

Mathematical Modelling to Predict the Best Inclination Angle for Maximum Distillate Output of A Solar Still [†]

Nawaf Mehmood Malik ^{*}, Mansoor Ali Zaheer, Asif Ali  and Abdul Haseeb 

Department of Mechanical Engineering, College of Engineering and Technology, University of Sargodha, Sargodha 40100, Punjab, Pakistan

^{*} Correspondence: nawaf998428@gmail.com[†] Presented at the 2nd International Conference on Advances in Mechanical Engineering (ICAME-22), Islamabad, Pakistan, 25 August 2022.

Abstract: Solar stills are generally used to obtain fresh and clean water from saline water sources using solar energy. This technique is very economical, as only the source of energy is solar energy. Many factors affect the efficiency of the solar stills, such as altitude, location, wind velocity, thickness, the inclination angle of the glass, etc. In this paper, mathematical modelling of three different solar stills with glass inclination angles of 15°, 30°, and 45° has been carried out to calculate the total radiation falling on these solar stills in addition to the calculation of the total heat transfer inside of them. These parameters are further utilized to compute the distilled water output from 10 a.m. to 4 p.m. by considering the location of the Sargodha, Punjab, Pakistan, on the 22nd of June.

Keywords: heat transfer; inclination angle; solar still

Citation: Malik, N.M.; Zaheer, M.A.; Ali, A.; Haseeb, A. Mathematical Modelling to Predict the Best Inclination Angle for Maximum Distillate Output of A Solar Still. *Eng. Proc.* **2022**, *23*, 5. <https://doi.org/10.3390/engproc2022023005>

Academic Editors: Mahabat Khan, M. Javed Hyder, Muhammad Irfan and Manzar Masud

Published: 20 September 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

A lot of the solar desalination plants that are operational today have a major drawback in that they are very costly and utilize a lot of energy [1]. Scientists have predicted that the demand for water will be 56% more than its supply by 2025 [2]. One of the most reliable technologies to solve water scarcity issues is water desalination using solar stills [3]. Factors that affect the yield of solar stills are solar intensity, the temperature of the air and its velocity, differences in temperature between the glass and water vapor, the water surface area, water depth, the inlet water temperature, the area of the basin, and the inclination angle of the glass [4].

Researchers have shown that for solar distillation, the most suitable material for these covers is glass, as it has higher solar radiation transmittance at different angles [5]. A 4 mm glass cover thickness is considered the best [6]. A 2 cm water depth is the best for producing the most distilled water using solar stills [7].

A higher water temperature inside the solar still will result in increased distilled water output [8]. The productivity of the solar still also depends upon the surface area of the collector [9]. The inclination angle of the glass surface and the direction of the glass cover on the still depend on the latitude of the specified location [10].

2. Methodology

The three different angles of inclination being used are 15°, 30°, and 45°. The total radiation falling on the solar stills is calculated theoretically; then, heat transfer calculations of the solar still are carried out to find the particular inclination angle on which maximum yield occurs. The calculations were conducted for a time period of 6 h on 22 June 2021 for the location of Sargodha city. The following assumptions were made while conducting the calculations [11]:

In the solar still, there is no leakage of vapors, and there is no heat loss in the basin.

1. There is a constant water level maintained in the basin.
2. Only filmwise condensation occurs, and it occurs in place of dropwise condensation.

Filmwise condensation is considered because in dropwise condensation, the transfer rates of heat are more than ten times those of film-type condensation [12]. The design of the solar stills with the inclination angles of 15°, 30° and 45° are given in Figure 1:



Figure 1. Solar stills with different inclination angles.

The area of the water surface is 0.403 m². The depth of the water is kept at 2 cm or 20 mm for best performance [1]. The thickness of the glass is kept at 4 mm for the best results [8], and the thickness of the base metal is 6mm. Glass is used for the cover material [7]. The calculations for total radiation on the solar still and heat transfer are for the passive single-slope solar still model.

3. Total Radiations Calculations on Solar Still

We can find the radiation (I_t) available to the solar still as follows:

$$I_t = [I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + I_{Pg} \left(\frac{1 - \cos \beta}{2} \right)] \tag{1}$$

The amount of solar radiation available above the surface of the Earth (I_0) is:

$$I_0 = \frac{12 * 3600}{\pi} G_{sc} \left(1 + 0033 \cos \frac{360n}{365} \right) \left[\cos \phi \cos \delta (\sin \omega_2 + \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} (\sin \phi \sin \delta) \right] \tag{2}$$

The incident angle of sun rays for tilted surfaces is θ . It can be computed as:

$$\theta = \frac{(\sin(\phi) \cos(\beta) \sin(\delta) - \cos(\phi) \cos(\gamma) \sin(\beta) \sin(\delta) + \cos(\phi) \cos(\omega) \cos(\beta) \cos(\delta) + \sin(\phi) \cos(\omega) \sin(\gamma) \cos(\delta) + \sin(\beta) \sin(\omega) \sin(\gamma) \cos(\delta)) \cos^{-1}}{\tag{3}}$$

