

Article

Enhancing Solar Still Performance Using Vacuum Pump and Geothermal Energy

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Abstract: Improvement in the performance of a solar still is investigated with the integration of a geothermal cooling system and a vacuum pump. Geothermal cooling is simulated to provide a cold, effective underground water temperature, which could reach 15–25 °C below ambient. Cooling is achieved by circulating water underground. As a result of this circulation, the cold fluid from the ground flows into a counter flow shell and tube heat exchanger. A vacuum pump is used to keep the solar still at a certain vacuum pressure. The sizes of the geothermal system and solar still are designed in such a way that the water outlet temperature from the ground and its flow rate are capable of condensing the entire vapor produced by the still. An analytical model was developed and then solved using the Newton–Raphson method for solving non-linear equations. A prototype was built to validate the analytical model. The results were in close agreement. A 305% increase in daily water productivity resulted from the proposed enhancements. After experimental validation, the effects of various parameters such as vacuum pressure, ambient temperature, and wind speed on the yield of geothermal solar still were examined. It was found that the increase in vacuum pressure enhanced performance, whereas the increase in wind speed had a detrimental effect on the yield of the solar still. A higher ambient temperature increased the yield of the solar still. Finally, the design of the heat exchanger for condensing the distilled water using geothermal cooling water was also investigated in terms of the increase in UA (the product of overall heat transfer coefficient and the area of heat exchanger) with inlet cooling geothermal water temperature.

Keywords: solar still; desalination; geothermal energy; vacuum pump; simulation

1. Introduction

The demand for fresh water is continuously increasing in line with population growth. In the current situation of rising oil prices along with concerns over declining oil reserves, the need to comply with the Kyoto Protocol has become vital for the reduction of greenhouse gases. Thus, it is of the utmost importance to find ways to use renewable energy sources for water desalination. The geographical location of the Kingdom of Saudi Arabia (KSA) gives it an advantage in utilizing solar energy to offset part of its domestic energy consumption. The abundance of freely available solar radiation, an average of 2200 thermal kilowatt hours (kWh) of solar energy per square meter of land area annually, is just waiting to be harnessed [1]. The combination of renewable energies such as solar and geothermal energy with desalination holds enormous potential for improving the potable water supply in the KSA.

Solar distillation is one of the oldest techniques to produce fresh water from brackish or saline water [2]. Numerous efforts have been made to enhance system performance so that the distillate

output is obtained at a reasonable cost. These efforts include active solar distillation, in which the basin of the solar still is integrated with a panel of collectors through heat exchangers [3], enhancing the solar still performance by cooling the glass cover with water film [4], and using a thermal-electrical solar still in which the water vapor is removed from the basin by a low-power fan and then passed through an external condenser [5].

Other techniques involve the use of a double basin solar still [6], upward-type double-effect solar distillers [7], a double-basin solar still integrated with collectors [8], a solar still with an internal condenser [9], a multi-effect active distillation system [10], and a solar still with dye [11]. Karthikeyan and Natarajan [12] conducted a comprehensive review of the factors influencing the performance and productivity of solar stills. Al-Nimr and Haddad [13] investigated the capability of a radiative cooling system in condensing water vapor from humid air in a solar still. A so-called radiative condenser was introduced and analyzed to distill pure water from the vapor of humid air. Moreover, Haddad et al. [14] proposed a basin-type solar still integrated with a packed-bed storage tank, which was used as an external condenser for the still. The packed-bed condenser was cooled during the night using a radiative cooling panel by circulating pure water into the packed-bed condenser and radiative cooling panel. Other recent publications aim to modify the design of the solar still to increase its productivity or to investigate still performance under a wide range of design and operating conditions [15–17].

A cool underground temperature is utilized in space-cooling applications [18,19]. The difference between ambient hot or cold temperatures and an underground fixed temperature is approximately 10–20 °C, depending on the time and location [20,21]. This allows for use either as a heat sink (in summer) or a heat source (in winter). In summer, the soil temperature in a hot and arid region at a few meters deep is lower than the mean daily outdoor air temperature and is significantly lower than the usual outdoor daytime air temperature. Thus, it can be used as a heat sink to cool the exterior warm air. A ground source heat pump (GSHP) is a heat pump system that uses the ground as a heat source or sink. The geothermal system connects a heat pump underground and permits the rejection of heat into the ground for cooling purposes [22]. A large number of modifications have been proposed to improve the performance of solar stills. These modifications have been classified into six types based on still design guidelines [23]. Sivakumar et al. [24] summarized the different techniques that have been applied to increase solar still efficiency. Different modifications, including cooling techniques, have been proposed by Ayoub et al. [25] to increase solar still productivity.

