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Madhlopa, A. (2006) *Study of diurnal production of distilled water by using solar irradiation distribution about solar noon.* In: Eurosun Conference, 2006-06-26 - 2006-06-29, Glasgow.

Study of diurnal production of distilled water by using solar irradiation distribution about solar noon

A paper presented at the EuroSun 2006 conference, 27-30 June 2006, Glasgow Caledonian University, Scotland

by

A. Madhlopa

Abstract

A solar irradiation distribution concept has been used to study the diurnal productivity of a solar still. In this study, a simple single-slope solar still was designed, constructed and tested outdoors (for 9 h starting from 4.5 h before solar noon each day) at the Malawi Polytechnic ((15^o 48′ S, 35^o 02′ E). Meteorological conditions were monitored during the distillation process. In addition, the distillate yield for 32 test days was experimentally and numerically investigated. It was found that the still produced up to 3.454 kg m-2 within 9 h of operation, and 4.820 kg m^{-2} day^{-1} under favorable weather conditions. The mean bias error (MBE) of the models for predicting distillate production improved by up to 57 % when the distribution pattern of solar irradiation was incorporated into the equations for numerical computation.

Keywords: diurnal production, solar irradiation distribution.

1. Introduction

Knowledge about the effect of climatic factors on the performance of solar water stills is vital for the development of this variety of thermal systems. Solar irradiation is one of these factors. It is the driving force of the evaporative process to produce vapour that condenses into clean water.

Many researchers have examined the effect of solar radiation on the performance of a still. The United Nations [1] and Malik et al. [2] report that the daily output of a solar still is affected by the way in which solar radiation is distributed throughout the day. Porta et al. [3] studied operating conditions in shallow stills. They found that sensitivity to thermal inertia yielded different distillate production patterns before and after midday. Tripathi and Tiwari [4] evaluated the performance of a solar still by using solar fractionation. They observed that the effect of solar fraction on system performance was particularly noteworthy at low altitude angle of the sun. However, information is scarce on the effect of solar irradiation distribution pattern on the performance of models that predict distillate production with solar irradiation as an input variable.

In this study, two models for prediction of diurnal distillate production are examined. The choice of these models is based on their simplicity and ease of data acquisition. Tiris et al. [5] correlated the daily distillate output (M_{wd}) with solar irradiation (H_d) using a linear model:

$$M_{wd} = a_1 + a_2 H_d \qquad (1)$$

where a_1 snd a_2 are coefficients of the model. This model is simple and can easily be applied even with limited facilities for data acquisition and processing. Mathioulakis et al. [6] proposed a simple model that includes the difference between mean water (T_{wm}) and ambient (T_{am}) temperatures:

$$M_{wd} = b_1 + b_2 H_d + b_3 (T_{wm} - T_{am}) \qquad (2)$$

It is observed that Eqs. (1) and (2) do not take into consideration the effect of solar irradiation distribution. In the present work, the concept of solar irradiation distribution, with symmetry about solar noon, is used to study the diurnal production of distilled water from a simple solar still. The system was designed, constructed and tested outdoors. The distilled water produced within 9 h was predicted with and without taking into account the distribution of solar irradiation about solar noon. It was found that the performance of the models improved when the total solar irradiation (H_d) was decomposed into its morning (H_m) and afternoon (H_n) components.

2. Methodology

2.1 System description

A single basin solar still was designed and constructed with one slope. The basin (0.80 m x 0.65 m) was constructed from galvanized steel (0.6 mm thickness), painted black on the inside part and placed horizontally on waste cotton insulation inside a wooden box (made of block board, 0.02 m thick). Wooden spacers (0.02 m thick) were fitted between the basin and the inner surface of the bottom part of the box to maintain the thickness of the insulation. The taller vertical side of the box was 0.42 m with a slope of 16^o along the breadth to optimize solar radiation collection at Malawi Polytechnic (15^o 48′ S, 35^o 02′ E), and flow of distillate on the inner surface of the glass cover. A rectangular galvanized steel channel was fitted inside the box, on the shortest vertical face. The inside part of the box was painted black, and a glass cover (4 mm thick) fitted on the top part of the box (Fig. 1). The system was mounted outdoors on a wooden table, 0.76 m above the ground, facing north at the test site. The basin was filled with tap water to a depth of 4 cm, and topped up once in the morning on every test day.

