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Predicting the yield of a single slope solar still: A comparison of models

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Abstract

Access to potable water is one of the greatest challenges facing humanity in the 21st century. This issue is particularly pronounced in developing countries near the equator and the 'sun-belt' regions, where increasing groundwater salinity and contamination of freshwater is commonplace. Given their abundance of solar energy, these areas have often relied on solar stills to desalinate water for both small and large volume applications, and as such significant amounts of research have been directed at understanding the yield of solar stills. This has led to the development of numerous thermal models for this very purpose. However, these models are often adapted to match the yield of an individual system with little reference to other similar systems. Where reference is made to other studies, it often relies on the 1961 work of Dunkle despite its widely discussed limitations.

Considering the ad-hoc treatment solar stills have received, this work compared the predicted yield of freshwater from single slope solar still cited in Algeria, using various models found in the literature. The results show that significant differences exist with regards to the predicted yield from all the models. Moreover, no firm conclusions on the heat and mass transfer processes inside single slope solar still enclosures could be drawn. In summary, the results suggest the need for a wider and more generalised treatment of the heat and mass transfer processes in single slope solar stills to deliver an improved and reliable prediction of their yield.

1. Introduction

Water resource availability is one of the most important factors for socio-economic development (Sharon et al. 2017). With only 2.5% of earth's water being fresh, availability and access to potable water is one of the greatest challenges facing humanity in the 21st century (Tiwari and Sahota 2017). Moreover, the demographic explosion and human developments toward a more comfortable life have quadrupled water consumption, which leads to inappropriate water supply (Rosegrant, 2002). In addition, rainfall shortages and water pollution in different regions in the world, especially in remote areas, constitute the major challenges facing people's daily life.

Whether the source of water is from underground or superficial resources, it is always very important to treat water before human consumption. According to Younos and Tulou (2005), one of the most prominent solutions for water treatment is water desalination. This can be done using three different purification technologies: chemical processes, membrane technologies and thermal approaches. Of these, the thermal desalination technique can handle high concentration of pollutants and large water demands. When paired with the use of solar energy, it is possible to produce freshwater in a sustainable and eco-friendly way (Ayoub and Malaeb 2012).

Passive single slope solar still is the most basic configuration to which all the different designs and geometries are compared to. The literature in this area has focused on increasing the single slope solar still yield by using different absorbers, glass and insulation materials (Tiris et al. 1996, Kaushika and Sumathy 2003, Abdallah et al. 2009, El-Sebaii et al. 2009, Panchal and Shah 2012, Srivastava and Agrawal 2013, Hansen et al. 2015, Harris et al. 2016). In many of these studies, the single slope solar still yield rate was analysed experimentally by varying the cover angle. From this, different and often conflicting conclusions were made about the optimum angle. In particular, several studies have suggested that the angle should be equal to latitude.

Now, according to Elango et al. (2015), the most efficient method to analyse any thermal system performance is thermal modelling. Based on the various energy balances of the solar still parts, different thermal models were developed to predict water production from solar stills. One of the most critical parameters is the heat and mass transfer between the absorber plate and glass cover. In determining this, the most often used equation that describes mass and heat transfer in a solar still was developed by Dunkle (1961). However, different researchers pointed out that Dunkle's model leads to an overestimation of solar still yield. This has resulted in the development of new models to overcome the shortcomings of this model. However, these models appear to have been developed in an ad-hoc manner. Therefore, the aim of this research is to evaluate and compare the performance of single slope solar still models to examine their prediction of annual water production.

2. Method

2.1 Solar still modelling

In order to predict the fresh water produced by a solar still, an energy balance based on the first law of thermodynamics is necessary to determine the temperatures of the absorber, water in the basin, and the cover of the still.

Under these conditions, the energy balance associated with the water in the solar still is given by Equation 1.

$$M_w Cp_w \frac{dT_w}{dt} = A_{abs} I_T(t) \tau_g \alpha_w + A_{abs} h_{abs-w}(T_{abs} - T_w) - A_{abs}(h_{cv} + h_{ew} + h_{r\,w-g})(T_w - T_g) \quad (1)$$

Similarly, the energy at the absorber can be given by Equation 2.

$$M_{abs} Cp_{abs} \frac{dT_{abs}}{dt} = A_{abs} I_T(t) \tau_g \tau_w \alpha_{abs} - A_{abs} h_{abs-w}(T_{abs} - T_w) - A_{abs} h_b (T_{abs} - T_a) \quad (2)$$