The literature review reveals that various options to improve the performance of solar stills have been investigated. However, a geothermal system integrated with a vacuumed solar still has yet to be explored in detail, especially for KSA conditions. In this study, a closed-loop geothermal cooling system will be integrated with a solar still to reject heat from the distilled water vapor into the ground to improve still performance. Geothermal cooling is used to provide a cold, effective underground water temperature, which could reach 15–25 °C below ambient. Cooling is achieved by circulating water underground. As a result of this circulation, the cold fluid from the ground flows into a counter flow shell and tube heat exchanger. The outer shell contains water vapor from the water still, whereas the inner tube contains the cold water pumped from the ground. The heat exchanger is used to condense the vapor produced by the still. The sizes of the geothermal system and solar still are designed in such a way that the water outlet temperature from the ground and its flow rate are capable of condensing all of the vapor produced by the still. The temperature of water exiting the ground is much lower than that attained in conventional condensers that utilize cold water from ambient conditions. In addition, geothermal energy is considered a renewable energy, which does not depend on conventional sources of energy. Using the above-modified still, four goals are expected to be achieved: (i) The vapor pressure and temperature inside the still can be reduced with a vacuum and, as a result, thermal losses from the vapor are reduced and the solar still can still produce condensed water even with low intensity of solar radiation; (ii) the vapor partial pressure inside the still can

be reduced, which enhances the evaporation rate from the still; and (iii) the low-temperature water exiting from the ground can enhance the condensation rate inside the condenser.

2. Modeling of Solar Still

The proposed system consists of a basic solar still. The schematic diagram is shown in Figure 1. The still contains water that is heated by the sun to the point of evaporation. The water evaporates and fills the still. A vacuum pump is installed at the top corner of the still to withdraw the vapor from the still. This vapor is directed into the outer shell of a shell-and-tube heat exchanger. Cold brine water flows into the inner tube of the heat exchanger, which causes condensation of vapor on the outer surface of the inner tube. This condensed water is collected in a container.

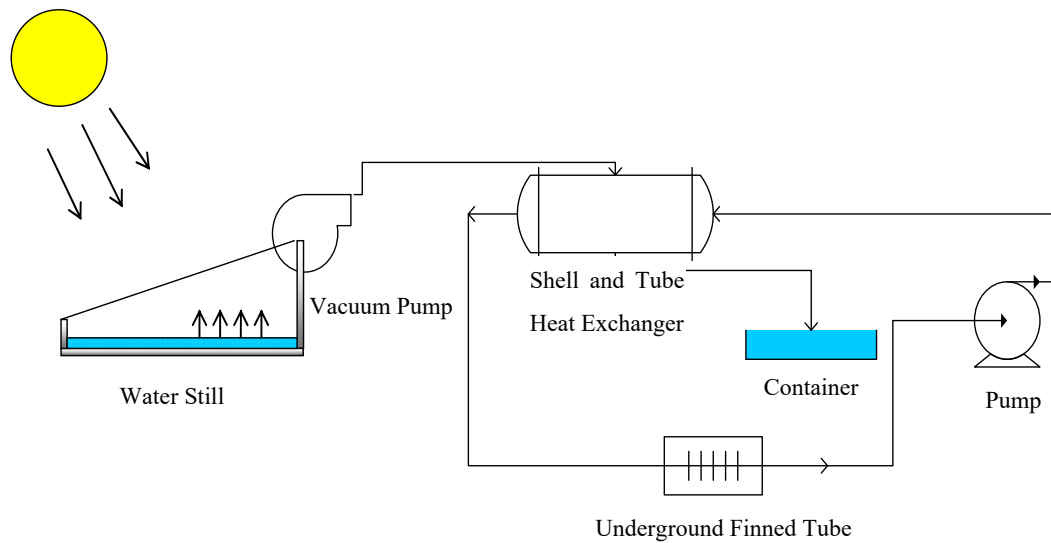


Figure 1. Proposed solar-geothermal still.

Geothermal energy is used to supply cold water to the inner tube. This is accomplished by passing the inner tube through the ground to a depth of 2–3 m. At this depth, the ground temperature is at least 20–25 °C below ambient temperature in most areas of the KSA [26]. At the lowest depth, fins are attached to the inner tube to enhance heat transfer from the inner tube to the ground. At the ground level, a pump is installed to withdraw cold water from the ground and circulate it to the shell-and-tube heat exchanger.

As shown in Figure 1, the vacuum pump will create suction (vacuum pressure P_o) inside the still to enhance vaporization and drive the vapor to the condenser to prevent it from condensing on the glass. This will also reduce the glass temperature T_g .

