PARAMETRIC ANALYSIS OF A SOLAR STILL WITH INVERTED V-SHAPED GLASS CONDENSER

by

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A parametric analysis of a solar still with an inverted V-shaped glass condenser is presented. Results are based on a new mathematical model obtained from a lumped-parameter analysis of the still, with an approach that makes each glass plate of the condensing system sensitive to orientation and depicts its thermal differences. Numerical computations are made to evaluate productivity and temperature differences between the condensing plates as a function of condenser orientation, extinction coefficient, and thickness. From this study it was found a significant influence of incident solar radiation on the thermal performance of each condensing plate. Large extinction coefficients and thick glass plates increase absorption losses that result in an appreciable temperature difference. An extinction coefficient of 40 m^{-1} produces a temperature difference of 2.5 °C between both condensers. A glass thickness of 10 mm may increase this temperature difference up to 3.5 °C. With respect to the production, due to the still orientation, a difference of 8.7% was found for the condensing plates facing an east-west direction. The proposed model is able to reproduce the temperature and distillate production differences that arise between both condensers in good agreement with experimental data. The overall performance of the still, studied with this new approach, was also in accordance with the widely used traditional models for solar distillation. In addition, the condensing plates parameters of the still can be used to force a differential heating such that for the whole day the temperature of one condensing plate is always higher.

Key words: *solar distillation, modeling, condensers differences, sensitivity to orientation*

Introduction

Solar distillation of seawater has been an alternative to sustainability for isolated communities in arid zones without freshwater services. The high availability of solar energy in some regions has made technologies that take advantage of direct solar heating very popular. An instance of this is the basin-type still design with glass condenser, one of the simplest and practical configurations for solar distillation. Thermal efficiency of this type of still will reach 30% at low radiation levels, and about 50% for energy intensities above 20 MJ/m^2 per day, meanwhile, pro-

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ductivity under average radiation conditions will be about 3.5 liters/m^2 per day, rising to 6.0 liters/m^2 per day for high radiation levels [1].

Research efforts have helped to optimize design and operational parameters of distillation equipment through computer simulations of the thermal processes involved in the operation of the still. This is accomplished by means of relations to estimate solar energy gains, energy exchange between the still and the environment through the glass cover and the basin bottom, and the internal physical processes where simultaneous heat and mass transfer exist. A number of parameters responsible for water production have been investigated with experimental and numerical work, where the latter is accomplished by means of computer simulations, based on models of the basic phenomena that offer an inexpensive way to research and develop technologies for solar water production.

Among the most studied parameters in this kind of solar apparatus is the influence of water depth on production, and it has been found that as this parameter increases, production decreases. Experiments developed by Garg and Mann [2] with single-sloped uninsulated stills, and varying water depths from 2-8 cm, have shown an average decrease in production of 13.8%. Numerical work reported by Toure and Meukam [3] shows a reduction of 19% in production for a change from 5-60 mm in water depth, accordingly, Nafey *et al*. [4] reported that as the water depth increases from 2-7 cm, the output decreases by 14%, in agreement with Phadatare and Verma [5]. Cooper [6] showed results for water depths from 1.2-30.5 cm, where a variation of 30% was found with marginal gains for stills without insulation, but a strong effect for insulated ones with shallow depths. Variations of 26% [7] and 7.4% [8] in productivity are reported for a change of 1.5 cm for low water depths.The changes may even be stronger as shown by computer simulations reported by El-Sebaii [9] and experimental work reported by Khalifa and Hamood [10].

With respect to the influence of wind speed, it has been reported that the output of the still varies asymptotically as this parameter increases, but discrepant results can be found in the literature. Cooper´s digital simulations [6] showed an output increase of 11.5% for increasing velocities from 0-4.8 mph, and an increase of 1.5% from 4.8-19.7 mph, while Badran [7] reported an increase of 35% on increasing the wind velocity from 2.7-5 m/s, but productivity predictions made by Nafey *et al.* [4] showed that productivity decreases by 13% when wind velocity changes from 1-9 m/s, while El-Sebaii [11] reported a decrease of 18.4% on increasing wind velocity from 0 m/s to a typical value of 8 m/s. Numerical results from Toure and Meukam [3] suggested that with an increase in wind speed from 0-9 m/s, the total production increase is less than 10%, but in the morning, increasing wind speed increases the production, and the results are reversed in the afternoon. El-Sebaii [9] agrees with this peculiar trend and found that daylight productivity increases rapidly as wind speed increases, and after sunset, the overnight productivity decreases slowly with increasing wind speed.

