Multi-Disciplinary Senior Design Conference
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**Project Number: 11411**

# EDUCATIONAL DESALINATION UNIT

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## ABSTRACT

The team goal was to design and fabricate an educational water desalinization tool for RIT-NY and RIT-Dubai that will demonstrate the small scale operation of a desalinization unit in an educational laboratory setting. The salt will be removed from seawater by using solar heat to first evaporate water and then collect the condensed water. In the process of completing this project, we will identify and provide solutions to international logistical issues encountered while working in a multi-national and multi-cultural environment.

The primary focus of this project is to better understand the desalinization process by focusing on designing and manufacturing a single laboratory-scale desalinization unit. The secondary focus of this project is to study and document processes, tools, and techniques for multi-national multi-disciplinary senior design projects. This project aimed to provide the foundation upon which future multi-national MSD projects will complete their senior design projects in a collaborative environment.

## NOMENCLATURE

Inputs from Typical Meteorological Year 3 Data

| | |
|---|---|
| $T_a$ | Ambient Temperature (C) |
| $I_{bt}$ | Incident beam radiation per unit area (W/m^2) |
| $I_d$ | Horizontal diffuse radiation per unit Area (W/m^2) |
| $G_t$ | Total (direct plus diffuse) solar energy Incident on the collector aperture (W/m^2) |
| $G_b$ | Beam (or direct) irradiation (W/m^2) |
| β | Incidence angle (degrees) |
| W | Wind velocity (m/s) |
| $T_{Ambient}$ | Output ambient temperature each hour |
| $H_d$ | Insolation Intensity. (MJ/m^2) |
| I | Insolation Intensity. (W/m^2) |

Still Variables

| | |
|---|---|
| $A_w$ | Surface Area of water in basin ($m^2$) |
| $A_g$ | Transparent Cover Area. ($m^2$) |
| h | Depth of Water in Basin (m) |
| ρ | Density of Salt Water (kg/m^3) |
| $V = hA_w$ | Volume of Water in Basin ($m^3$) |
| $\sigma$ | Stefan – Boltzmann constant |
| $SC_w$ | Specific Heat of Water ( kJ/Kg*K) |
| $C_w = V\rho SC_w$ | Heat capacity of water in basin (kJ/K) |
| $D_i$ | Inside Tube Diameter (m) |
| $h_{fi}$ | Heat transfer coefficient inside absorber tube (W/mC) |
| k | Absorber thermal conductivity (W/mC) |
| L | Collector length (m) |
| Θ | Acceptance Angle |
| $c_i = 1/\sin\theta$ | Concentration Ratio |
| $A_a$ | Absorber area (m^2) |

Compound Parabolic Collector Variables

| | |
|---|---|
| $T_p$ | The collector stagnation temperature |
| $C_p$ | Heat Capacity of Water (kJ/K) |
| $N_g$ | Number of glass covers |
| $\varepsilon_p$ | Emissivity of glass cover |
| $\varepsilon_g$ | Absorber plate emissittance |
| $\rho_m$ | Mirror reflectance |
| $D_o$ | Outside Tube Diameter (m) |

## INTRODUCTION

Water is one of the basic needs that the world's population relies upon in order to survive. Given the critical nature of water to humanities' survival and the manner in which numerous parts of the world struggle to provide water supplies to their citizens, RIT created a Sustainable Water Systems family of projects to provide a compelling solution to the problem of sufficient, accessible, economical, and sustainable water supply.

In recent decades, Dubai (UAE) has seen a significant growth in its population. The tremendous growth in this region of the world has led to Dubai becoming a major metropolitan in the world. Hence, a growing need has risen to provide this region with a sustainable water source.Projects addressing this issue are very important not only the growing region of Dubai, but to the rest of the world as well. Themajority of the world's population is within walking distance of a body of water, and it will soon become very critical for the world's population to harvest these water supplies in order to meet the world's growing water needs. Understanding the desalination process is therefore a critical component of these efforts.

In order to meet growing water demands, Dubai has been focusing on desalination efforts due to their proximity to the Arabian Sea. Numerous desalination plants have been built near or around Dubai in order to meet water needs, and many more will be built as this region continues to grow.