The energy balance on the water side at a certain instant of time is

$$I_t \tau_g = (h_{rw} + h_{cw})(T_w - T_g) + h_e [P(T_w) - P(T_g)] \quad (1)$$

The energy balance on the glass is

$$I_t \alpha_g + (h_{rw} + h_{cw})(T_w - T_g) = h_g (T_g - T_a) \quad (2)$$

where I_t is the solar radiation at the tilted surface, τ_g is the glass transmissivity, α_g is the glass absorptivity, T_w is the water temperature, and T_g is the glass temperature. h_{rw} is the radiation heat transfer coefficient from the water given as [27]

$$h_{rw} = \varepsilon \sigma \left[\frac{(T_w + 273)^4 - (T_g + 273)^4}{T_w - T_g} \right] \quad (3)$$

where ϵ is the emissivity and σ is the Stefan–Boltzmann constant. h_g is the glazing heat transfer coefficient given as [27]

$$h_g = \epsilon_g \sigma \left[\frac{(T_g + 273)^4 - (T_a + 261)^4}{T_g - T_a} \right] + 5.7 + 3.8V \quad (4)$$

where V is the wind speed at the location and ϵ_g is the glass emissivity. h_{cv} is the convection heat transfer coefficient from the water given as [28]

$$h_{cv} = Ck_m \left(\frac{g \rho_m \beta}{\mu_m \alpha_m} \right)^{\frac{1}{3}} \left[(T_w - T_g) + \frac{T_w [P(T_w) - P(T_g)] (M_a - M_w)}{M_a P_o - P(T_w)(M_a - M_w)} \right]^{\frac{1}{3}} \quad (5)$$

where $C = 0.075$; ρ_m , k_m , μ_m , and α_m are the density, thermal conductivity, viscosity, and thermal diffusivity, respectively, of the mixture corresponding to saturated mixture properties at approximately 50 °C. M_a and M_w are the molar masses of air and water, respectively. P_o is the pressure inside the still (less than 101 kPa), which depends on the vacuum pump used, ranging from 50 to 101 kPa. $P(T)$ represents saturated vapor pressure at temperature T , g is the gravity, and β can be defined as $\beta = \frac{1}{T_g + 273}$.

h_e is the evaporative mass heat transfer coefficient given as [29]

$$\frac{h_e}{h_{cv}} = \frac{h_{fg}}{C_{pa}} \frac{R_a}{R_w} \frac{P_o}{[P_o - P(T_w)] [P_o - P(T_g)]} \quad (6)$$

where C_{pa} is the specific heat capacity of dry air, h_{fg} is the heat of evaporation, and R_a and R_w are the gas constants.

After simultaneously solving Equations (1)–(6), we will get T_a and T_g . The condensation rate will then be calculated from [27]

$$\dot{m}_w = \frac{C k_m R_a}{C_{pa} R_w} \left(\frac{g \rho_m \beta}{\mu_m \alpha_m} \right)^{\frac{1}{3}} \left[(T_w - T_g) + \frac{T_w [P(T_w) - P(T_g)] (M_a - M_w)}{M_a P_o - P(T_w)(M_a - M_w)} \right]^{\frac{1}{3}} \frac{P_o [P(T_w) - P(T_g)]}{[P_o - P(T_w)] [P_o - P(T_g)]} \quad (7)$$

This $\dot{m}_w$ needs a condenser to fully condense the vapor. Thus, an analysis is performed to calculate UA ; then, $\dot{m}_w$, the geothermal water flow rate required to condense vapor, is calculated. The heat transfer from the condensing fluid side is

$$q = \dot{m}_w h_{fg} \quad (8)$$

The heat transfer from the cooling water side is

$$q = \dot{m}_c C_c (T_{c,o} - T_{c,i}) \quad (9)$$

where C_c is the specific heat of cooling water, and $T_{c,o}$ and $T_{c,i}$ represent the outlet and inlet temperature of the cooling fluid, respectively. It is assumed that the available water temperature from the geothermal source is 15–25 °C below ambient temperature.

The heat transfer may also be calculated as

$$q = \epsilon \dot{m}_c C_c (T_w - T_{c,i}) \quad (10)$$

where ϵ is the effectiveness of the heat exchanger given by

$$\epsilon = 2 \left\{ 1 + c + \sqrt{1 + c^2} \frac{1 + \exp \left[-NTU \sqrt{1 + c^2} \right]}{1 - \exp \left[-NTU \sqrt{1 + c^2} \right]} \right\} \quad (11)$$

NTU is the number of transfer units

$$NTU = UA/C_{\min} \quad (12)$$

where U is the overall heat transfer coefficient of the condenser, and A is the area of the heat exchanger. It is assumed that the vapor has the same temperature as the water in the basin (T_w). c is defined as

$$c = \frac{C_{\min}}{C_{\max}} \quad (13)$$

ϵ and NTU can be obtained by solving Equations (8)–(13). The model developed above is a set of twelve non-linear equations. A computer simulation program based on these equations was developed in FORTRAN (IBM, Armonk, NY, USA), which uses the Newton-Raphson method for non-linear equations. The program solves the model by an iterative procedure in which the user has to provide realistic guesses of all the variables in the model.