A condenser composed of two or more flat surfaces requires additional considerations in the incoming energy analysis. Cooper [12] presented a work related to the absorption of radiation in a still with gable-type glass cover, where optical properties depend on the inclination of each side, and a mean transmittance to estimate the energy that reaches the water was defined. Incident solar energy on surfaces facing different directions, as those found in double-sloped solar stills, may vary considerably, as shown by Singh *et al.* [13], where daily radiation on condensers change appreciably with still orientation, especially for highly inclined condensers. Concerning the cover thickness, Toure and Meukam [3] studied the variation of the productivity for different thickness of the condenser, and found that daily total production is practically the same for values from 4-10 mm.

Mathematical models that include the parameters of the condensing plates to show their thermal differences for a double-sloped solar still have not been found in the literature.

Model description

The model is based on the analysis of a still with inverted V-shaped condenser. A general sketch of this geometry is shown in fig. 1. Unlike the traditional models, where only three elements can be found, four elements can be identified in the thermal analysis: solar collector, basin water, and two glass condensers mounted on opposite sides of the still, at an angle of 45° above the horizontal. Glass material has been considered for the covers, since this is commonly found in the construction of this type of stills. The solar collector, attached to the bottom of the basin, is normally blackened to improve solar gains and contribute to the efficiency of the still due to its high absorptance. The base is considered insulated to prevent losses of energy through the bottom to the environment.

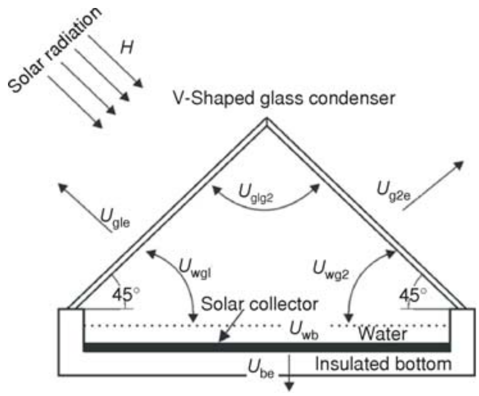

Figure 1. General sketch of a solar still with an inverted V-shaped condenser

Energy balance equations are obtained from a lumped-parameter analysis. For the purpose of this work, four expressions are derived concerning each of the four elements of the still.

An energy balance of the still applied to the water mass gives:

$$C_{\mathrm{w}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = H_{\mathrm{w}} + U_{\mathrm{wb}}(T_{\mathrm{b}} - T_{\mathrm{w}}) - U_{\mathrm{wg1}}(T_{\mathrm{w}} - T_{\mathrm{g1}}) - U_{\mathrm{wg2}}(T_{\mathrm{w}} - T_{\mathrm{g2}}) \tag{1}$$

One of the condensing plates exchanges energy with water, the other condenser, and the surroundings:

$$C_{\mathrm{g1}} \frac{\mathrm{d}T_{\mathrm{g1}}}{\mathrm{d}t} = H_{\mathrm{g1}} + U_{\mathrm{wg1}}(T_{\mathrm{w}} - T_{\mathrm{g1}}) - U_{\mathrm{g1g2}}(T_{\mathrm{g1}} - T_{\mathrm{g2}}) - U_{\mathrm{g1e}}(T_{\mathrm{g1}} - T_{\mathrm{e}}) \tag{2}$$

The equation for the second condensing plate is similar:

$$C_{\mathrm{g2}} \frac{\mathrm{d}T_{\mathrm{g2}}}{\mathrm{d}t} = H_{\mathrm{g2}} + U_{\mathrm{wg2}}(T_{\mathrm{w}} - T_{\mathrm{g2}}) - U_{\mathrm{g2g1}}(T_{\mathrm{g2}} - T_{\mathrm{g1}}) - U_{\mathrm{g2e}}(T_{\mathrm{g2}} - T_{\mathrm{e}}) \tag{3}$$