This project is a pioneering project within the Sustainable Water Systems family of projects, and the first one to focus on desalination water cleaning efforts. It is not a direct continuation of a previous senior design project. Ultimately, this project's objective is to develop a cleaning technology that will be placed in series with a biological cleaning system to achieve both salt/mineral free and bio-contaminant free water stream.

The unique nature of this project lies in the fact that there is no historical context with respect to a divided Senior Design team. This project is paving the way for developing a MSD program in RIT Dubai. The team of 3 Mechanical Engineering students spent the first quarter in Dubai while pioneering the way for future students to follow a curriculum similar to RIT's for future Dubai Senior Design projects.

This project has three main goals:

- Develop a water purification system that will be the building blocks for future generations of engineers to work from
- Design the system for use in a laboratory as a hands on, learning tool
- Understand the logistics required for a Senior Design project to successfully be completed in Dubai

**PROCESS**

The first step was to identify who and what our customer desired. Customer needs were identified through a series of interviews with the principle customer, Dr. Hensel. The overall scope of the project was deliberately kept moderately narrow in order to accommodate half the team being located at the RIT Dubai campus.

The primary design objective identified from customer needs was to desalinate enough water for an individual to subsist on a daily basis. From Dr. Stevens (ME Faculty), Dr. Hensel (ME Department Chair and Project Customer), and online resources this was identified as about two liters per day. This was identified to be the average amount over the course of a year. This 'average' definition became a critical point as the identification of customer needs progressed.The next major customer need focused on developing a system that could be implemented in an educational setting. Interpreting this need led to the true need of a system easily transported from the interior to exterior of the building.The customer also indicated the system should derive most of its energy from a renewable source. This also had to be consistent with resources that would be available to RIT Dubai students.Overall, the customer indicated they wanted a system that could be used utilized in an educational setting to desalinate water using renewable resource, with an overall build budget of $1500.

There are two parts to the results of this project. The first initial results are based off the theoretical model the team created. The theoretical model was created and uses data from the National Solar Radiation Data Base. This data represents the typical meteorological year (TMY3) for Rochester, NY.

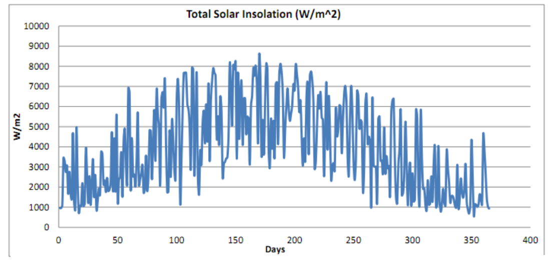


**Fig. 1** Total Solar Insolation for Rochester, NY

Fig. 1 shows the daily values that were imported from this data and used in the calculations. The complete theoretical modeling of the system was based on two different papers. The solar still is based on the paper by V. Belessiotis et al [1], and the concentrated parabolic collector was model from S. A. Kalogiro [2].

The first major design decisions focused on integrating desalination process with a renewable resource. The options were relatively limited. Multiple options were researched then compared using simplified theoretical models to quantify an estimated daily output. This eliminated a few options immediately as they were not realistic nor met the 2L/day criteria. The Solar Still option was the best combination of cost effectiveness, simplicity, daily mass output, and educationally rewarding concepts due to its proven methodology.

The method chosen to add energy to the system was a Compound Parabolic Collector (CPC). This unit was designed to sit on the lower shelf, directly under the Solar Still (placed on the upper shelf), when being transported. This CPC would then be pulled out upon reaching a testing location, and piped into the Solar Still. This effectively doubles the surface area collecting solar insolation without changing the footprint of the overall system. This integrates the customer objectives of helping insure a 2L/day usable water output, developing a system that is easily transportable, and demonstrating some interesting engineering principles.