3. Experimental Set-Up

Solar radiation measurements were conducted at the metrological station located at the top of the Mechanical Engineering Department's building at King Saud University (KSU), as shown in Figure 2. The station is equipped with an Eppley Normal Incidence Pyrheliometer, Eppley rotating shadow band radiometer set-up, and a Precision Spectral Pyranometer. The discussion of the conversion of horizontal and diffuse radiation into I_t was omitted for brevity; however, the analysis reported in reference [4] was used for this purpose.



Figure 2. Solar radiation measurement station at King Saud University.

Figure 3 shows the solar still during testing and in its manufacturing phase. The main body was built with 3 mm galvanized steel. The still was built with a length, width, and height of 1 m, 1 m, and 0.6 m, respectively. The system was constructed mainly from a galvanized steel absorber plate (of thickness 0.04 m) that was painted black to increase the absorptivity. A Perspex sheet (6 mm) was

used as the transparent top cover because of its low thermal conductivity and high transmissivity, compared with glass and lexan. Glass wool was used as insulation material because of its low density and cost. The tilt angle was set at 24.4° facing south based on the optimum calculations for Riyadh [30]. The inside was painted black to enhance the heat transfer. Geothermal energy was simulated using a cooler to maintain the water temperatures within the controlled range of $20\text{--}40^\circ\text{C}$. A heat exchanger with 316 Stainless Steel Shell and Tube, 0.85 m^2 surface area, and $17.3\text{ m}^3/\text{hr}$ flow capacity (35185K45, McMaster) was used. Temperature measurements were taken by various calibrated K-type thermocouples (OMEGA 5TC-GG-K-20-36), which were installed to measure the glass cover temperature, the absorber plate temperature, the ambient temperature, and the air-vapour mixture temperature. A 30-channel data acquisition system (OMB-DAQ-54, Omega) was installed to get the thermocouple data in real time. The output distillate water was collected using a calibrated tube. The experiment was carried out between 9:00 and 18:00 during the months from January to June 2018 at King Saud University under the climatic conditions of Riyadh, Saudi Arabia. Two identical solar stills were manufactured. One of the solar stills was tested with the addition of a geothermal system and vacuum pump (called enhanced solar still) and the other one was tested in parallel without those enhancements (called conventional solar still).



Figure 3. (a) Solar still during manufacturing and (b) vacuumed solar still during testing.

The experimental error analysis indicated the implication of the error in measured parameters on the uncertainty of the results. Detailed analysis of the various experimental parameters was carried out using the differential method according to Moffat [31]. Summary of the uncertainty values of the experimental parameters is listed in Table 1.

Table 1. Uncertainty values of the experimental set-up.

Parameters	%, Uncertainty
Solar radiation	0.97
Water temperature	0.63
Temperature	0.86
Mass flow rate	1.17

The power requirement for running the vacuum and geothermal pumps was about 150 W on average. There are plans to fulfill the electrical energy demand by using solar panels so that the system can also be used effectively in arid zones where grid connectivity is not available. In future studies, the authors plan to connect a number of stills through a single line for a geothermal water and vacuum generation that will make it a more attractive solution for the given water productivity.

4. Results and Discussion

4.1. Comparison of Experimental and Analytical Results

Figure 4 shows the comparison of the analytical and experimental results. The result of the analytical model for the enhanced solar still at the vacuum pressure of 90 kPa and geothermal temperature difference of 15 °C is shown along with the identical experimental result. The figure also shows the experimental result for a conventional solar still. It is evident that the analytical result is in close agreement with the experimental data. Comparison of the experimental result of the conventional still and enhanced still showed major improvement in hourly productivity. An average increase of 305% in hourly productivity is evident.

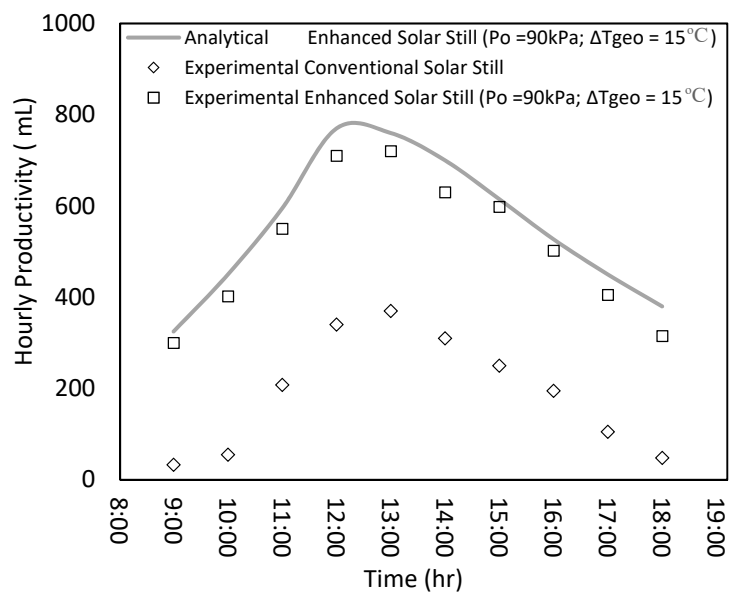


Figure 4. Comparison of analytical and experimental results.

