Designing and Manufacturing a High Productivity Desalination Unit

Hussein Zein Korany[1, 2, *]
[1]Mechanical Engineering Department, College of Engineering, Qassim University, Buraidah 51452, Saudi Arabia [2]Mechanical
[2]Design and Production Department, Faculty of Engineering, Cairo University, Giza12613, Egypt
*dr.husseinzein@qec.edu.sa

Abstract

The world is progressing toward the renewable energy field. The Saudi government, represented by Saudi Vision 2030, is aiming to position itself alongside the world's leaders in this field. The Solar Still Desalination System represents renewable energy, where drinkable water is produced from saline water by using the solar energy of the sun to evaporate water so that it may be cooled and collected, thereby purifying it. The main objective of this paper is to design and manufacture a desalination unit with high productivity. The main goal is to achieve desalination productivity of 3 L/day of fresh water, which is equivalent to the daily needs of one person, using only natural resources "Green Energy". To achieve this objective, a passive (no external heat sources are needed) stepped solar still desalination unit will be designed and manufactured due to its high productivity of freshwater. The experimental results showed that the performance of the designed desalination system was satisfactory.

Keywords: Solar still; Desalination system; saline water; Freshwater; Design parameters; Efficiency.

1. Introduction

Aristotle (384–322 BC) gave one of the earliest historical descriptions of the desalination process: "Now the sun, moving as it does, sets up processes of change and becoming and decay, and by its agency, the best and sweetest water is carried out every day and is dissolved into vapor and rises to the upper regions, where it is condensed again by the cold and so returns to the earth; this is the regular cycle of nature." [1].

Drinkable Water is an important part of human nutrition, directly as drinking water or indirectly as a constituent of food, in addition to various other applications in daily life [2]. According to "Institute of Medicine of the National Academies" the suggested amounts of water to consume per day are 3.7 liters/day for adult males, and 2.7 liters/day for adult females [3]. In 2019 the "General Authority for Statistics" have conducted a census regarding the population of Saudi Arabia. The results were: 15,466,126 adult males, and 10,362,080 adult females, are living in Saudi Arabia [4]. Meaning that Saudi Arabia's population by itself consumes well over 85 million liters of water per day.

The Process of Desalination involves the removal of salts or any impurities in the water that comes from the sea, rivers, oceans, etc.., and it is considered one of the most common techniques to get freshwater for human consumption [6]. The process of water desalination can be categorized into three major techniques that are [7]:

1. Thermal Process
2. Membrane-Based Process (Non-thermal)
3. Solar-Based Process

Thermal desalination processes are based on the intentional changes in the physical state of water to separate the salt and obtain fresh water, with help of conventional technologies to operate the process [8 and 9]. Thermal Desalination is divided into 2 subsections: Evaporation, Crystallization.

Solar Still Desalination Systems are devices that use solar radiation to distill salt or briny water to produce drinkable water. This concept is also useful in the context of supplying water to urban or unaccommodated communities [10]. Types of Solar Still Desalination Systems: solar stills are classified into two different types:

Passive Solar Still: In the case of passive stills, the water in the basin goes through direct heating, which means that no external sources are needed, the process of passive stills occurs in one system.

Active Solar Still: The water in active solar stills goes through direct heating as well, but it also receives preheated water via an external source.

The world is progressing toward renewable energy projects, as well as the Saudi Government with its vision for 2030, the main objectives of this paper are to design and manufacture a desalination unit with high productivity. The main goal is to achieve desalination productivity of 3 L/day of freshwater, which is equivalent to the needed consumption of one person, using only natural resources "Green energy". The design is completely safe and complies with the standards. The production of water requires minimum energy.

2. Constraints and Design Requirements

2.1. Brainstorming for Design Parameters and Constraints:

There are many parameters to be considered when designing a Solar Still Desalination Unit (S.S.D.U), based on the literature review, the design parameters are:

- Inclination angle.
- Area of the basin.
- Configuration of Solar Still System (Single, Double, and …etc).
- Distance between the glass cover and the basin.
- Mechanical properties of the used materials of (S.S.D.U).

