation:

\[ \pi((0.275m)^2 - (0.05m)^2) \cdot \left(\frac{1000W}{m^2}\right) \cdot (97\%) \approx 222.8W \]

The full design is shown in Figure 14.

**Figure 14: Study’s final design**

Red indicates the motors, blue indicates floating pool noodles, the multistage sits below the turntable completely submerged and the solar concentrator sits above to collect solar energy. Onshape Cad

**Discussion**

The predicted solar thermal efficiency of the multistage, \( \eta \), can be calculated using the equation

\[ \eta = \frac{n h_{fg}}{q_{solar} A} \]

where \( h_{fg} \) is the enthalpy of water vaporization, \( n \) is the vapor production rate under steady state, \( q_{solar} \) is the input solar flux (1000 W m\(^{-2}\)), and \( A \) is the effective solar absorbing area. The calculated efficiency for a system where the air gap is 2.5mm≤ and has 10 stages is ~450% [10]. However, due to a difference in insulation material of, prior study using insulation with thermal conductivity of 0.022 W m\(^{-1}\)K\(^{-1}\) and current study using insulation of ~0.2 W m\(^{-1}\)K\(^{-1}\), and also a difference in orientation, prior study being horizontal and current study being vertical, there may be a slight variance in predicted and actual efficiency.

The Hydrogel met expectations in pore size and distribution in that the -80°C freeze dried hydrogel had a great pore distribution and greater pore size than the -196°C freeze dried hydrogel. This changed the water’s vaporization enthalpy within the hydrogel by ~269 J g\(^{-1}\) in comparison to the previous study. This is likely due to the fact that an even distribution would increase the effect of the hydrogels ability to bond with the water.

The thermally resistant resin has a deformation temperature of 238°C so, in order to ensure the system isn’t compromised, the ideal max temperature of the first stage of the multistage is 200°C. The hydrogel’s heat of deformation was also tested up to the temperature of 200°C and it showed no damage. Additionally, the hydrogel will be in contact with and absorbing water molecules that will consistently act as a cooling system.

The approximate cost of fueling this system can be calculated using the equation:
The cleansing ability of this system is very high due to the fact that it uses evaporation. Evaporating water kills bacteria and pathogens [12] and leaves residue such as salt and microplastics behind. This system will produce pure, clean and safe water. Additionally, the floatation capabilities of the system offer versatility giving it the possibility to not just work in small bodies of water but also function in lakes or even the ocean. A reliable water source out at sea could enable ships to carry more cargo instead of water reserves opening it to both military and commercial applications.

Future research includes the synthesis of ten hydrogels to fill the multistage to enable the testing of the multistage’s real world production rate. However, the synthesis of the hydrogels is limited by the lab access and current budget. Further research can also be performed regarding the effect of differing temperatures and durations of drying on the hydrogels pore dispersion and size.

**Conclusion**

This study designed and tested a system capable of producing 1.84 L hr\(^{-1}\) of clean water by utilizing a highly energy efficient multistage, energy decreasing hydrogels and a solar tracking concentrator. The system’s 180 L hr\(^{-1}\) m\(^{-2}\) rate capability also enables the system to have a much greater production rate with more multistages or a multistage with a greater surface area which can be powered by a larger nested paraboloidal collector. The system’s ability to float and track the sun enables it to function anywhere on earth. Whether it be in poverty stricken developing countries, out at sea keeping sailors hydrated or even in your back-yard so that you can drink water knowing it is cleansed of salt, microplastics and bacteria. This study enables industry level efficiency partnered with robust engineering to be brought to the individual in a market where it can make the difference between life and death.
References