The bottom absorber exchanges energy with the surroundings and the water:

$$C_{\mathrm{b}} \frac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}t} = H_{\mathrm{b}} - U_{\mathrm{bw}}(T_{\mathrm{b}} - T_{\mathrm{w}}) - U_{\mathrm{be}}(T_{\mathrm{b}} - T_{\mathrm{e}}) \tag{4}$$

For solar radiation incidence, Sun declination is found [12]:

$$\delta = 23.45 \sin\left[\frac{2\pi(284 + n)}{365}\right] \tag{5}$$

Components of global radiation can be found with the following expressions [14]:

$$G = G_{\max} \cos^{1.2}\left(\frac{\pi t}{N}\right) \tag{6}$$

$$G_{\mathrm{b}} = G_{\mathrm{b-max}} \cos^{1.5}\left(\frac{\pi t}{N}\right) \tag{7}$$

For number of daylight hours given [15]:

$$N = \frac{2}{15}\cos^{-1}(-\tan\delta\tan\phi) \tag{8}$$

Radiation incident on an inclined surface is found [15]:

$$R_{\mathrm{b}} = \frac{\cos\theta}{\cos\theta_z} \tag{9}$$

where the angle between beam radiation and the normal to the plane is:

$$\begin{gathered}\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \\ + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega\end{gathered} \tag{10}$$

and beam radiation over a horizontal plane is:

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{11}$$

Optical properties have been modeled with equations for transmittance, reflectance, and absorptance [15]. Meanwhile transmission of energy through the glazing is:

$$\tau_{\mathrm{a}} = \exp\left(-\frac{k_{\mathrm{ext}} L}{\cos\theta_2}\right) \tag{12}$$

The difference with other models lies in an energy balance that uses two equations for the condenser system, and that it takes into consideration the energy fractions of the incident radiation in the analysis of each condenser.

A mean transmittance due to the contribution of both condensing plates has been adopted [12]:

$$\tau_{\mathrm{m}} = \tau_1 f_1 + \tau_2 f_2 \tag{13}$$

The cover losses are estimated for the convective mode [16]:

$$h_{\mathrm{c}} = 2.8 + 3.0v \tag{14}$$

The radiative mode can be written [15]:

$$h_{\mathrm{r}} = \varepsilon\sigma(T_g^2 + T_s^2)(T_{\mathrm{g}} + T_{\mathrm{s}}) \tag{15}$$

For the sky temperature [17]:

$$T_{\mathrm{s}} = 0.0552 T_e^{1.5} \tag{16}$$

Heat losses through the basin are by conduction and convection:

$$U_{\mathrm{be}} = \left(\sum_{i=1}^{n}\frac{L_{\mathrm{i}}}{k_{\mathrm{i}}} + \frac{1}{h_{\mathrm{b}}}\right)^{-1} \tag{17}$$

For the heat exchange between the blackened solar collector and the water mass [18]:

$$\mathrm{Nu} = 0.069\mathrm{Ra}^{1/3}\mathrm{Pr}^{0.074} \tag{18}$$

As simultaneous heat and mass transfer exist, Dunkle´s relations [19] for convective and evaporative heat transfer in a humid environment are used:

$$h_\mathrm{c} = 0.884\sqrt[3]{T_\mathrm{w} - T_\mathrm{g} + \frac{P_\mathrm{w} - P_\mathrm{g}}{268.9 \cdot 10^3 - P_\mathrm{w}} T_\mathrm{w}} \tag{19}$$

$$h_\mathrm{e} = 16.276 \cdot 10^{-3} h_\mathrm{c} \frac{P_\mathrm{w} - P_\mathrm{g}}{T_\mathrm{w} - T_\mathrm{g}} \tag{20}$$

The internal radiation is estimated [15]:

$$h_\mathrm{t} = \frac{\sigma (T_w^2 + T_g^2)(T_w + T_g)}{\dfrac{1}{\varepsilon_\mathrm{w}} + \dfrac{1}{\varepsilon_\mathrm{g}} - 1} \tag{21}$$