2.2. The Technical Design and Other Realistic Constraints:

Regarding the productivity of the S.S.D.U, the more effective design parameters for the S.S.D.U are presented in reference [11], some parameters are controllable, and some are adjustable, but the constraints can be regarded as the climatic parameters because they are dependent upon the geographic location of the system. The productivity of the S.S.D.U is influenced by three factors; namely ambient, operating, and design conditions. Ambient conditions include ambient temperature, isolation, and wind velocity. While operating conditions are included water depth, various dyes, still orientation, and inlet temperature [11]. The main constraints considered for the present study are:

- Solar still does not require any external power sources.
- The system is manufacturable.

Pathing the way for manufacturing and evaluation.

2.3. Kepner-Tregoe Decision Analysis (KTDA)

The Kepner-Tregoe Process for Problem Solving and Decision Making (PSDM). It is a step-by-step, conscious process for solving problems, making good decisions, and analyzing potential risks and opportunities [12]. The comparison was done between Six S.S.D.U. Four of them are passive S.S.D.U as presented in Table 1:

- Single Slope, single basin S.S.D.U.
- Double Slope S.S.D.U.
- Pyramid S.S.D.U and Single Slope.
- Double basin S.S.D.U.

In addition, the other two are active of S.S.D.U:

- Nocturnal S.S.D.U.
- Single slope hybrid (PV/T) S.S.D.U.

When designing any project, the process of decision-making is achieved by brainstorming a list of musts and wants, musts will include all those that are essential for any solution to be effective, and they act as design constraints for the system.

The design constraints ***(musts)*** for the System are:

- The System is manufacturable.
- The System does not require an external power source.

After applying the design constraints (**musts**), there was only the passive S.S.D.U. These types of passive S.S.D.U are commonly used. The 'wants' are those expendable requirements that you would like the solution to include, expendable meaning that they are not as essential as the 'Musts'.

Based on the literature review [13 - 17], the design requirements ***(Wants)*** for the System are:

- Productivity
- Estimated price
- Efficiency
- The number of sides to absorb solar radiation is shown in Figures 1, Figures 2, and Figures 3.

Weighting and rating mechanisms are done based on the estimation of the degree of importance of the design requirements ***(Wants)*** according to the literature review [13 - 17].

Figure 1: Single Slope S.S.D.U [13].

Figure 2: Doube Slope S.S.D.U [13].

Figure 3: Pyramid Slope S.S.D.U [13].

2.4. Adverse consequence table

The second step is to create the adverse consequence table for the top two S.S.D.U. as shown in Table 2. The Probability of occurrence is gathered by comparing a set of research papers regarding S.S.D.U systems, and the problems or instructions for future S.S.D.U systems [18 - 21].

Table 1: KT decision analysis.

	Alternative:		A: Single Slope, single basin S.S.D.U		B: Double Slope S.S.D.U		C: Pyramid S.S.D.U		D: Single Slope, double basin S.S.D.U		E: Integrated S.S.D.U		F: Single slope hybrid (PV/T) S.S.D.U	
Musts	1. The System is Manufacturable		GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO
Musts	2. Doesn't require an external power source		GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO	GO	NO GO
Wants		Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
1. Productivity		10	8	80	9	90	10	100	6	60				
2. Cost		7	10	70	8	56	5	35	9	63				
3. Efficiency		7	10	70	6	42	9	63	7	49				
4. Number of sides to absorb solar radiation		6	7	42	8	48	10	60	7	42				
			Total A: 262		Total B: 236		Total C: 258		Total D: 214		Total E:		Total F:	

Table 2: adverse consequences.

CONSEQUENCE	ADVERSE CONSEQUENCES			
	Probability of Occurrence (P)	**Seriousness (S)**	**P * S**	**Total**
SOLUTION NAME (Single Slope, single basin S.S.D.U)				
Using non-optimum materials	85%	4	3.4	7.8
Not Using reflectors and mirrors to maximize the productivity	70%	2	1.4	
Less overall production than the Pyramidical S.S	100%	3	3	
SOLUTION NAME (Pyramidal S.S.D.U)				
Using non-optimum materials	85%	4	3.4	12.35
Lacking the ability to enhance the design of the Pyramidical S.S.D.U	100%	5	5	
Not Using reflectors and mirrors to maximize the productivity	70%	2	1.4	
Limiting the ability to adjust the tilt angle according to the parameters of the design	85%	3	2.55	

The final score is obtained by subtracting the adverse consequence score from the total KTDA score; as in Table 3. To achieve high productivity of freshwater, it's found that the stepped and weir type inclined solar still, shown in Figure 4, improves the distilling output by more than 50 % [18]. In addition, aluminum oxide materials enhanced the distillate by 88.97% [19]. As a result, the final selection of the solar still desalination unit is a single slope, single basin, with multi-steps as a modification to increase the efficiency and overall productivity as shown in Figure 4 for the stepped solar step desalination unit.

