Capstone Design Project – Solar Powered Production of Clean Water

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Abstract

Access to clean water and making solar energy economical are two of the 14 National Academy of Engineering's Grand Challenges for Engineering in the 21st Century. Two capstone projects are currently underway at The Citadel that will use solar power to produce clean water. The goal of the first project is to create a prototype desalination plant that can produce drinking water from salt water. The goal of the second project is to create a prototype system that can harvest drinking water from humidity in the ambient air. Both prototypes must be easily transportable, use only solar power, and provide enough drinking water for a household. This paper compares the designs of the two prototypes, provides costs and parts lists, discusses challenges encountered, and lays the foundation for future capstone projects that will aim to improve upon these initial designs.

Keywords

Desalinization, Dehumidification, Senior design, Capstone project

Introduction

The National Academy of Engineering lists access to clean water and economical production of solar energy as two of the 14 Grand Challenges for Engineering in the 21st Century[1]. These challenges are excellent starting points for capstone projects in engineering. At The Citadel, two complimentary capstone projects are underway that will use solar power to produce clean water. The goal of the first project is to create a prototype desalination plant that can produce drinking water from salt water. The goal of the second project is to create a prototype system that can harvest drinking water from humidity in the ambient air. Both prototypes must be easily transportable, use only solar power, and provide enough drinking water for a household. These prototypes could be used almost anywhere, but the designs will be targeted for clean water access in developing countries and in disaster relief areas where clean water is most urgent. For example, low cost solar powered units would have been very useful in disaster relief efforts after recent hurricanes in Puerto Rico and the Bahamas. Both projects require students to employ their knowledge of thermodynamics to produce basic engineering models of their systems. This paper compares the designs of the two prototypes, provides costs and parts lists, discusses challenges encountered, and lays the foundation for future capstone projects that will aim to improve upon these initial designs.

Solar Powered Desalination Plant

Only 2.5% of the Earth's water is fresh with even less actually drinkable[2]. With much of the Earth's population clustered near oceans, harvesting drinking water from saltwater is a logical solution.

Utility scale desalination plants use reverse osmosis to produce freshwater, but this process requires a very large energy input. For example, a plant in California will cost one billion dollars to construct and will only supply 7% of San Diego's water demands[3]. Evaporation, on the other hand, has been around for centuries, and it may be an economically viable clean water solution in developing countries.

For this capstone project, students were required to produce 8 liters of clean water per day from salt water using only a 100 W solar panel. Additional requirements were to keep the unit low cost and easily transportable. The basics of thermodynamics for evaporation are on a *T*-*v* diagram in Fig. 1. The line is a constant pressure isobar, which represents how evaporation must proceed at atmospheric pressure. The saltwater starts at point a, and it must be heated to at least point b to begin evaporation. Between points *b* and *c* is the vapor dome where phase change occurs. It is not yet known how far into this liquid vapor region the saltwater should be heated to produce sufficient vapor. Testing will be required after the prototype is constructed.

Considering the water to be evaporated as a closed system, the 1st Law of Thermodynamics is given by

$$Q - W = \Delta U \tag{1}$$

where *Q* is heat added/removed, *W* is the work done by/on the system, and *U* is the internal energy of the water. Since no work will be done in the process, the 1st Law can be rewritten as

$$Q = m(u_2 - u_1) \tag{2}$$

where *u* is the specific internal energy and *m* is the mass of the water. The initial internal energy, u_1, corresponds to point a in Fig. 1. The final internal energy, u_2, is somewhere inside the vapor dome. The values for internal energy are from thermodynamic steam tables to determine the heat required to vaporize some mass *m* of water. The power required, *P*, is found using

$$P = Q/t \tag{3}$$

where *t* is time. These equations determine how much water can produced over a given time with a set amount of power.

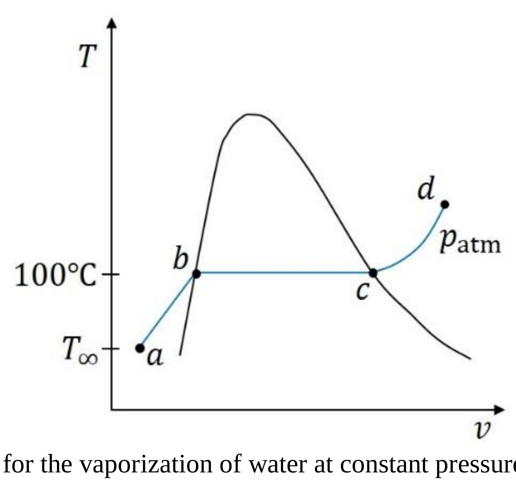

Fig. 1: T-v diagram for the vaporization of water at constant pressure (see Moran et. al[4]).