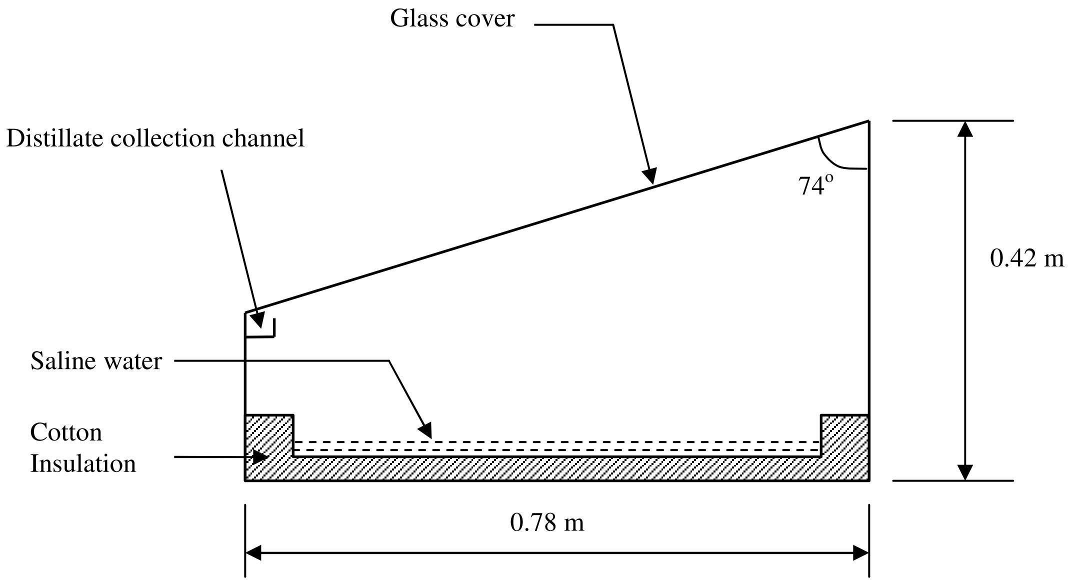


Fig.1: A cross-sectional view of the solar still.

2.2 Meteorological measurements

Data was acquired over a period of 9 h, with symmetry about solar noon (starting from 4.5 h before local solar noon), [7]. Outside this period, the solar altitude angle is low. Tripathi and Tiwari [4] report that the solar fraction inside a conventional solar still with single slope is very influential at lower values of the solar altitude.

Two mercury-in glass immersion thermometers (T_{wA} and T_{wB}) were used to measure the temperature of water during the experimental period. These thermometers were inserted on opposite vertical sides of the basin, halfway between the bottom of the basin and the water surface. Ambient temperature was monitored using a minimum and maximum mercury-in-glass thermometer placed in a room with louvered windows, and the louvers were kept open to allow free circulation of air. Wind velocity was measured using a Casella low-speed air meter (N 1462) while the intensity of global solar radiation was measured by a first-class Kipp & Zonen pyranometer (CM 6B) mounted in the plane of the inclination of the transparent cover, and connected to a Kipp & Zonen solar integrator (CC 14). The amounts of solar radiation received by the system in the morning (H_m) and afternoon (H_n) were recorded [7]. There were 32 points in the final set of data.

2.3 Data processing

The mean temperature of water (T_{wm}) was computed from the initial (T_{wAi} and T_{wBi}) and final (T_{wAf} andT_{wBf}) temperature readings, while the mean ambient air temperature (T_{am}) was calculated from the minimum (T_{amin}) and maximum (T_{amax}) readings of ambient temperature.

$$T_{wm} = (T_{wAi} + T_{wBi} + T_{wAf} + T_{wBf})/4 \quad (3a)$$

$T_{am} = (T_{amin} + T_{amax})/2$ (3b)

The values of T_{wm} and T_{am} were used to obtain the temperature difference $(T_{wm} – T_{am})$.

The solar irradiation factor (R) developed by Chang et al. [7] was used to incorporate the concept of solar irradiation distribution about solar noon:

$R = H_m/H_n$ (4)

where H_m and H_n are levels of global solar irradiation in the morning and afternoon, respectively. These authors used R to screen test data for thermosyphon solar water heaters. It is noted that the total solar irradiation intercepted by the system (H_d) can be expressed as:

$H_d = H_m + H_n$ (5)

By using Eqs. (1), (2) and (5), modified models that predict the diurnal production of distilled water were derived:

$M_{wd} = c_1 + c_2 H_m + c_3 H_n$ (6a)

$M_{wd} = d_1 + d_2 H_m + d_3 H_n + d_4 (T_{wm} – T_{am})$ (6b)

The efficiency (η) of the system was computed by:

$\eta_d = L M_{wd} / A_c H_d$ (7)

where A_c is the absorber area, L is specific latent heat of vaporization of water at the mean water temperature (T_{wm}), and M_{wd} is distillate productivity within the test period (9 h).