And the energy balance at the cover is given by Equation 3.

$$M_g Cp_g \frac{dT_g}{dt} = A_g I_T(t) \alpha_g + A_g (h_{cv} + h_{r\,w-g})(T_w - T_g) - A_g h_{cv\,g-a}(T_g - T_a) - A_g h_{r\,g-a}(T_g - T_a) \quad (3)$$

From inspection of these equations, it is apparent that they rely on two terms, h_{cv} and h_{ew}, which relate to the heat and mass transfer in the solar still. Given that thermal energy in solar stills is driven by free convection between the transparent cover and water surface. The heat and mass transfer equations used to predict solar still performance constitute the most essential factor that determine the amount of produced water. Over the years, different thermal models have been developed in order to predict more precisely the yield from a solar still. In saying this, it is these two variables that have been the source of much discussion in the literature.

Dunkle (1961) suggested using the empirical equation for convective heat transfer and the Grashof number developed by (Sharpley and Boelter 1938) to estimate the convective and evaporative heat transfer coefficients inside the solar still as shown in Equations 4 and 5.

$$\mathrm{h}_{cv} = 0.884\left[\left(T_w - T_g\right) + \frac{(P_w - P_g)*(T_w + 273.15)}{268.9*10^3 - P_w}\right]^{1/3} \quad (4)$$

$$\mathrm{h_{ew}} = 0.0163 * \mathrm{h_{cv}} * \left[\frac{\mathrm{P_w - P_g}}{\mathrm{T_w - T_g}}\right] \quad (5)$$

Meanwhile, Adhikari et al. (1990) performed an indoor experiment to determine the heat and mass transfer inside a solar still. They suggested that the amount of water produced by a solar still could be determined using Equation 6.

$$\dot{\mathrm{m}} = \alpha * (\Delta T')^n * (P_w - P_g) \quad (6)$$

where Table 1 shows the constants n and α that should be used in this relationship.

Table 1: n and α values for different working conditions

Average temperature (ºC)	$\alpha*10^9$	
	$Gr < 2.51*10^5$ (n=1/4)	$Gr>2.51*10^5$ (n=1/3)
40	8.1202	9.7798
60	8.1518	9.6707
80	8.1895	9.4936

In their study Shawaqfeh and Farid (1995) developed a new relationship for heat and mass transfer in single slope solar stills. Dunkle's model was rejected in the study because of the simplifying assumptions it made. In their study, Shawaqfeh and Farid (1995) developed two relationships describing the heat and mass transfer inside a single slope solar still. The model was like Dunkle's but considered the effect of water vapour pressure as shown in Equation 7.

$$h_{ew} = \frac{\lambda_w * M_w}{2 * C_{p_{mix}} * M_{mix}}\left[\frac{1}{P_{(a)w}} + \frac{1}{P_{(a)g}}\right] h_{cv1} \quad (7)$$

Using their mass transfer model in conjunction with indoor measurements on a 20º single slope solar still, Shawaqfeh and Farid (1995) generated a correlation to describe convective the heat transfer coefficient h_{cv} as shown in Equation 8.

$$h_{cv1} = 0.057 * Ra' \quad (8)$$

More recently, Rahbar and Esfahani (2012) performed a numerical study to investigate the heat transfer inside 2-D single slope solar stills. From this, they developed a relationship to describe the convective heat transfer process in terms of the solar still's aspect ratio for a range of Rayleigh numbers, as shown in Equation 9. They paired this with Equation 5 to determine the water produced.

$$Nu = 0.28\,(Ra)^{0.25}(A_R)^{-0.16} \quad (9)$$

Finally, Jamil and Akhtar (2017) also investigated the effect of single slope solar still geometry on its performance. In their study, experimental work was performed to analyse the relationship between the Nusselt number and the specific height, leading to the correlation shown in Equation 10 and as Rahbar and Esfahani (2012) did, they used Dunkle's expression to determine h_{ew}.

$$Nu = 0.0462\ (A_R)^{0.15}(Ra)^{0.34} \quad (10)$$

In order to evaluate the relationships presented in the literature, and their impact on the prediction of the water produced, MATLAB was used to solve the energy balance and determine the absorber, water and cover temperatures. Having determined these, the production of potable water for each of the relations in the literature, was determined from Equation (11).

$$\dot{\mathrm{m}} = \frac{h_{ew}\mathrm{A}_{abs}(\mathrm{T}_w - T_g)}{\lambda_w} \quad (11)$$

In applying the energy balance, several assumptions were made:

- The water level inside the solar still basin is constant (M_w)
- The solar still is well sealed (no air/water vapour leaks).
- The cover, water and absorber temperatures were the same at all points on these
- The relationships to describe the radiation heat transfer and wind loss from the cover were the same for all models.