In Figure 5, the calculated numerical values of the he/hcv ratio corresponding to the Chilton-Colburn model [32] are shown as a function of the average still temperature for a typical temperature difference fixed at $\Delta T = T_s - T_g = 10$ °C. The Chilton-Colburn model was selected for comparison as it is a well-known numerical model for solar stills, which has been validated with experimental results with impressive accuracy even at very high mass flow rate yields corresponding to the higher range of solar still operating temperatures. Figure 5 clearly demonstrates the significance of enforcing a vacuum in the solar still, as the he/hcv ratio of the presented model is higher than that of conventional solar stills based on the Chilton-Colburn model. The difference in ratios is insignificant at low average still temperatures of up to 40 °C. The difference increases substantially at higher still temperatures.

Figure 6 presents the ratio of the mass flow rate per unit still area and convective heat transfer versus the average still temperature for the proposed model compared with that of the Chilton-Colburn model for a typical temperature difference fixed at $\Delta T = T_s - T_g = 10$ °C. Again, performance improvement is evident with the presented model as the ratios are higher at all still temperature ranges. Apparently, the he/hcv ratio for a fixed value of ΔT increases dramatically at higher operational temperatures, whereas for a fixed average still temperature, the corresponding deviation between both models grows as the temperature difference increases.

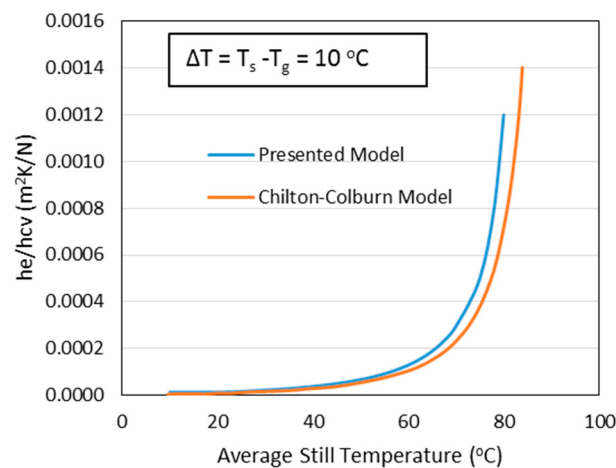


Figure 5. h_e/h_{cv} corresponding to Chilton-Colburn model.

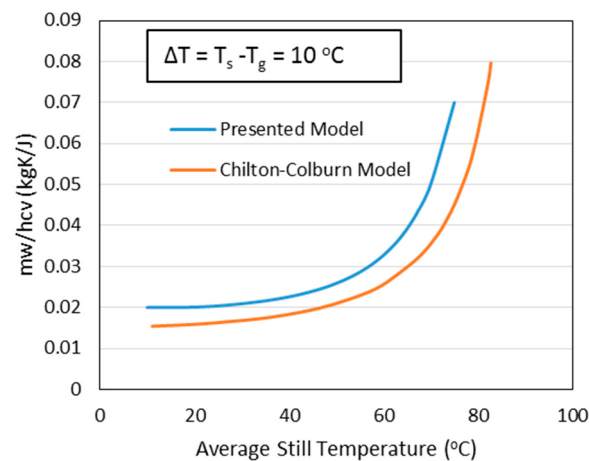


Figure 6. m_w/h_{cv} Corresponding to Chilton-Colburn Model.

4.2. Parametric Studies Based on the Analytical Model

Once the analytical model was proved to be reliable, an extensive parametric study was done to see the effect of vacuum pressure, ambient temperature, and wind speed. This study was important to select the best location for such systems within KSA.

The effect of vacuum pressure on the production of desalinated water is presented in Figure 7. Real-time values of wind velocity and ambient temperature were obtained from the meteorological station. Two representative days for the winter and summer were considered for discussion. Figure 7 shows that the water yield of the solar still increases with the increase in vacuum pressure. The yield increased by approximately 19% at noon when the pressure inside the still decreased from 110 kPa to 50 kPa.