Combined measurement errors for the primary data points were calculated by using procedures reported by Holman and Gajda [8] and Mathioulakis et al. [9]. Uncertainties in measured mass of distillate, latent heat of water vaporization, absorber area and solar irradiance were used to compute the combined uncertainty for each data point. For solar irradiance, the uncertainty was computed by taking into account the standard uncertainties arising from non-linearity, directional response, spectral selectivity, temperature response, tilt response and non-stability [10]. A least squares regression (LS) analysis was performed on the test data to estimate the values of coefficients of Eqs. (2) and (6), [11].

The performance of the models was examined by using the mean bias error (MBE) and root mean square error (RMSE), commonly reported in literature:

$MBE = \Sigma(M_{wd} – M_{es})/k$ (8a)

$RMSE = \{\Sigma(M_{wd} – M_{es})^2/k\}^{0.5}$ (8b)

where k is the number of observations. The value of MBE is equal (or close) to zero for an adequate model. Similarly, low values of RMSE are preferable. It should also be mentioned that the difference between the observed (M_{wd}) and estimated (M_{es}) values is a residual, and that the distribution of residuals is normal for a good model [11]. In this study, the distribution type of the residuals was determined by using a technique reported by Ianetz et al. [12].

3. Results

3.1 Distillate production

Fig.2 shows the hourly distillate production (M_{wh}) on a typical day. It is seen the rate of production is maximum around 14:00 h, nearly 2 h after solar noon. This delay is attributed to the thermal inertia of the system.

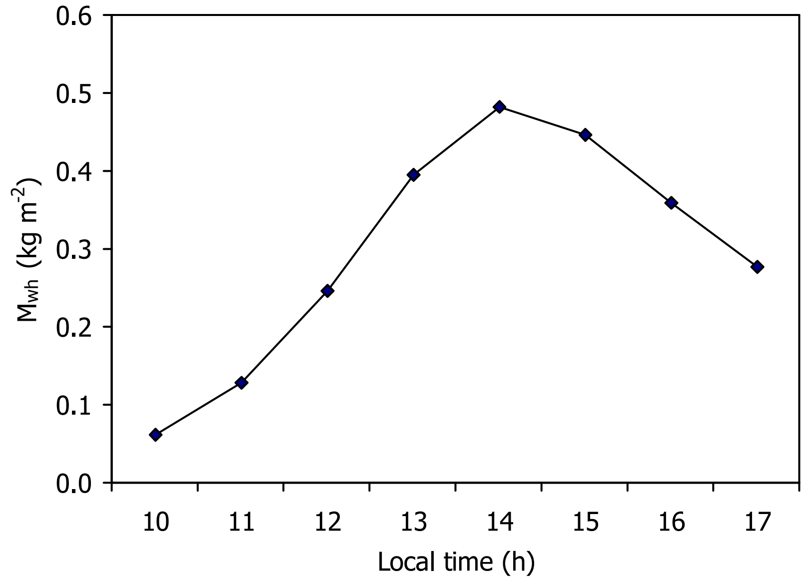


Fig.2: Variation of hourly distillate production (M_{wh}) with local time on a typical day (28th August 2005).

The levels of diurnal (M_{wd}) and daily (M_{wt}) distillate production during five typical days. are presented in Table 2, (maximum observed uncertainty = 0.013 kg m^{-2}). M_{wd} varied between 2.844 and 3.454 kg m^{-2}, depending on meteorological conditions. The minimum and maximum observed values of M_{wd} were 0.820 and 3.454 kg m^{-2} respectively. It is seen that M_{wt} varied between 3.882 and 4.820 kg m^{-2}. The minimum and maximum observed values of M_{wt} were 1.501 and 4.820 kg m^{-2} respectively. It was also found that the daily efficiency of the system varied between 20 and 30 %.

Table 2: Diurnal (M_{wd}) and total daily (M_{wt}) distillate production during five typical days.

Date	M_{wd} (kg m^{-2})	M_{wt} (kg m^{-2})
12/9/2005	2.844	3.966
13/9/2005	3.027	4.246
14/9/2005	2.856	3.882
15/9/2005	2.911	4.054
16/9/2005	3.454	4.820

3.3 New correlations

For the Tiris et al. [5] model, the following correlations were obtained:

$M_{wd} = -0.798 + 0.119\, H_d$, ($r^2 = 0.949$) (9a)

$M_{wd} = -0.791 + 0.117\, H_m + 0.120\, H_n$, ($r^2 = 0.949$) (9b)

It is seen that the values of the coefficients of H_m and H_n are different. This indicates that the irradiation distribution about solar noon has some influence on the distillate production. In the absence of this influence, these coefficients would have the same value. The Tiris et al. [5] model and its corresponding modified model yield the same value of r^2.