The production of the still is described by:

$$m'' = \frac{q_\mathrm{e}}{h_\mathrm{fg}} \tag{22}$$

The model includes expressions for estimating the energy transmission through glazing, for which an ample treatment is offered by Duffie and Beckman [15]. The new solution approach also considers the contribution of solar energy to the total heat gains for the water and solar collector, and to the distillate yield for each condensing plate [12, 20]. The equation by Watmuff *et al.* [16] was used for convective heat transfer from the condensers to the environment, and an expression by Bejan [18] was adopted to give the model analysis capability under water mass variations.

The resulting model was implemented in a C-language computer program, and the fourth order Runge-Kutta method was used to solve the differential equations. Physical and optical properties fed to the model correspond to data for common materials found in regular stores, such as window glass, wood, and polystyrene.

Results and discussion

Results presented in this section were obtained with the computer model supplied with simulated climatic information corresponding to spring time. The influence of the main parameters on productions and temperatures are presented, showing the thermal differences for each condensing plate.

Thermal mass of cover and solar collector was not neglected, and among the most relevant optical parameters and thermodynamic properties taken for numerical calculation are: water emittance = 0.96, glass emittance = 0.88, bottom absorptance = 0.95, specific heat of water = 4190 J/kgK, specific heat of absorber bottom = 1465 J/kgK, specific heat of glass cover = 820 J/kgK, ambient temperature = 15 °C, wind speed = 2.5 m/s, and 45° in cover tilt angle. An effective area of 1 m^2 was considered for the solar collector. Typical values were chosen according to common materials used in stills manufacturing. The overall performance of the still is also revised in order to make a comparison of results with the traditional models reported in the literature.

Condensing plates temperature dependence in terms of extinction coefficient and thickness

Cover main parameters, such as glass extinction coefficient and thickness, have been included in the model to determine the changes that result in daily temperatures evolution. Figures (2-4) show results for the cover facing an east-west direction, since this is the orientation that corresponds to the major thermal differences between both condensers [20].

The case for the extinction coefficient is presented in fig. 2. Two representative values for this parameter were chosen, showing the effect of using poor-grade and high-grade glass condensers. The condenser with better optical properties (4 m^{-1}) shows less absorption losses.

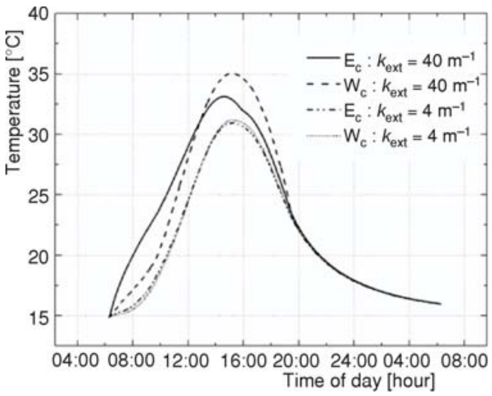

Figure 2. Variation of condensers temperature with extinction coefficient

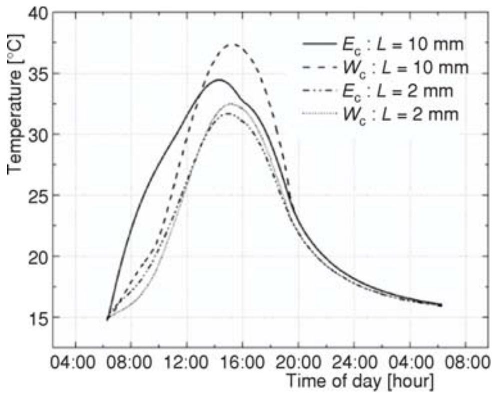

Figure 3. Variation of condensers temperature with cover thickness

This means that less energy is stored in the glass, and therefore the temperatures are lower. For the case with poor optical characteristics (40 m^{-1}), more energy is absorbed producing higher absolute condenser temperatures. The difference between the temperatures of both condensers is more evident for the latter case, due to the different orientation of each plate. A maximum temperature difference of 2.5 °C is attained, with higher temperature values for the east cover in the morning and a reversing effect in the afternoon.