Table 3: Highest Score S.S.D.U

Solar Still Desalination System	Score
Single Slope, single basin S.S.D.U	262 - 7.8 = 254.2
Pyramidal S.S.D.U	258 - 12.35 = 245.65

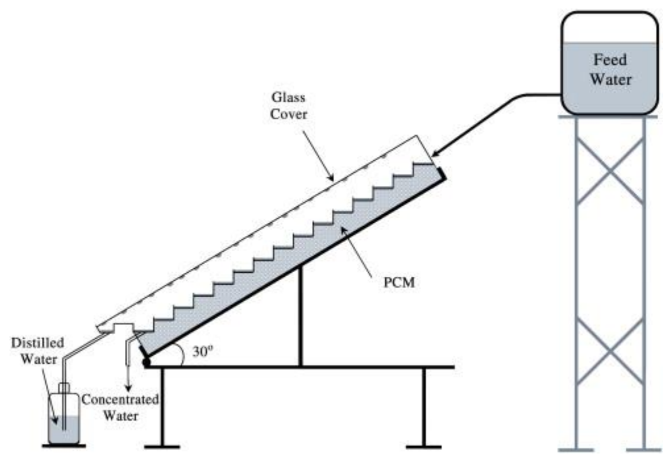


Figure 4: Cross-sectional view of a schematic diagram of stepped solar still [16].

3. Design of the Stepped Solar Still Desalination Unit (S.S.D.U.)

Figure 5 is shown the design of the stepped solar step components according to the input volume of the saltwater to the system. Figure 6 displays the proposed model of the solar desalination system.

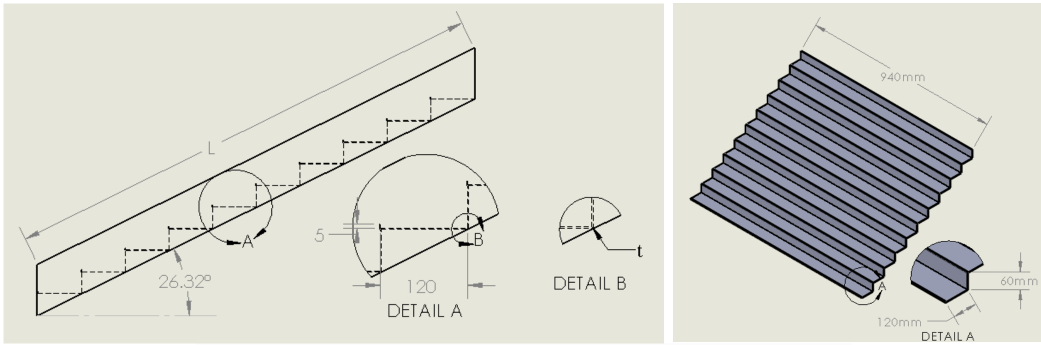


Figure 5: Dimensions of the basin of the desalination unit.