For the Mathioulakis et al. [6] model, the following correlations were obtained:

$M_{wd} = -0.927 + 0.110\ H_d + 0.023\ (T_{wm} - T_{am})$, ($r^2 = 0.966$) (10a)

$M_{wd} = -0.913 + 0.106\ H_m + H_n + 0.023\ (T_{wm} - T_{am})$, ($r^2 = 0.967$) (10b)

It is observed that the values of coefficients of H_m and H_n are different. Again, this indicates that the irradiation distribution about solar noon has some influence on the distillate production. It is seen that r^2 improved from 0.966 to 0.967. This improvement is attributed to the splitting of H_d into its morning and afternoon components.

3.4 Model performance

Table 3 shows the values of the mean bias error (MBE) and root mean square error (RMSE) for the original models reported by Tiris et al. [5] and Mathioulakis et al. [6] and their corresponding modified models. For the Tiris et al. [5] model, the MBE improved by 23 % (on magnitude basis) from –0.013 kg m^{-2} for the original model to 0.010 kg m^{-2} for the modified model. It is also observed that the value of MBE for the modified model is within the measurement error. The RMSE (0.141 kg m^{-2}) did not change significantly.

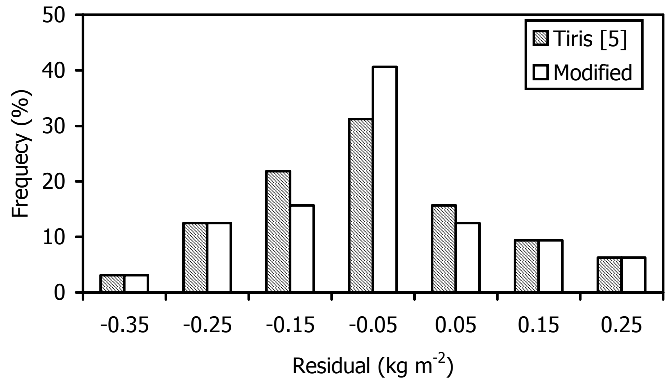
Table 3: Variation of the mean bias error (MBE) and root mean square error (RMSE).

Model	MBE (kg m^{-2})	RMSE (kg m^{-2})
Tiris et al. (1996), original	-0.013	0.141
Tiris et al. (1996), modified	-0.010	0.141
Mathioulakis et al. (1999a), original	0.007	0.115
Mathioulakis et al. (1999a), modified	-0.003	0.113

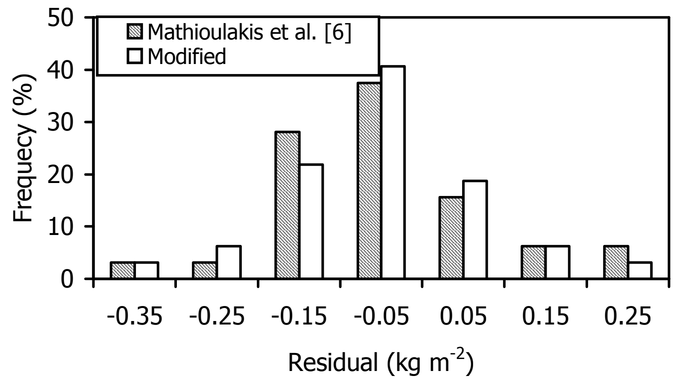
For the Mathioulakis et al. [6] model, it is observed that the MBE improved by 57 % from 0.007 kg m^{-2} for the original model to -0.003 kg m^{-2} for the modified model. It is seen that the values of MBE are within measurement error for both forms of the model. The RMSE improved (by 2 %) from 0.115 kg m^{-2} (original model) to 0.113 kg m^{-2} (modified model). Fig.5 shows the distributions of residuals for the Tiris et al. [5] and Mathioulakis et al.. [6] original models and their corresponding modified forms. For the Tiris et al. [5] model, both distributions of the residuals for the original and modified models are normal with the same modal class. However, the residual distribution for the original model has a flatter peak (kurtosis = 0.567) than that for the modified model (kurtosis = 0.652). This shows that the latter model yields a better distribution of residuals. For the Mathioulakis et al. [6] model, both distributions of the residuals for the original and modified models are also normal with the same modal class. Again, the original model has a flatter peak (kurtosis = 0.082) than that for the corresponding modified model (kurtosis = 0.344). This indicates that the modified model yields a better distribution of residuals.

4. Conclusion

The diurnal production of distilled water from a simple solar still has been studied experimentally and numerically by using the concept of solar irradiation distribution with symmetry about solar noon. The solar still was tested outdoors for 9 h starting from 4.5 h before solar noon, and the amount of distillate collected on each test day was modeled. The performance of models for predicting the distillate production improved when the distribution pattern of solar irradiation was incorporated into the numerical computation.



(a)



(b)

Fig.5: Comparison of residual distributions for a) Tiris et al. [5] and modified Tiris et al. [5], and b) Mathioulakis et al. [6] and modified Mathioulakis et al. [6] models.

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