The effect of ambient temperature on the yield of desalinated water is presented in Figure 8. Real-time values of wind velocity were obtained from the meteorological station, and the vacuum pressure was kept at 70 kPa. Two representative days for the winter and summer were considered for discussion. It is clear from the figure that the water yield of the solar still increased with the increase in ambient temperature. There was an increase of approximately 17% yield at noon when the ambient temperature increased from 25 °C to 50 °C.

The effect of wind speed on the production of desalinated water is presented in Figure 9. Real-time ambient temperature was obtained from the meteorological station, and the vacuum pressure was kept at 70 kPa. It is obvious from the figure that the water yield of the solar still decreased with the increase in wind speed. This can be attributed to the increase in heat losses with the wind speed.

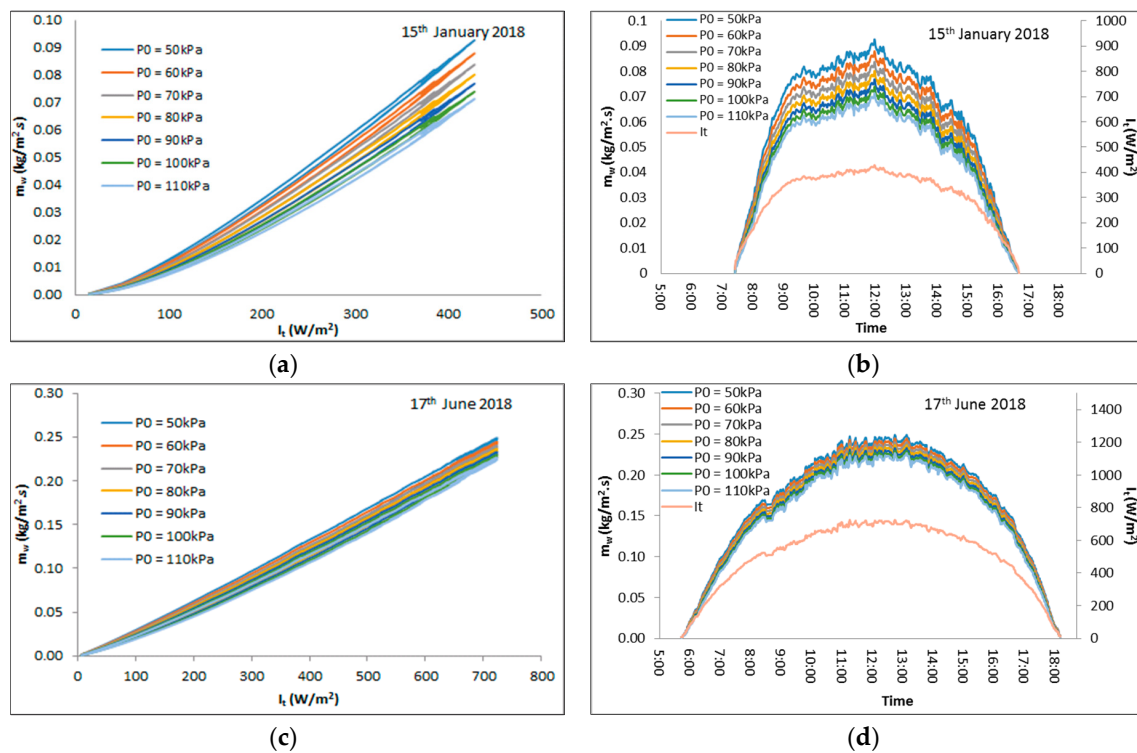


Figure 7. Effect of vacuum pressure on the production of a geothermal solar still. (a,b) represent the analysis for a winter's day on 15 January 2018. (c,d) represent the analysis for a summer's day on 17 June 2018.