For the cover thickness results, shown in fig. 3, the overall effect for the condenser with a thickness of 10 mm is a higher temperature, because of the energy absorption losses that result from the Sun rays traveling longer distances within the glass. Like the extinction coefficient parameter, the opposite direction of each plate and higher thickness values make temperature differences between the condensers get higher. The result is a maximum temperature difference of 3.5 °C.

Modeled cover temperatures reproduced in good agreement the trends reported in experimental work [20]. However, in the cited work the maximum cover temperatures reported reach 55 °C, in contrast to the numerical model developed in the present paper that shows maximum temperatures of 35 °C. This can be explained by the constant ambient temperature set to 15 °C, while the experimental still was subject to variable ambient temperatures from 15-32 °C. These temperature variations fed to the model will raise cover temperatures in accordance with the maximum experimental temperatures reported.

Numerical models offer the simplicity of manipulating parameters to simulate hypothetical solar still configurations as shown in the temperature plots presented in fig. 4. In this case the two condensers have different optical and physical properties, simulating the use of a still with a combination of a thin high-grade (2 mm, 4 m^{-1}) and a thick low-grade (10 mm, 40 m^{-1}) glass condensers. The combination is such that for the whole day the temperature of one cover is always higher. This behavior is representative of triangular cavities heated differentially, where the convection phenomenon is driven by a single-cell flow pattern [21]. This could benefit the mass transfer in natural convection with low turbulence flows like those found in inverted V-shaped solar stills operating at low temperatures. It has been reported that the peripheral layers of these structures have a major participation in the heat and mass transfer processes [22].

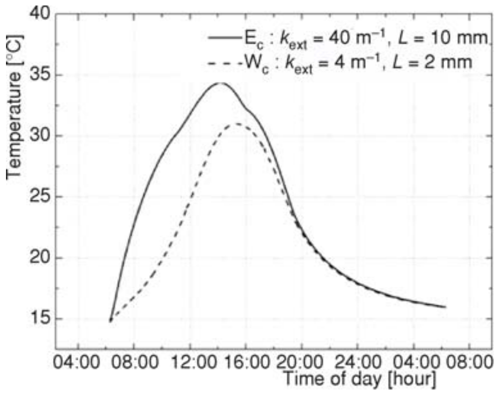

Figure 4. Variation of condensers temperature for the condensing plates with asymmetrical parameters

Condensing plates production dependence in terms of still orientation

As the model is sensitive to orientation, the distillate production dependence on the orientation of the still can be depicted. Results are shown in fig. 5 for a changing azimuth. This figure shows the production for each condensing plate, as well as the total value of the still. An azimuth of 0° corresponds to condensers facing an east-west direction.

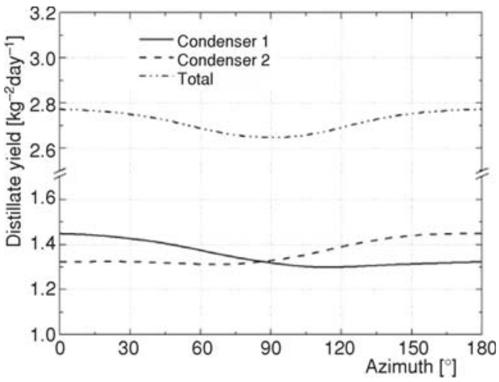

Figure 5. Variation of condensers productivity with still orientation

For the conditions simulated, the maximum difference in production of both condensers is for the still with an azimuth of 0°, with a difference of 0.13 kg/m^2 per day, representing 8.7% of the production of each condensing plate. This orientation corresponds to the total maximum distillate of the still, which agrees with results presented by Sing *et al.* [13] for a maximum output with the cover facing an east-west direction. Meanwhile, for an azimuth of 90°, total yield is the minimal value attained. As the still's condensers are symmetrical, production of each glass plate is symmetrical for an azimuth from 0-180°, so is the total production with respect to this parameter. From here it can be noted that a bad orientation may degrade the production of the still by 4.5%.