Figure 1 shows the geometry of the single-slope solar still used in this study to compare the different thermal models.

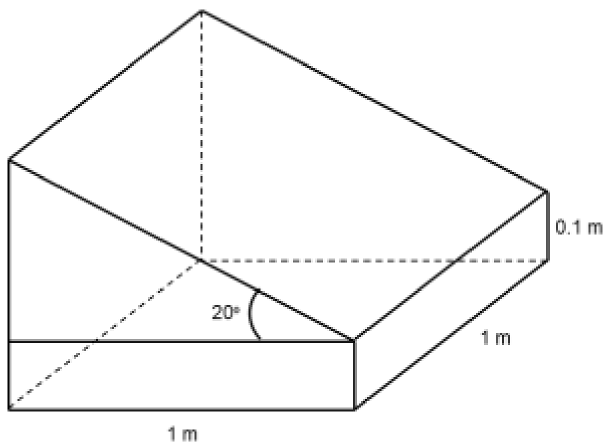

Figure 1: Schematic diagram of the solar still

In undertaking the calculation of the water production, the hourly data for ambient temperature, wind velocity and solar irradiation of was generated for one year using Meteonorm software for Laghouat, a city in the southern part of Algeria. The location was selected because of the abundance of solar irradiation and the existing need for freshwater in remote areas of the city. As an initial comparison of the selected models, two days corresponding to the highest and lowest irradiation days were chosen. Figure 2 and 3 show the weather conditions of the 27th of May and 31st of December respectively. However, the annual water production was determined by simulating the solar still for the duration of the full year.