The final design concept is provided in Fig. 2. Saltwater is boiled in a container using a heating element similar to that used in hot water heaters. Water vapor escapes through a tube at the top of the container. The vapor then condenses and collects in a freshwater container. The solar panel will be placed over the top of the unit to provide power to the heater. For the initial project this year, a low voltage power source will be used in place of a solar panel to keep costs down and allow for easier testing. The cost and parts list in Table 1 shows the major system components with a total cost estimate of $167.

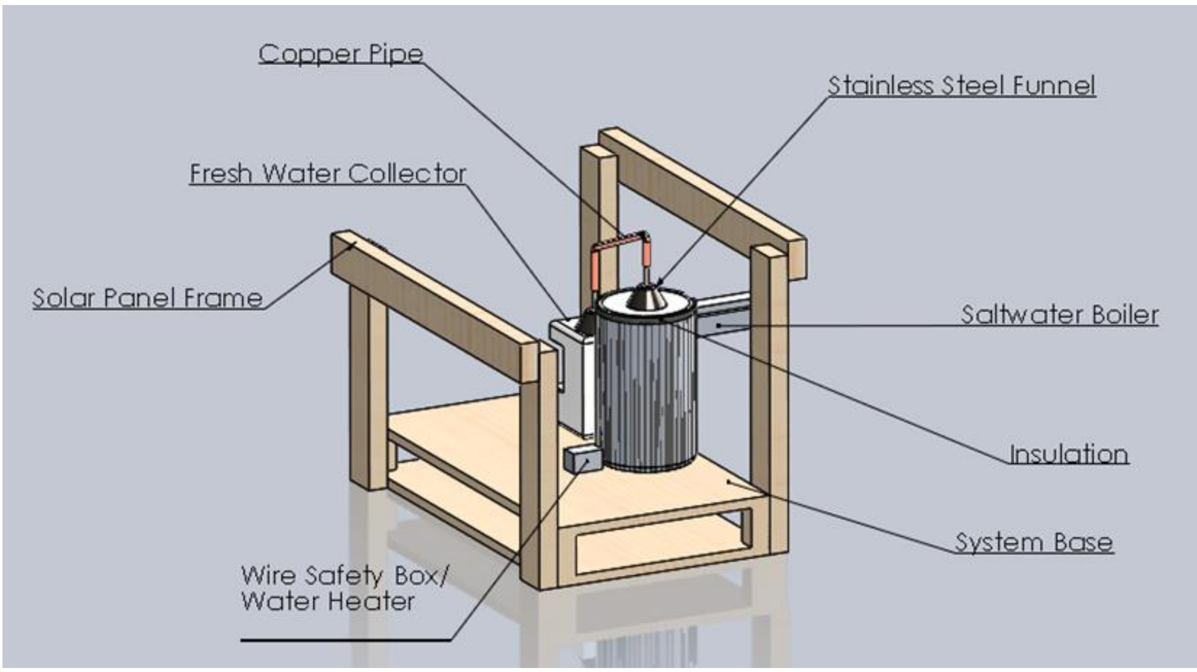

Fig. 2: Basic solar powered desalination plant.

Table 1: Parts List and Cost for Desalination Unit

Part	Unit Cost	Quantity	Total Cost
Wood Screws	$7.99	1	$7.99
2x4 Whitewood Stud	$3.14	5	$15.70
Funnel	$5.95	1	$5.95
Contact Adhesive	$9.09	1	$9.09
Copper Tubing	$13.28	1	$13.28
Heating Rod	$14.99	1	$14.99
Water Container	$5.11	1	$5.11
Pressure Cooker	$44.95	1	$44.95
Wire Box	$3.87	1	$3.87
Brass Fitting	$7.95	1	$7.95
Insulation	$21.75	1	$21.75
Conduit	$16.15	1	$16.15
		Total	**$166.78**

Solar Powered Dehumidification Plant

Dehumidifiers are used in areas such as industrial processes and ventilation systems. Expensive dehumidifiers are even in desert locations that produce water from the arid, ambient conditions.

Therefore, producing drinking water from the humid conditions typically found in developing countries near the equator is a straightforward task. For this capstone project, students were required to collect 8 L of water per day from ambient air using only a 100 W solar panel for power. Again, additional requirements were to keep the unit low cost and easily transportable.

The governing equations for a dehumidification process can be found in Moran et. al[4], and it is depicted in Fig. 3. In terms of mass conservation, the mass of dry air flowing through a dehumidifier is constant. The mass balance on the water is given by

$$\dot{m}_{v,in} = \dot{m}_{v,out} + \dot{m}_w \quad (4)$$

where $\dot{m}_v$ is the mass flow rate of water vapor and $\dot{m}_w$ is the mass flow rate of condensed water. The mass of water condensed is related to the mass of dry air by the humidity ratio, ω, according to

$$\dot{m}_w = (\omega_{in} - \omega_{out})\dot{m}_a \quad (5)$$

Equation 5 enables an estimate of the amount of water produced based by the system. An energy balance on the system in Fig. 3 gives the following

$$\frac{\dot{Q}_{cv}}{\dot{m}_a} = \left(h_{a,out} - h_{a,in}\right) + \omega_{out}h_{g,out} - \omega_{in}h_{g,in} + (\omega_{in} - \omega_{out})h_{f,w} \quad (6)$$

where $\dot{Q}_{cv}$ is the heat removed, h_a is the enthalpy of dry air, h_g is the enthalpy of water at the saturated vapor state, and h_f is the enthalpy of water at the saturated liquid state. Equation 6 gives the power requirements for the system in terms of heat removal.