The diffuse fraction is calculated using the model of Orgill and Holland:

$$\text{For } 0 < K_t < 0.35 \text{ when } I_d/I = (1 - (K_t) 0.249) \tag{4}$$

$$\text{For } 0.35 \leq K_t \leq 0.75 \text{ when } I_d/I = (1.577 - (K_t) 1.84) \tag{5}$$

$$\text{For } 0.75 < K_t \leq 1 \text{ when } I_d/I = (0.177) \tag{6}$$

The beam radiation tilt factor (R_b) is given as:

$$R_b = \frac{\text{Cos}\theta}{\text{Cos}\theta_z} \tag{7}$$

4. Heat Transfer Calculations of the Solar Still

The convective transfer of heat between glass and water (Q_{cwg}) is calculated as follows:

$$Q_{cwg} = 0.884[(T_w - T_g) + \frac{P_w - P_g}{268e^3 - P_w} \times T_w (T_w - T_g)] \tag{8}$$

The water temperature in the water basin (T_w) and glass temperature is calculated as:

$$T_w = \frac{f(t)}{\alpha} (1 - \exp(-\alpha_w \tau_w)) \exp(-\alpha_w \tau_w) \tag{9}$$

Here, the emittance of glass is kept at 0.05 [13]. The water heat capacity present in the basin is 4.184 J/K [14]. The absorptivity of the glass is 0.05 [15]. The absorptance of the base plate is 0.92 [16]. The temperature of the glass (T_g) can be calculated using the following formulas given below:

$$T_g = \frac{(0.022612T_w^2 - 15.76T_w + 2392) * T_w * h_w * T_a * Ar + Ar(0.048T_a - 9)T_s}{(0.022612T_w^2 - 15.76 * T_w + 2392) * h_w * T_a * Ar + (0.040T_a - 9)} \tag{10}$$

To calculate the temperature of the base plate (T_b) or water basin, use the given Equation:

$$T_b = \frac{\alpha_b \tau_g \tau_w I(t) + h_{cblw} \times T_w + U_b \times T_a}{h_{cblw} + U_b} \tag{11}$$

The evaporative mass transfer to the glass cover (m_{ev}) from the water surface is calculated as:

$$M_d = 3600 \int_{t_1}^{t_2} M_{ev} dt \tag{12}$$

The solar water desalination unit's thermal efficiency (η) can be calculated as

$$\eta = \frac{q_{ewg}}{I_t} \tag{13}$$

5. Results and Discussion

Solar Still with glass inclination angle of 45° gives maximum distilled output as compared to its counter parts in Sargodha region on 22 June. Its productivity is 12.41% more than the solar stills with an inclination angle 30° and 13.35% more than the solar still with an inclination angle of 15°, as shown in Tables 1–3.

Table 1. Time, total radiation, and distillate water for 15° solar still.

Time (Hours)	Total Radiations I_t (W/m ²)	Distillate Water (Liters)
10–11 a.m.	1200.121	0.539977
10–12 p.m.	1199.938	1.197339
12–1 p.m.	1199.994	1.992371
1–2 p.m.	1200.184	2.950399
2–3 p.m.	1200.212	3.320589
3–4 p.m.	1200.043	3.592003

Table 2. Time, total radiation, and distillate water for 30° solar still.

Time (hours)	Total Radiations I_t (W/m ²)	Distillate Water (Liters)
10–11 a.m.	1256.421	0.585175
10–12 p.m.	1256.443	1.305578
12–1 p.m.	1256.436	2.190179
1–2 p.m.	1256.411	3.277347
2–3 p.m.	1256.407	3.630326
3–4 p.m.	1256.431	3.916858

Table 3. Time, total radiation, and distillate water for 45° solar still.

Time (hours)	Total Radiations It (W/m ²)	Distillate Water (Liters)
10–11 a.m.	1176.705	0.993127
10–12 p.m.	1176.471	1.477627
12–1 p.m.	1176.551	2.303178
1–2 p.m.	1176.776	3.465561
2–3 p.m.	1176.806	3.838896
3–4 p.m.	1176.613	4.606433

6. Conclusions

In this paper, we applied numerical modelling techniques to calculate the distillate water output of passive solar stills with three different inclination angles, i.e., 15°, 30°, and 45°. The location of Sargodha, Punjab, Pakistan, on 22 June was the considered context. Results were calculated after every hour of operation from 10 a.m. to 4 p.m. After applying the mathematical modelling technique, it was shown that solar stills with a 45° angle achieve the maximum amount of distillate, which was 4.606433 L more than the solar stills with 15° and 30° inclination angles, which had distillate outputs of 3.592003 L and 3.916858 L, respectively. A proven mathematical technique used to find the distillate water output of passive solar stills was proposed by Bao Nguyen [17], and we have further utilized this method to predict the best inclination angle for maximum passive single-slope solar still productivity.