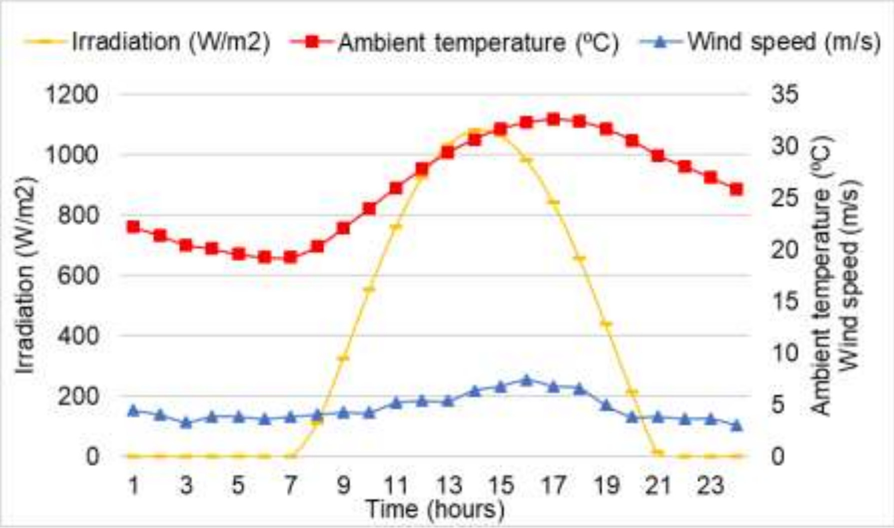

Figure 2: Hourly variation of weather conditions on 27th of May

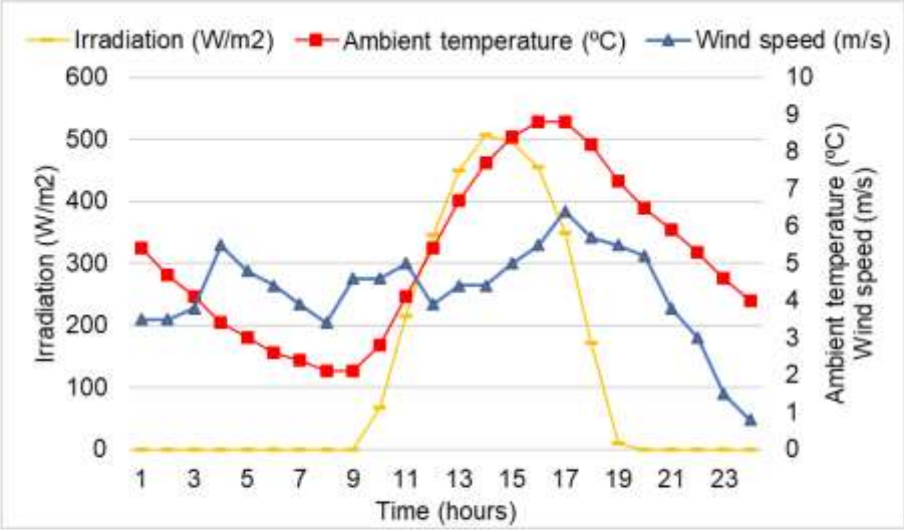

Figure 3: Hourly variation of weather conditions on 31st of December

3. Results

Having developed the solar still model, it was decided to explore the differences in the convective heat transfer coefficient (h_{cv}) from each of the previous studies during the two selected days. Figures 4 and 5 show that the values of h_{cv} from the models vary quite widely throughout the day. Although the difference is low early in the morning, this increases with the increase of the temperature difference between the absorber and cover glass as a result of the increase in solar irradiation.

It is clearly shown that estimations from the model developed by Adhikari et al. (1990) are very high compared to all other models. Although Dunkle's (1961) model predicts a lower heat transfer coefficient than Adhikari et al.'s model, compared to Jamil and Akhtar (2017), Rahbar and Esfahani (2012) and Shawaqfeh and Farid (1995) estimations, Dunkle's model predicts a heat transfer coefficient with up to 30% higher.

The difference in these estimations is due to the different conditions under which the models were developed. For example, Dunkle (1961) developed his model using two parallel surfaces while in the other models, a restricted range of aspect ratio and cover angle were taken into account. This led to the high yield prediction by Dunkle (1961) and Adhikari et al. (1990) due to the absence of geometric factors in their equations (4) and (6) and different temperature range of their experiments. Dunkle's model considers that the absorber and cover are parallel while the Adhikari et al. (1990) model is based on experimental work that can be valid only for the same working conditions.

Conversely, the Shawaqfeh and Farid (1995) model predicted the lowest heat transfer coefficient because the latter correlation was developed for a solar still with a cover angle of 20º. Whereas, according to Palacio and Fernandez (1993), the convective heat transfer mode increases with an increase of the cover angle. Therefore, the low h_{cv} is due to the angle of the experiment in which the correlation was developed. Finally, the Jamil and Akhtar (2017) and Rahbar and Esfahani (2012) predictions appear to be similar, however since mass transfer is directly linked to the convective heat transfer, the small difference in h_{cv} between the models could lead to bigger differences in the overall efficiency of the solar still.