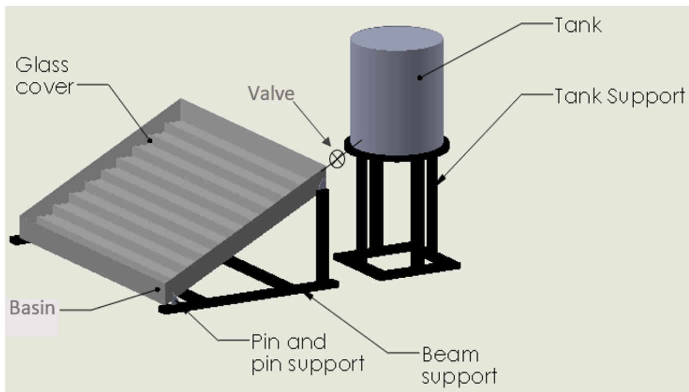


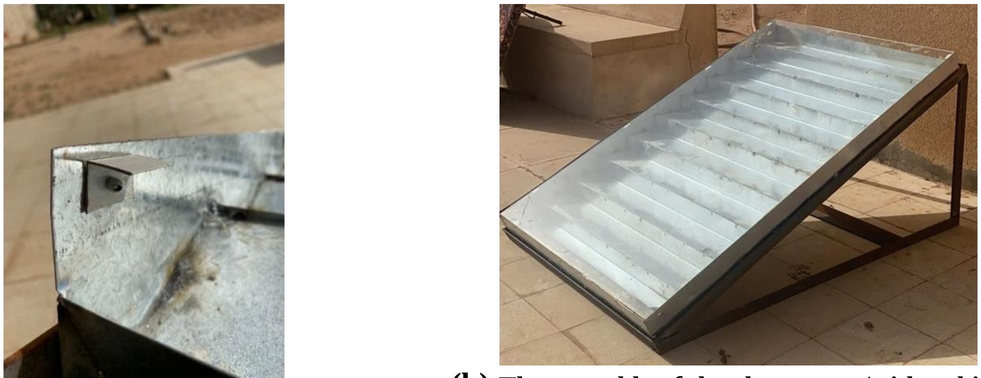
Figure 6: The proposed model of the solar desalination system

4. Manufacturing of Desalination Unit

This section contains all manufacturing processes of the Stepped Solar Still Desalination Unit (S.S.D.U), according to the design components. Figure 7 (a) shows the stages of manufacturing the basin, starting with cutting the sheet steps, then bending for each step, and finally assembling the steps of the basin by using the welding process. Figure 7 (b) displays the assembly of the main base with the basin of the S.S.D.U. Figure 8 shows the installation of aluminum stands on which to place the glass cover on top of the basin. Figure 9 demonstrates the paint of the basin with black color. Finally, Figure 10 displays the S.S.D.U. after assembling its all components.

(a) Assembly of stepped basin component **(b) Assembly of the main base with the basin of the S.S.D.U.**

Figure 7: The stages of manufacturing for the basin of the S.S.D.U.



(a) **The installation of aluminum stands**

(b) **The assembly of the glass cover (with a thickness of 6 mm) on top of the basin**

Figure 8: The installation of aluminum stands on which to place the glass cover on top of the basin.

Figure 9: Painting the basin with black color.

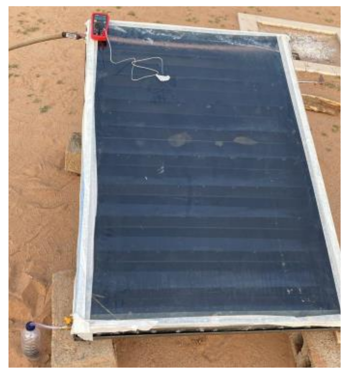


Figure 10: The Stepped Solar Still Desalination Unit (S.S.D.U).

5. Results and discussion

This section aims to evaluate the performance of the final product, investigated the amount of the output freshwater theoretically and experimentally, and the efficiency of the final product. The temperatures of the solar unit are measured during three sample days, which were Wednesday 11/5/2022, Thursday 12/5/2022, and Friday 13/5/2022, the process of measurement was achieved by applying thermal probes as well as a K-type thermocouple, the average temperature values are presented in Figure 11, Figure 12, and Figure 13. Based on Figure 11, Figure 12, and Figure 13 the maximum temperature at 1:00 PM and 2:00 PM. The maximum temperature of the inside glass was 68.2˚C at 1:00 PM on 1st day. While the maximum temperature of the water was 66.2˚C at 1:00 PM on 1st day. Moreover, the maximum temperature of the outside glass was 63.7˚C at 2:00 PM on 1st day.