The final design of the CPC was determined through a combination of variables.The parabolic shape and the number of CPC's were established by finding both an acceptance angle and pipe diameter that gave an acceptable concentration ratio, while also ensuring that it would fit within the width of the cart's lower shelf. A pipe diameter of 5.1cm [2 in] and an acceptance angle of 50degrees gave an acceptable concentration ratio of 1.31 and three CPC troughs. In order to satisfy the customer need of a sustainable system, the CPC would be angled at 33 degrees from vertical in order to create a thermo syphon effect. In order to maximize energy output, the angle should have been adjustable to both Rochester and Dubai latitudes. However, for simplicity and due to restrictions of the height of the cart (30 inches) and the length of the copper pipes (42 inches), this angle was chosen. Orienting the axis of the CPC north-south within the hours of 8 am to 4 pm allows the system to sufficiently meet or exceed customer needs.

In order to decrease heat losses, the troughs were fully constructed out of foam and a glass cover was placed over the troughs to trap the heat while also keeping the reflective surface free of dust and particles. Mylar was chosen as a reflective surface on the CPC to maximize reflectivity towards the copper pipe which was chosen for its excellent conductive properties to pre-heat the water before entering the solar still.

Assumptions

There were many assumptions that were made in this analysis that were justified using sensitivity analysis. These assumptions are as follows:

(1) The data is analyzed at the end of each hour for the entire year. The system is assumed to be at steady state between the hours.
(2) The collector optical efficiency is assumed to be 60%
(3) The bottom and edge heat losses of the CPC are neglected
(4) The mass flow rate of water through the CPC is 1 kg/hr
(5) The overall transmittance–absorbance product of the CPC is, assumed to be: $\tau\alpha = 0.6$
(6) The Glass Cover Temperature is equal to Ambient Temperature
(7) The Partial Pressure calculations used assume the water is between 10 C and 150 C
(8) Convective Heat Transfer Coefficient between glass and the environment for the Solar Still is assumed to be: $h_{cgs} = 15$
(9) Convective heat transfer Coefficient between water in basin and inside of cover for the Solar Still is assumed to be: $h_{cwg} = 5$

Pre-calculations

The partial pressures were calculated using equations that can be found in the appendix of V. Belessiotis et al [X]. Also for the analysis the Sky temperature and wind heat transfer coefficients were calculated for every hour using the TMY3 data and the following equations:

$$T_s = 0.0552 T_a^{1.5} \quad [1]$$

$$h_w = 5.7 + 3.8 * W \quad [2]$$

Using equations from V. Belessiotis et al [X] the latent heat of vaporization, radiative heat transfer coefficient between glass cover and environment and the radiative heat transfer coefficient between the water in the basin and glass cover were all calculated. The evaporative heat transfer coefficient between the water in the basin and the glass cover was also calculated using the partial pressures calculated above.

Solar Still Heat Losses

Total Heat Flow Factor for the Solar Still is calculated by the following equation:

$$U_t = \left(\frac{1}{U_i} + \frac{1}{A_r U_o}\right)^{-1} \quad [3]$$

The overall upward heat flow factor ($U_i$) for the Still is the sum of the convective, evaporative and radiative heat transfer coefficients between the water and the glass cover. The outside heat losses ($U_o$) is calculated from 70% of the wind heat transfer coefficient and the radiative losses from the glass cover to the sky.Finally, the Area Ratio ($A_r$) is the ratio of the glass surface area to the water surfacearea.

CPC Analysis

From S. A. Kalogiro [Y] the upward heat loss coefficients was calculated using the following equation:

$$U_t = \frac{1}{\left[\frac{N_g}{\frac{C}{T_p}\left[\frac{T_w - T_a}{N_g + f}\right]^{0.33} + \frac{1}{h_w}}\right]} + \frac{\sigma(T_w^2 + T_a^2)(T_w + T_a)}{\left[\frac{1}{\varepsilon_p + 0.05 N_g (1 - \varepsilon_p)} + \frac{2N_g + f - 1}{\varepsilon_g} - N_g\right]} \quad [4]$$

Since the bottom and edge losses on the still are neglected, this is the only heat loss term used in the calculation for the collector efficiency factor:

$$F' = \frac{\left(\frac{1}{U_l}\right)}{\left(\frac{1}{U_l} + \frac{D_o}{h_{fi} D_i} + \left(\frac{D_o}{2k} + \ln\left({}^{D_o}/_{D_i}\right)\right)\right)} \quad [5]$$