Results of the modified model in comparison with traditional models

Modeling the overall performance of the still with the modified model has been carried out, in order to make a comparison with results obtained with traditional models reported in the literature. Figure 6 shows the total distillate yield for various parameters. Results for distillate yield as a function of the glass cover thickness show a decrease in production as cover thickness increases. Common glasses range from 3-6 mm in thickness, and according to this figure, water production falls from 2.93-2.55 kg/m^2 per day, which represents 12.9% of total distillate. The model responded to variations in this parameter, in contrast to the work reported by Toure and

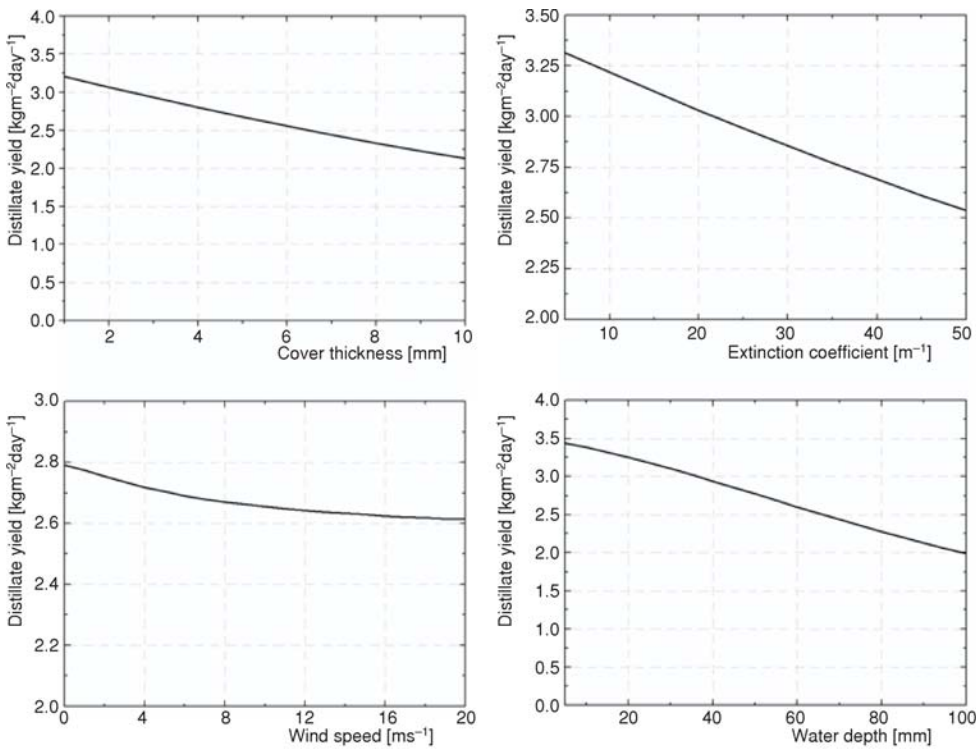

Figure 6. Overall productivity dependence on various parameters

Meukam [3], for shallow solar stills, where production had no variation for values from 4-10 mm.

Daily water production of the still exhibits a linear dependence of production to the variation of the glass extinction coefficient, where distillate yield decreases as this coefficient increases. This parameter is associated with the optical quality of glazing, with a typical value of 4 m^{-1} for *water white* glass, while a value of 32 m^{-1} can be found in poor quality glass [15]. As it can be seen, a high-grade glass would produce 3.31 kg/m^2 per day and a low-grade glass 2.83 kg/m^2 per day. Therefore, the use of a poor optical quality glass cover results in a degradation of 14.5% in total production.

For wind speed, increasing this parameter results in a decrease in the distillate yield, with stronger effects for low wind velocities. An asymptotic tendency can be identified for higher wind speed values. For changing speeds from 1-9 m/s, a decrease in production of 0.11 kg/m^2 per day was found, which represents 3.9% of the total distillate. These results are in agreement with those presented by Nafey *et al.* [4] for the decreasing trend, but his value of 13% found for the same velocity variations is in contrast with the 3.9% found in the results shown in fig. 6. These results show a poor sensitivity of the still to this parameter, and are in contrast with reports found in the literature where production increases as wind speed increases [3, 6, 7].