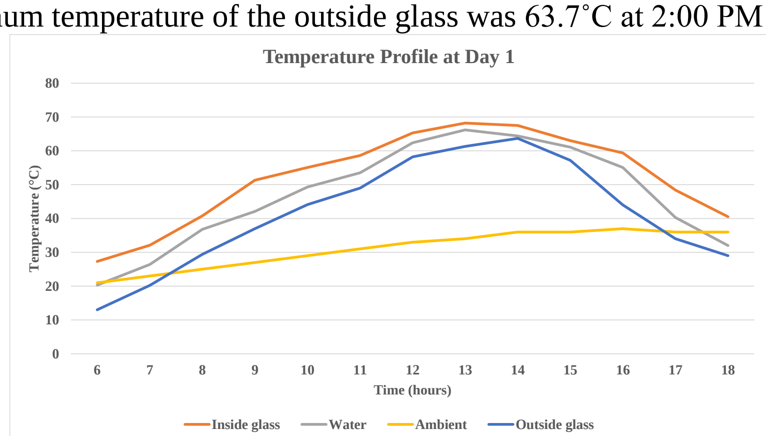


Figure 11: Temperature Profile on Day 1

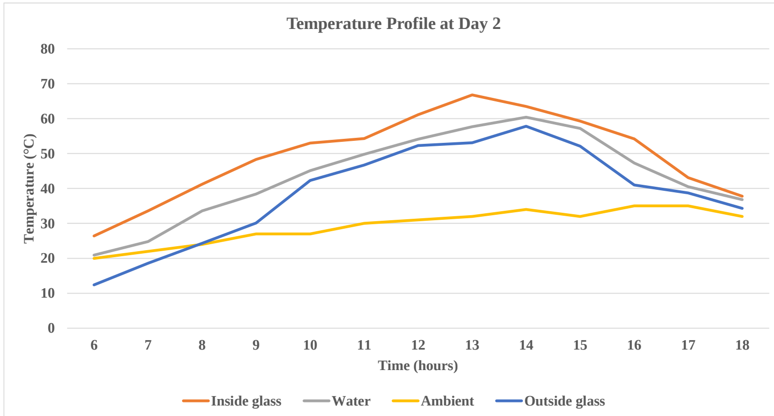


Figure 12: Temperature Profile on Day 2

Regarding the amount of the output freshwater during the days of evaluations, the maximum output of freshwater in 1 hour is between 400 ml at 1:00 PM, when the sun is directly vertical on the unit. In order to compare the amount of freshwater theoretically and experimentally, the following equations will be used [22]:

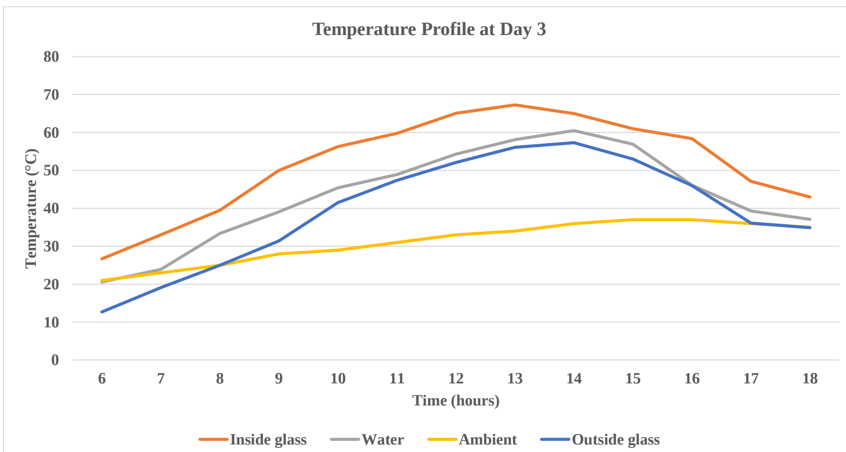


Figure 13: Temperature Profile on Day 3

- Partial vapor pressure (P_w) in the unit of (N/m^2) at water temperature (T_w)

$$P_w = 100(0.004516 + 0.0007178\, T_w - 2.649 * 10^{-6}\, T_w^2 + 6.944 * 10^{-7}\, T_w^3) \qquad \text{Eq. (1)}$$

- Partial vapor pressure P_g in the unit of (N/m^2) at glass temperature (T_g)

$$P_g = 100(0.004516 + 0.0007178\, T_g - 2.649 * 10^{-6}\, T_g^2 + 6.944 * 10^{-7}\, T_g^3) \qquad \text{Eq. (2)}$$

- The Dunkle convective heat transfer coefficient from the water surface to the glass cover (kJ/kg)

$$h_{c,w} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}} \qquad \text{Eq. (3)}$$

- Evaporation heat transfer q_{ew} in the unit of (W/m^2)

$$q_{ew} = 0.0163\, h_{cw}(P_w - P_g) \qquad \text{Eq. (4)}$$

- The hourly output volume V_{th} from the S.S.D.U. in the unit of (L)

$$V_{th} = 3600\, \frac{q_{ew}}{L_v}\, A_b \qquad \text{Eq. (5)}$$

Where:

L_v = latent heat of vaporization (kJ/kg)

L_v =2320 kJ/kg.