Using the equation provided by S. A. Kalogiro [Y] the useful energy gain per unit of collector length (W/m) was calculated for one collector trough. This was then translated to the entire system by multiplying by the number of collectors and the length. The total useful energy gained for entire CPC system in Watts can be given by:

$$Q_u = NL\left[F' \frac{A_a}{L}\left(n_o G_b - \frac{U_l}{C}\right)(T_w - T_a)\right] \quad [6]$$

This useful energy is then converted into a change in temperature, $\Delta T$, then added into the equation to calculate the change in the water temperature inside the still:

$$T_w(i+1) = \Delta T + \left(T_w(i) + 3600\left(\frac{A_w}{1000 * C_w}\right)\left(n_o I - U_t(T_w - T_a) - U_b(T_w - T_a)\right)\right) \quad [7]$$

This equation is then used to calculate the next hour's mass of output water:

$$M_{out} = A_g \left(\frac{h_{ewg}}{h_{fg}}\right)\left(\frac{U_t}{U_i}\right)\Delta t(T_w - T_a) \quad [8]$$

Fig. 2 and Fig. 3 show results from the simulations, showing the hourly temperature of the water and the mass output of the still, for each hour of the typical meteorological year in Rochester, NY. The average mass output is the desired result which was calculated to be 3.88 kg/day. This satisfies the minimum output desired and allows for an error in the model and still produce sufficient desalinated water to meet our customer's needs.

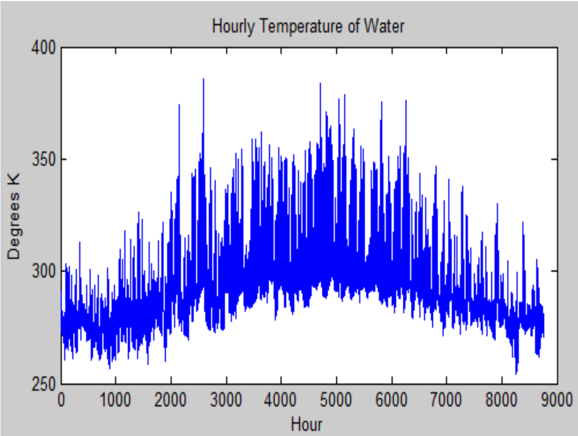


**Fig. 2**Hourly water temperature for one year

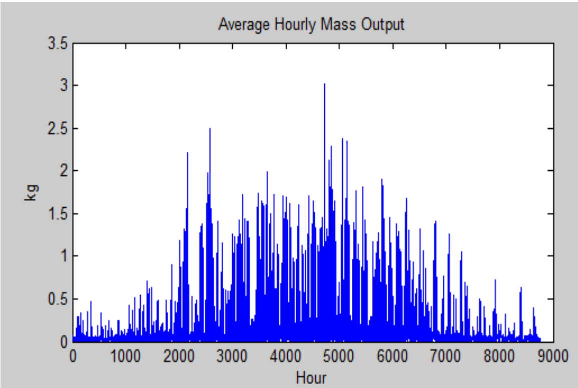


**Fig. 3**Average mass output for one year

Using the theoretical model shown above the team performed sensitivity analysis on certain parameters, (surface area, angle, etc.). The results of the modeling indicated a conveniently transportable size still while producing about 25% more usable water than customer requirements dictated. This 'conveniently transportable still' was also sized based off the dimensions of a donated sheet of 304 Stainless Steel. Certain assumptions were made in the theoretical modeling that simplified the process, but also made it optimistic with respect to daily mass output. A higher average daily mass output was desired in order to accommodate errors in the model.