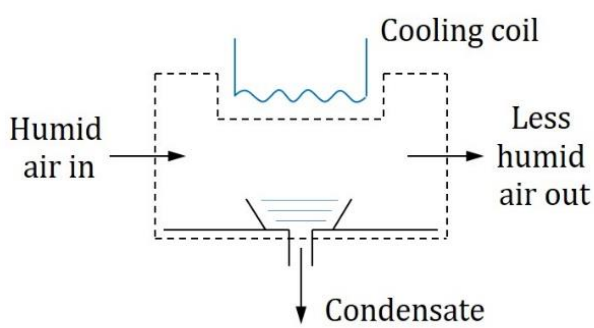

Fig. 3: Schematic of a dehumidification process (see Moran et. al[4]).

The basic design concept is shown in Fig. 4. Humid air will be drawn into a box-like container. A refrigerated space next to this container will cool water that circulates in a loop between the refrigerated space and humid space. Condensation will occur on this loop within the humid space. Water will fall and collect in a container at the bottom of the unit. The cost and parts list is provided in Table 2 with a total estimated cost of $244.

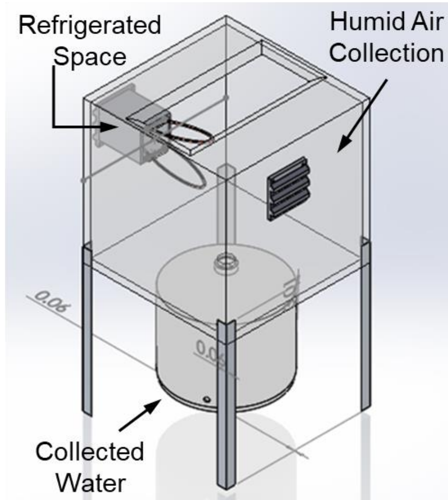

Fig. 4: Solar powered water collection via dehumidification.

Table 2: Parts List and Cost for Dehumidifier

Part	Unit Cost	Quantity	Total Cost
Fan	$17.96	1	$17.96
Thermoelectric Cooling Unit	$19.99	1	$19.99
Self-Adhesive Rubber Seal Strip	$10.50	1	$10.50
Wire Shrink Tubes	$6.22	1	$6.22
HDPE siding	$75.66	1	$75.66
Reflective Foil Tape	$3.35	1	$3.35
FoamSealR	$8.50	1	$8.50
Soft Copper Coil Tubing	$9.61	1	$9.61
Brass Compression Coupling Fitting	$4.37	1	$4.37
Return Air Vent Grille	$9.36	1	$9.36
Aluminum Angle	$20.58	1	$20.58
Insect Screen	$4.20	1	$4.20
5 Gallon Jug	$8.45	1	$8.45
1/2" Air and Water Hose	$15.99	1	$15.99
		Total	**$244**

Challenges Encountered

As of the time of writing of this paper, the parts are being ordered so that final prototype construction and testing can begin. One challenge that has come up in parts ordering is finding all parts from only a few approved vendors and at reasonable prices. While it would not be the most popular idea with administrators, it would be significantly easier to give students a blank check and tell them to get what they need. Putting this responsibility on the students is a good exercise in management, and with graduation dependent on successful prototypes, the chance for malfeasance would be very low.

The design teams were required to build two prototypes during their first semester of work. Historically, one of these prototypes is a 3D print of the design. For these projects, students wanted to prove the science behind their designs as one form of the prototype. For example, the desalination team wanted to use a heater coil to boil water. Their goals were to observe power required to create vapor as well as potential setups for the condensation plumbing. This proved difficult without some of the parts already on hand.

This illustrates a basic challenge in senior design. The department wants students to think completely through their designs before teams are allowed to order parts. This forces students to plan and minimizes (hopefully) waste. On the other hand, this policy makes it difficult to conduct early proof of concept tests.

References

1 National Academy of Engineering, *NAE Grand Challenges for Engineering*, www.engineeringchallenges.org, 2017.

2 "Freshwater Crisis," *National Geographic*, www.nationalgeographic.com, Accessed November 11, 2019.

3 Bienkowski , B. "Desalination is an expensive energy hog, but improvements are on the way," *Public Radio International*, www.pri.org, 2015.

4 Moran, M. J., Shapiro, H. N., Boettner, D. D., and Bailey, M. B., *Fundamentals of Engineering Thermodynamics*, 9th edition, Wiley, 2018.

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