- Deviation (%)

$$\text{Deviation} = \left(\frac{V_{th} - V_{exp}}{V_{th}}\right) * 100\% \quad \text{Eq. (6)}$$

- Efficiency (%)

$$\text{Efficiency} = \left(\frac{V_{exp}}{V_{Input}}\right) * 100\% \quad \text{Eq (7)}$$

The results for calculating the amount of freshwater theoretically and experimentally are shown in Table 4. It's clear that the third day has less deviation (21.62 %) and the second day has the best efficiency (21.42 %). The amount of freshwater theoretically and experimentally is shown in Figure 14, Figure 15, Figure 16, and Figure 17.

Table 4: The final result for calculating the amount of freshwater.

Day	P_w, (kPa)	P_g, (kPa)	h_{cw}, (kJ/kg)	q_{ew}, (W/m^2)	V_{Input}, (L)	V_{th}, (L)	V_{exp}, (L)	Deviation	Efficiency
1	10.41	7.96	1.55	61.91	5.6	1.29	0.93	27.9 %	16.6 %
2	9.95	6.87	1.49	74.75		1.56	1.2	23.07 %	21.42 %
3	9.47	7.13	1.39	53.15		1.11	0.87	21.62 %	15.53 %

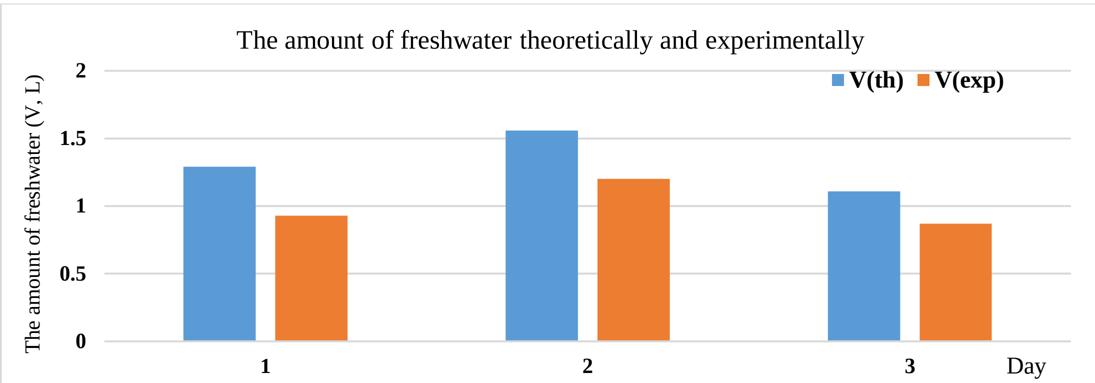


Figure 14: The amount of freshwater theoretically and experimentally.