Overall production dependence on water depth has been studied through the thickness of the water film loaded into the still. It is observed in fig. 6 that as water thickness increases, water production decreases in a nearly linear fashion. A variation from 2-8 cm in this parameter produces a change of 0.97 kg/m^2 per day, or a 30% drop of the total distillate. For the same range, other authors have found about 14% of change in output [2] in stills with single-sloped condensers and 48% for brine depth ranging from 1-10 cm [10]. Cooper´s work [6] developed in double-sloped stills, reported a production change of about 30% for a thickness variation of 1.2-30.5 cm. These results are in slight contrast with those obtained by Badran [7] and Tarawneh [8] for low water depths, where a variation of 1.5 cm in this parameter resulted in a productivity change of 26% and 7.4%, respectively.

Conclusions

An analysis of the main parameters affecting the thermal performance of solar stills with inverted V-shaped condenser system has been presented. This analysis was based on a modified numerical model developed to depict the differences in temperature and production of the condensing plates. A significant influence of incident solar radiation on the thermal performance of each condensing plate was found. Large extinction coefficients, typical of poor optical quality glasses, and thick glass plates, increase absorption losses that results in an appreciable temperature difference. A cover glass with an extinction coefficient of 40 m^{-1} produces a temperature difference of 2.5 °C between both condensers, while a glass thickness of 10 mm may increase this temperature difference up to 3.5 °C. With respect to the production asymmetries due to the still orientation, the major differences were found for the condenser plates facing an east-west direction with 0.13kg/m^2 per day, which represents a change of 8.7%. The overall performance of the still was also tested with the new model, and it was found that variations in orientation and water mass might decrease production by 4.5% and 30%, respectively, Meanwhile, design parameters, such as the cover extinction coefficient and thickness may reduce water production by 14.5% and 12.9%, respectively. Increasing wind speed from 1-9 m/s reduces distillate yield by 3.9%. The overall performance of the still, obtained with the new model, is in accordance with the widely used traditional models for solar distillation. In addition, the proposed model is able to reproduce the temperature and distillate production differences that arise between both condensers in good agreement with experimental data. The condensing cover parameters of the still can be used to force a differential heating such that for the whole day the temperature of one condensing plate is always higher. An improper combination of operational and design parameters may appreciably degrade the production of the still.

Nomenclature

C – thermal capacity, [$Jm^{-2}K^{-1}$]
E – east
f – fraction of total radiation, [–]
G – total solar radiation, [Wm^{-2}]
H – corresponding fraction of absorbed radiation, [Wm^{-2}]
h – heat transfer coefficient, [$Wm^{-2}K^{-1}$]
h_{fg} – latent heat of vaporization, [Jkg^{-1}]
k – thermal conductivity, [$Wm^{-1}K^{-1}$]
k_{ext} – glass extinction coefficient, [m^{-1}]
L – wall thickness, [m]
m'' – mass flow rate, [$kgm^{-2}s^{-1}$]
N – number of daylight hours
Nu – Nusselt number, (= hD/k), [–]
P – partial pressure of water vapor, [Nm^{-2}]
Pr – Prandtl number, (= $\mu c_p k$), [–]
q – heat flow rate, [Wm^{-2}]
Ra – Rayleigh number, (= GrPr), [–]
R_b – ratio of beam radiation for tilted surfaces, [–]
T – temperature, [K]
t – time, [s]
U – global heat transfer coefficient, [$Wm^{-2}K^{-1}$]
v – wind speed, [ms^{-1}]
W – west

Greek symbols

β – cover slope, [deg.]
γ – azimuth, [deg.]
δ – Sun declination, [deg.]
ε – emittance, [–]
ϕ – latitude, [degree]
θ – angle of incidence, [deg.]
σ – Stefan-Boltzmann constant

τ – transmittance, [–]
ω – hour angle, [deg.]

Subscripts

a – absorption losses
b – bottom, beam radiation
c – convective, condenser
e – environment
g – glass cover
m – mean
r – radiative
s – sky
w – water
z – zenithal

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