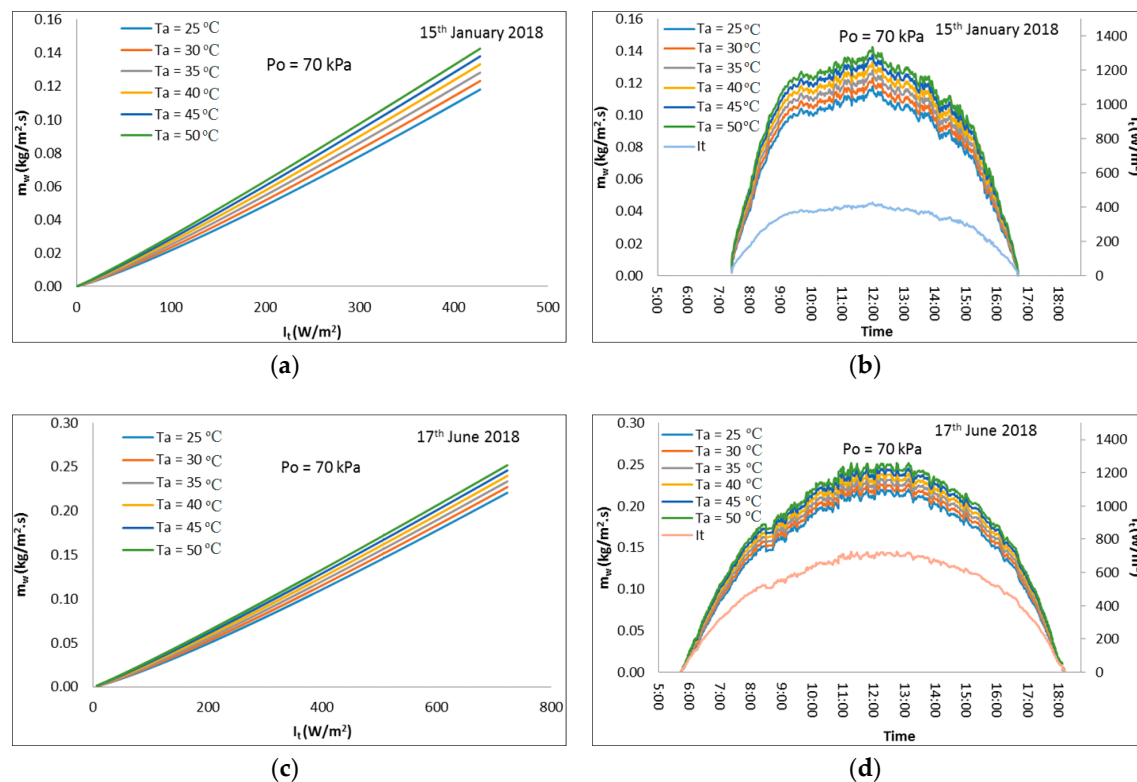


Figure 8. Effect of ambient temperature on the production of a geothermal solar still. (a,b) represent analysis for a winter's day on 15 January 2018. (c,d) represent analysis for a summer's day on 17 June 2018.

The effect of the inlet temperature of geothermal water on the heat exchanger design is presented in Figure 10. The UA for each mass flow rate increased with the increase in inlet temperature. Since the effectiveness is proportional to NTU ($NTU = UA/C_{min}$), the optimum area of the heat exchanger should be selected in the design of the inlet mass flow rate of geothermal water.