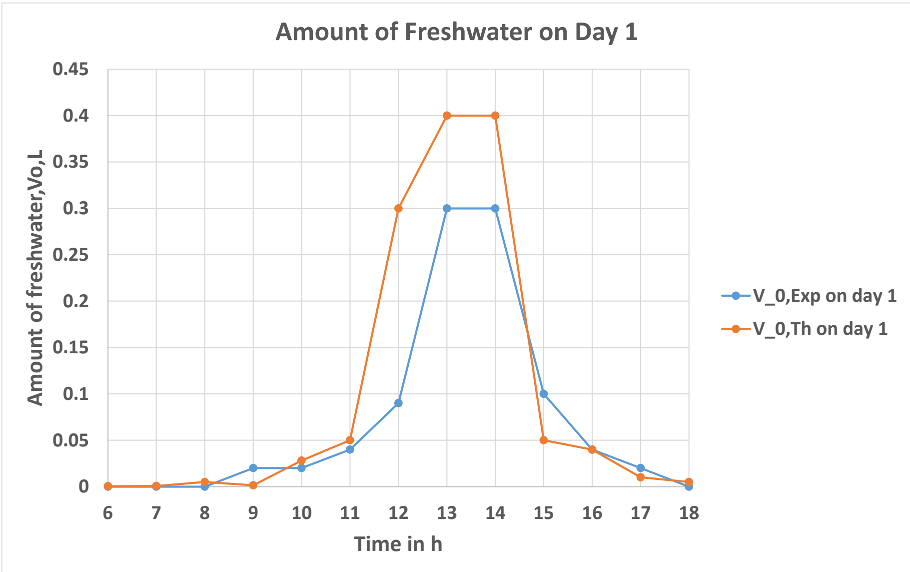


Figure 15: The amount of freshwater on day 1

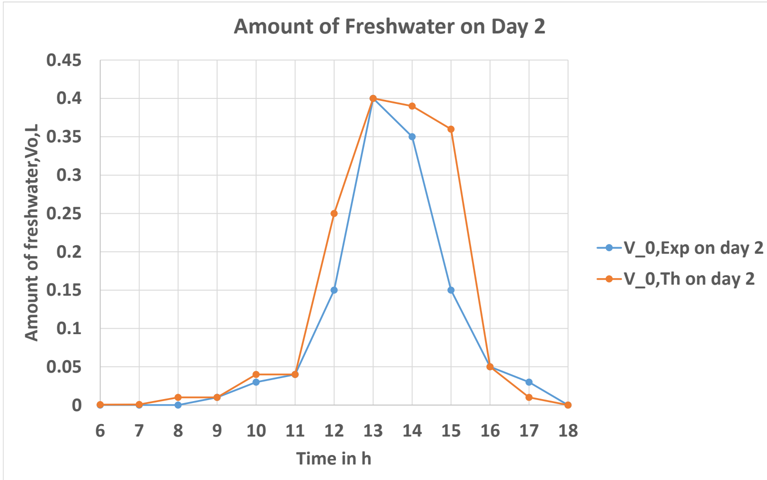


Figure 16: The amount of freshwater on day 2

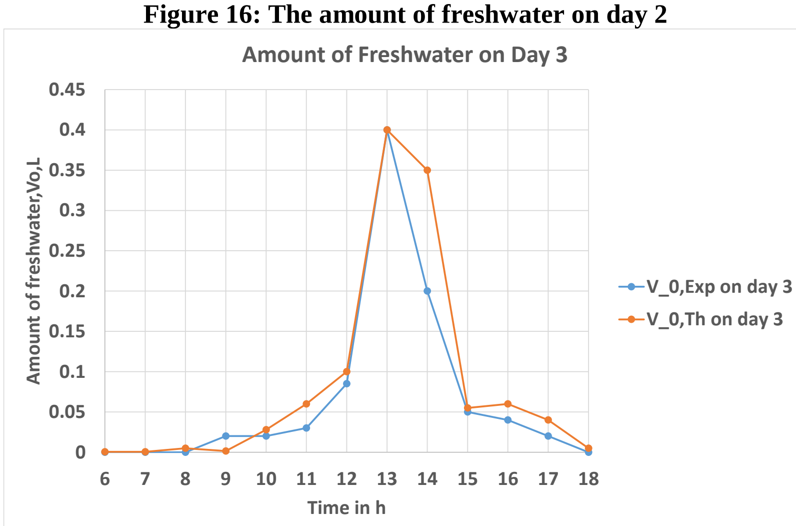


Figure 17: The amount of freshwater on day 3

As shown in the last three figures, there is almost the same difference (deviation) between the amounts of freshwater theoretically and experimentally on days of evaluations. Where on day 2 and day 3, the output of the freshwater theoretically and experimentally was the highest compared with day 1.

1. Conclusion

A passive still type of stepped solar still desalination unit was designed and manufactured successfully. Also, the performance of the desalination unit is evaluated theoretically and experimentally. It was discovered that the desalination system's efficiency is consistent with what is found from the literature review for the majority of desalination systems [13-14] and [17]. By taking into consideration the following recommendations, it is possible to enhance freshwater's productivity and efficiency:

- Decreasing the thickness of the glass cover to be less than 6 mm will increase the absorbed solar energy.
- Install wheels for the desalination unit to facilitate its transportation and to be able to always direct it in the direction of sunlight.
- Properly insulating the bottom and side walls of the desalination system results in lower heat losses.
- Use reflectors to enhance the absorbability of sunlight.