Construction

The basin of the solar still was constructed using .159 cm [.063 in] steel sheet metal. The full sheet was cut into three pieces of the correct size for the bottom and sides, the back, and the front. To avoid additional cuts and welding, each of these pieces was bent to form the remaining features using a break. The three pieces were then welded together along what became the front and back edges of the basin. The basin was then ground and a layer of Solkote was applied to the bottom. Holes were drilled in the basin for the inlet of salt water, outlet of desalinated water, and the inlet and exit for the CPC. The collection trough was cut to size from the sheet metal, bent to an acute angle using the break and bolted at an angle to the front of the still. The sides of the still were made from polycarbonate cut to size using a table saw and bolted to the flanges on the sides of the basin. The valves were installed, the edges in the still were sealed with silicon glue, and the top edges were covered by neoprene for a waterproof gasket. The glass was then placed on and held in place by brackets made from polycarbonate. The still was placed on top of insulation board on the cart.

The CPC geometry was cut into two Masonitepieces using a laser cutter. These templates were then used to cut the CPC shape into the foam board using a hot bow. Mylar was then attached to the foam outlines to form the geometry of the CPC. The CPC frame was constructed from square steel tubing and bolted to the bottom of the box that would contain the CPC. The box was constructed from 1.27cm [.5 in] plywood and the CPC sections were inserted. The receiver tubes used were 5.08 cm [2 in] copper pipes. These were painted with Solkote and inserted into the CPC box. The manifolds were then constructed from CPVC pipe and attached to the receiver tubes. The glass was placed on top, inside the edges of the box, and held in place with polycarbonate clamps. The interface from the CPC to the still was made using 2.54cm [1 in] flexible tubing.

Data Acquisition

The scope of our project includes its use a lab demonstration stand, therefore a user friendly GUI logging the main parameters is necessary. The system operates without any external controls, however for a proper lab to be developed around the system the model must be compared to experimental results. The parameters identified as necessary are insolation, glass temperature, water temperature, salinity and yield. Insolation is measured using a pyranometer, it is not necessary to have a dedicated pyranometer, but for testing it is helpful. In the future the data will be available from the weather station on campus. Ultimately we could use other data such as wind speed and ambient temperature in a more complex model which could also be derived from data logged by this weather station. The glass and water temperatures require permanent dedicated equipment for measurement. For this type k thermocouples and Omega DAQ devices were used. This option to use individual DAQ systems was exercised because it is easier and less expensive than an 8 channel I/O. Yield is measured simply by a graduated cylinder and salinity is measured by a hydrometer.

## RESULTS AND DISCUSSION

After extensive testing of the system the results prove that we met all of the engineering specifications. The maximum daily output during testing was 3.65 liters, which is almost double the required output of 2 liters.

Using the data that was collected, the theoretical model was also evaluated. The results from two of the days of testing, and the theoretical predictions are shown if Figures 4 and 5 below:

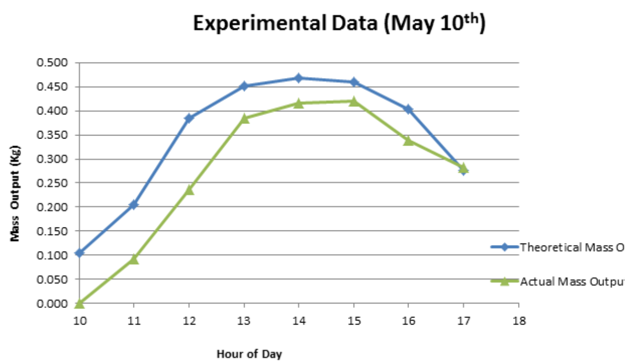


**Fig. 4** Collected Data and Theoretical Predictions for May 10, 2011

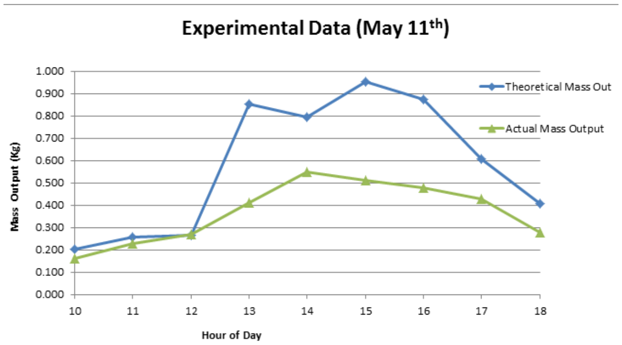


**Fig. 5** Collected Data and Theoretical Predictions for May 11, 2011

The theoretical prediction, overestimates the mass output for the system by 23%, on average. The difference is attributed to the following reasons:

(1) The theoretical model assumes the system is already primed, meaning that it was operating prior to the first data point. This is very obvious in the mass output graph for May 10$^{th}$, where the first 3 hours are spent getting the system completely primed. If this time frame is ignored, the system output is within 15% of the theoretical predictions.