Author Contributions: Conceptualization, N.M.M. and M.A.Z.; methodology, N.M.M. and A.H.; software, N.M.M. and A.A.; validation, N.M.M. and A.A.; formal analysis, N.M.M. and M.A.Z.; investigation, N.M.M. and A.H.; data curation, M.A.Z.; writing—original draft preparation, N.M.M.; writing—review and editing, N.M.M. and A.H.; supervision, A.H.; project administration, N.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Chandrashekhara, M.; Yadav, A. Water Desalination System Using Solar Heat: A Review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1308–1330. [CrossRef]
- Shatat, M.; Worall, M.; Riffat, S. Opportunities for Solar Water Desalination Worldwide: Review. *Sustain. Cities Soc.* **2013**, *9*, 67–80. [CrossRef]
- Kabeel, A.E.; Abdelgaied, M.; Mahmoud, G.M. Performance Evaluation of Continuous Solar Still Water Desalination System. *J. Therm. Anal. Calorim.* **2021**, *144*, 907–916. [CrossRef]
- Sharshir, S.W.; Ellakany, Y.M.; Algazzar, A.M.; Elsheikh, A.H.; Elkadeem, M.R.; Edreis, E.M.A.; Waly, A.S.; Sathyamurthy, R.; Panchal, H.; Elashry, M.S. A Mini Review of Techniques Used to Improve the Tubular Solar Still Performance for Solar Water Desalination. *Process Saf. Environ. Prot.* **2019**, *124*, 204–212. [CrossRef]
- Sarkar, M.N.I.; Sifat, A.I.; Reza, S.M.S.; Sadique, M.S. A Review of Optimum Parameter Values of a Passive Solar Still and a Design for Southern Bangladesh. *Renew. Wind. Water Sol.* **2017**, *4*, 1. [CrossRef]
- Panchal, H. Performance Investigation on Variations of Glass Cover Thickness on Solar Still: Experimental and Theoretical Analysis. *Technol. Econ. Smart Grids Sustain. Energy* **2016**, *1*, 7. [CrossRef]
- Keshitkar, M.; Eslami, M.; Jafarpur, K. Effect of Design Parameters on Performance of Passive Basin Solar Stills Considering Instantaneous Ambient Conditions: A Transient CFD Modeling. *Solar Energy* **2020**, *201*, 884–907. [CrossRef]
- Panchal, H.; Mevada, D.; Sathyamurthy, R. The Requirement of Various Methods to Improve Distillate Output of Solar Still: A Review. *Int. J. Ambient. Energy* **2021**, *42*, 597–603. [CrossRef]
- Durkaieswaran, P.; Murugavel, K.K. Various Special Designs of Single Basin Passive Solar Still—A Review. *Renew. Sustain. Energy Rev.* **2015**, *49*, 1048–1060. [CrossRef]

10. Goshayeshi, H.; Safaei, M.R. Effect of Absorber Plate Surface Shape and Glass Cover Inclination Angle on the Performance of a Passive Solar Still. *Int. J. Numer. Methods Heat. Fluid Flow.* **2019**. ahead-of-print. [[CrossRef](#)]
11. Panchal, H.; Shah, P. Modelling and Verification of Single Slope Solar Still Using ANSYS-CFX. *Int. J. Energy Environ.* **2011**, *2*, 985–988.
12. Çengel Yunus, A.; Ghajar, A.J. *Heat and Mass Transfer: Fundamentals & Applications*, 4th ed.; McGraw-Hill: New York, NY, USA, 2011.
13. Dev, R.; Tiwari, G.N. Characteristic Equation of a Passive Solar Still. *Desalination* **2009**, *245*, 246–265. [[CrossRef](#)]
14. Ferrer, G.; Barreneche, C.; Solé, A.; Martorell, I.; Cabeza, L.F. New Proposed Methodology for Specific Heat Capacity Determination of Materials for Thermal Energy Storage (TES) by DSC. *J. Energy Storage* **2017**, *11*, 1–6. [[CrossRef](#)]
15. Monteiro, J.; Baptista, A.; Pinto, G.; Ribeiro, L.; Mariano, H. Assessment of the Use of Solar Desalination Distillers to Produce Fresh Water in Arid Areas. *Sustainability* **2019**, *12*, 53. [[CrossRef](#)]
16. Bergström, D.; Powell, J.; Kaplan, A.F.H. The Absorptance of Steels to Nd:YLF and Nd:YAG Laser Light at Room Temperature. *Appl. Surf. Sci.* **2007**, *253*, 5017–5028. [[CrossRef](#)]
17. Bao, N.T. The Mathematical Model of Basin-Type Solar Distillation Systems. In *Distillation*; Steffen, V., Ed.; IntechOpen: Rijeka, Croatia, 2019.