References

[1] Delyannis, E. “Historic background of desalination and renewable energies,” Solar Energy, 75(5), 2003, pp. 357–366. https://doi.org/10.1016/j.solener.2003.08.002

[2] Ford TE Microbiological safety of drinking water: United States and global perspectives. Environ. Health Perspect. 1999; 107 (Suppl. 1), pp. 191–206.
[3] Dietary Reference Intakes. "The Essential Guide to Nutrients Requirements" Institute of Medicine of the National Academies: Washington DC, 2006, p. 543.
[4] General Authority for Statistics, Population in Kingdom by Gender, Age Group,and Nationality (Saudi/Non-Saudi) https://www.stats.gov.sa/en/1007-0.
[6] Asadollahi, Mahdieh, et al. "Enhancement of Surface Properties and Performance of Reverse Osmosis Membranes after Surface Modification: A Review," Desalination, vol. 420, 2017.
[7] Eltawil, Mohamed A., et al. "A Review of Renewable Energy Technologies Integrated with Desalination Systems," Renewable and Sustainable Energy Reviews, vol. 13, no. 9, 2009, pp. 2248–54.
[8] Tiwari, G., and Lovedeep Sahota "Advanced Solar-Distillation Systems: Basic Principles, Thermal Modeling, and Its Application (Green Energy and Technology)," 1st ed., Springer, 2017.
[9] Prajapati, Mitul, et al. "Groundwater for Sustainable Development," Geothermal-Solar Integrated Groundwater Desalination System: Current Status and Future Perspective, 2021, pp. 2–12.
[10] Davim J. P. "Modern mechanical engineering: research, development and education," Berlin: Springer; 2014.
[11] Muftah, A. F., Alghoul, M., Fudholi, A., Abdul-Majeed, M., & Sopian, K. "Factors affecting basin type solar still productivity: A detailed review," Renewable and Sustainable Energy Reviews, 32, 2014, 430–447. https://doi.org/10.1016/j.rser.2013.12.052
[12]Website:https://www.kepner-tregoe.com/lp/problem-solving-and-decision-making-workshop/, visited on 16/10/2021 at 11:32 AM.
[13] Husham M. Ahmed, et al. "Impact of Different Configurations on Solar Still Productivity." Journal of Advanced Science and Engineering Research Vol 4, No 2, 2014, pp. 118–126.
[14] Modi, Kalpesh V., et al. "An Approach to Optimization of Double Basin Single Slope Solar Still Water Depth for Maximum Distilled Water Output." Journal of Renewable and Sustainable Energy, vol. 10, no. 4, 2018, pp. 2–8. Crossref, doi:10.1063/1.5023088.
[15] H.E.S. Fath, et al. "Thermal-Economic Analysis and Comparison between Pyramid shaped and Single-Slope Solar Still Configurations." ELSEVIER, 2003, pp. 7–10.
[16] Singh, Rajindar, and Hankins. Emerging Membrane Technology for Sustainable Water Treatment. 1st ed., vol. 1, Maarssen, Netherlands, Elsevier Gezondheidszorg, 2016, pp. 3-13.
[17] Rajaseenivasan, T., and K. Kalidasa Murugavel. "Theoretical and Experimental Investigation on Double Basin Double Slope Solar Still." Desalination, vol. 319, 2013, pp. 25–32. Crossref, doi:10.1016/j.desal.2013.03.029
[18] Narayanan, S. S., Yadav, A., & Khaled, M. N. A concise review on performance improvement of solar stills. SN Applied Sciences, 2(3), 2020. https://doi.org/10.1007/s42452-020-2291-5
[19] Sharshir, S., Yang, N., Peng, G., & Kabeel, A. Factors affecting solar stills productivity and improvement techniques: A detailed review. Applied Thermal Engineering, 100, 2016, pp. 267–284. https://doi.org/10.1016/j.applthermaleng.2015.11.041
[20] Tabrizi, F. F., Dashtban, M., & Moghaddam, H. Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system. Desalination, 260(1–3), 2010, pp. 248–253. https://doi.org/10.1016/j.desal.2010.03.033
[21] Tanaka, H., et al. "Experimental Study of Basin-Type, Multiple-Effect, Diffusion-Coupled Solar Still." Desalination, vol. 150, no. 2, 2002, pp. 131–33.
[22] Soteris A. K. "Solar Energy Engineering: Processes and Systems," 2nd ed., Academic Press, 2014, pp. 430-448.