(2) Many of the assumed values may be within 10-15% of the actual values, causing some discrepancy between the predicted and recorded values.

(3) The theoretical model assumes the system is completely sealed and there are no losses on through the sides of the still. The sealing of the glass on top of the system has been somewhat problematic, and the acrylic sides do allow for heat loss. This would cause the model to overestimate the output because the losses are neglected.

(4) The theoretical model assumes ***all*** evaporate water is collected. Through observation, the team has determined that the water droplets become too large and drop of the glass as they travel down. This does not always happen, and happens much less in the glass used on May 10$^{th}$ and May 11$^{th}$. This could also be why the data does not match the theoretical prediction for May 6$^{th}$.

## CONCLUSIONS AND RECOMMENDATIONS

The chosen design was an appropriate first iteration of the family of project that will focus on Sustainable Water Systems. The design met the desired objective of providing enough water for one person's daily consumption. In the process, there were successes and failures that the team encountered.

The team had a successful design stage given that the team was separated between two campuses for the first quarter of Senior Design. The successful design was derived through properly distributing the sub-systems between the two sub-teams, hence designing the Solar Still in Rochester and the CPC in Dubai. It allowed for both sub-teams to be involved in the design stage while handling a portion of the system.

The team had success in evaluating the theoretical model of the system, including the CPC, in order to predict the expected results. Combining the systems' theoretical models once the teams were together in Rochester was successfully completed once the team worked out the differences between the two theoretical models.

The major team successes lied in proving the concept of Solar Desalination while making enough water for one person's daily consumption. The team designed a system that is mobile to ease transportation. Specifically, the system can be a great asset in a laboratory setting. The data collection that the system enables will allow it to be an educational tool. The team successfully met all of the customer needs while dealing with the obstacles a multi-national project carries.

The team had failures in understanding the difference in regular CPVC material and that of Fire CPVC. Two types of CPVC were ordered for the CPC manifold, and during construction it was realized that the two are not compatible with one another. Hence, the team made a bearing fitting to accommodate the two different materials.

Given the changes of the Solar Still glass dimensions after a different cart was chosen to transport the Solar Still and the CPC, an order of an incorrect glass dimension was placed. The glass was tempered to make it safer for handling, but made it impossible to cut to the right dimension. As a result, there was an inch and a half of glass overhang on each side of the Solar Still.

The tempered glass was broken during setup of the Solar Still after too much stress was concentrated on the edge of the glass with one of the bolts that helps to hold the glass down. This allowed the team to experiment with non-Solar (Low FE) glass, and compare the two results.

The recommendations that the team would like to make would be to design the Solar Still and the CPC with the same glass dimensions. Given the possibility of breaking glass during setup or disassembly, it would be beneficial to take the CPC glass and place it onto the Solar Still. The team also found that successful results can be obtained through the use of non-Solar (Low FE) glass, and this option is much more inexpensive.

The diameter of the copper pipes in the CPC can be reduced in order to reduce cost. The team designed the CPC with 2” diameter copper pipes, but later realized that a smaller diameter pipe could have achieved the same results with a lower cost.

The material used to build the SolarStill, 16 Gauge 304 Stainless Steel sheetmetal, was difficult to work with. A material easier to work with, potentially Aluminum or Polypropylene, would allow more room for error as well as decrease SolarStill manufacturing time.

The customer satisfaction was achieved because the team successfully designed the system to the customer needs while building the infrastructure for future multi-national Senior Design projects. Even though there were failures along the way, it allowed the team to provide recommendations for future Sustainable System Projects within the Mechanical Engineering department.

## REFERENCES

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[2] S. Kalogirou, “Solar thermal collectors and applications,” *Progress in Energy and Combustion Science*, vol. 30, 2004, pp. 231-295.

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