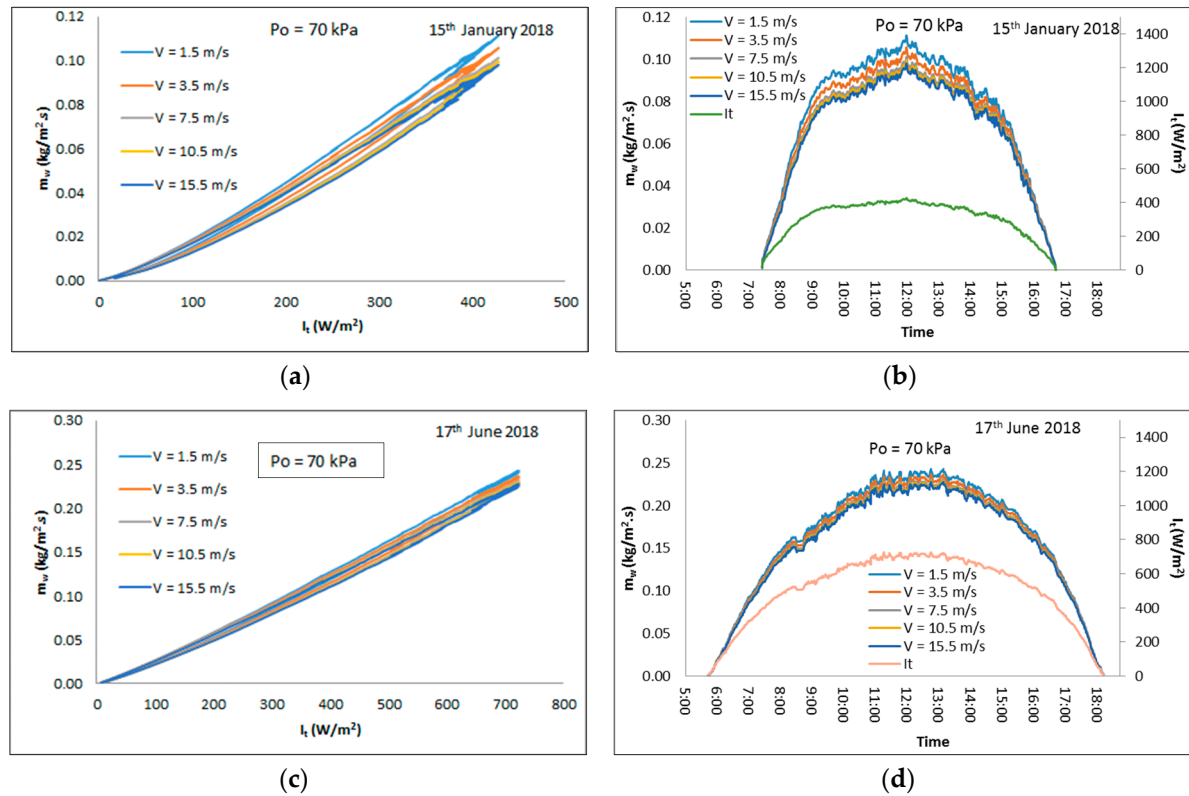


Figure 9. Effect of wind speed on the production of a geothermal solar still. (a,b) represent analysis for a winter's day on 15 January 2018. (c,d) represent analysis for a summer's day on 17 June 2018.

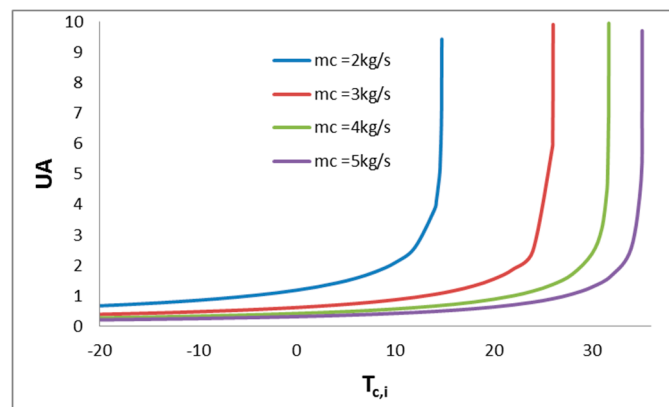


Figure 10. UA versus the inlet temperature of geothermal water.

5. Conclusions and Recommendations

A geothermal cooling system integrated with a solar still to improve the water still performance was investigated experimentally and analytically. A prototype was built to validate the analytical model. An analytical model was developed and then solved using the Newton-Raphson method for solving non-linear equations. The effects of various parameters such as vacuum pressure, ambient

temperature, and wind speed on the yield of the geothermal solar still were examined. The following conclusions were drawn from the study:

- The analytical and experimental results were in close agreement;
- A 305% increase in daily water productivity resulted from the proposed enhancements;
- The increase in vacuum pressure enhanced the yield of the solar still;
- The increase in wind speed had a detrimental effect on the yield of the solar still;
- The increase in ambient temperature increased the yield of the solar still.

Finally, the design of the heat exchanger for condensing the distilled water using geothermal cooling water was also investigated in terms of the increase in UA with inlet cooling geothermal water temperature. The proposed model showed performance improvement when a vacuum pump was included in a hybrid solar-geothermal still.

Author Contributions: S.N.D. and A.E.-L. conceived the idea, developed the mathematical model and performed the experiments; S.N.D., A.E.-L. and M.A. developed the methodology and analyzed the data; A.E.-L. and H.A.-A. contributed in analysis tools, project administration and funding acquisition; S.N.D. wrote the paper.

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Abbreviations

A	Area of Heat Exchanger (m^2)
C	Constant
C_p	Specific Heat (kJ/kgK)
C_c	Specific Heat of Geothermal Water (kJ/kgK)
ΔT_{geo}	Difference between Ambient Temperature and Geothermal Water Temperature
Exp.	Experimental
h	Heat Transfer Coefficient ($\text{W/m}^2\text{K}$)
h_{fg}	Heat of Evaporation (kJ/kg)
g	Gravity (m/s^2)
I	Solar Radiation (W/m^2)
k	Thermal Conductivity (W/mK)
M	Molar Mass (kg/mol)
$\dot{m}_w$	Mass Flow Rate of Water (kg/s)
$\dot{m}_c$	Mass Flow Rate of Geothermal Water (kg/s)
NTU	Number of Transfer Units
P	Pressure (kPa)
$P(T)$	Saturated Vapor Pressure at T (kPa)
R	Gas Constant (kJ/kgK)
T	Temperature (K)
U	Overall Heat Transfer Coefficient ($\text{W/m}^2\text{K}$)
V	Wind Speed (m/s)
Greek	
α	Absorptivity
β	Constant
ε	Emissivity
ϵ	Effectiveness of Heat Exchanger
τ	Transmissivity
σ	Stefan-Boltzman Constant
ρ	Density (kg/m^3)
μ	Viscosity (Ns/m^2)

Subscript

a	Air
c	Convection
e	Evaporation
g	Glass
m	Mixture
o	Vacuum
r	Radiation
t	Tilted surface
w	Water

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