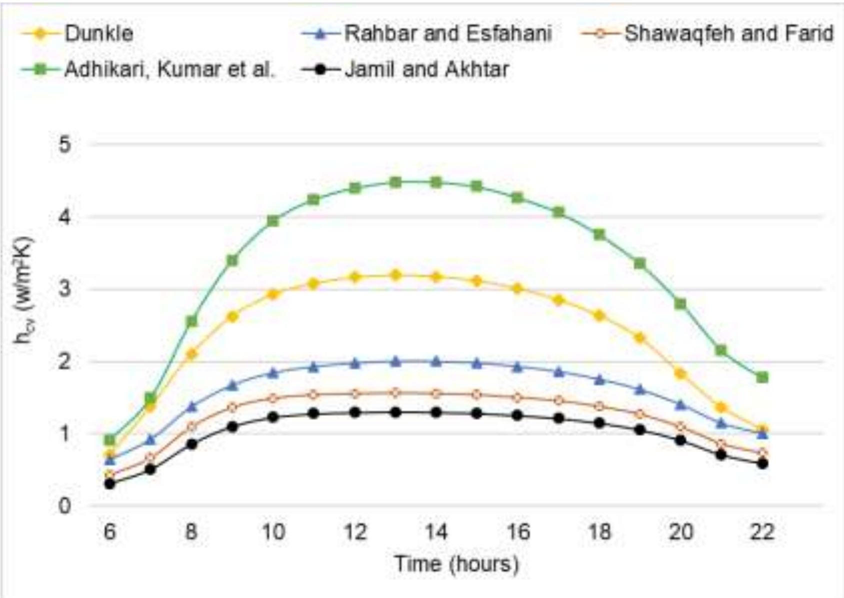

Figure 4: Convective heat transfer on 27th May

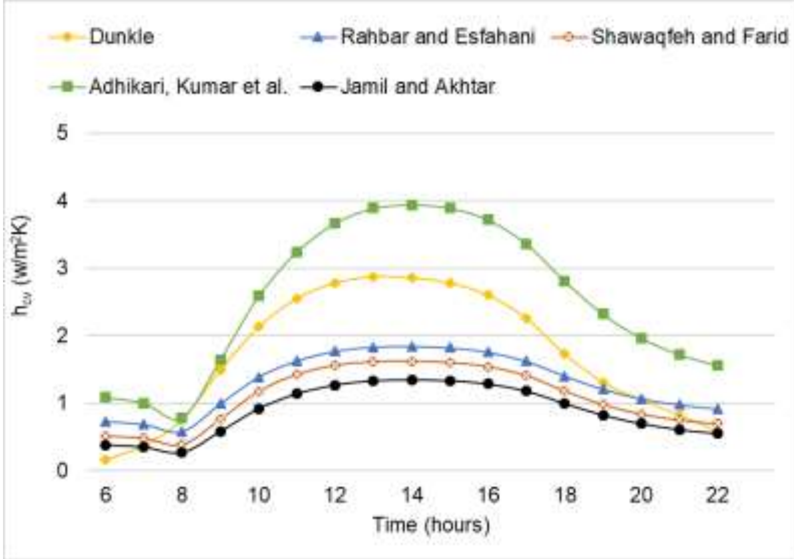

Figure 5: Convective heat transfer on 31st of December

Now as expected, the maximum and minimum monthly water production follows the same trend of the solar energy irradiation and was higher during summer months while the lowest was found during winter. Figure 6 shows the yearly amount of freshwater produced by the solar still for each thermal model. As expected, the amount of water produced using the different models was different since they are based on different heat transfer correlations. One can see clearly that the amount of water produced using the Dunkle (1961) and Adhikari et al. (1990) models is high compared to the other models. The total amount of water from the latter model exceeds the one predicted by Dunkle's model by almost 40% and the others by more than 50%. The high estimation of water production by the two models is due to the restrictions related to the condition in which the models were developed.

Despite the close agreement between Jamil and Akhtar (2017), Rahbar and Esfahani (2012) and Shawaqfeh and Farid (1995), compared to the two other models, the predicted amount of water produced by each is still significantly different. This discrepancy raises a significant issue as to which model is correct, and can it be universally applied.

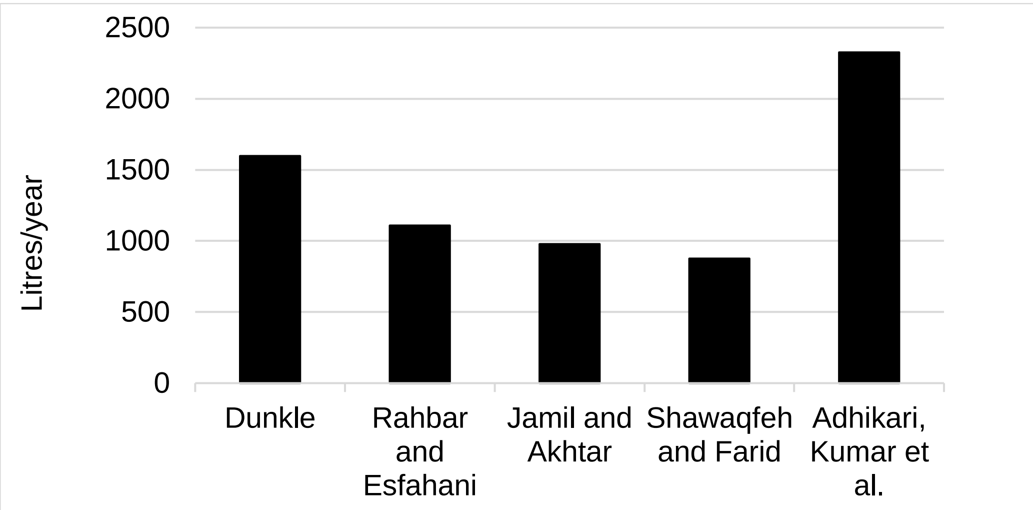

Figure 6: Predicted amount of water for each model per year

4. Conclusions

This work has shown that there are numerous existing thermal models in the literature that predict solar still performance. From the model, it was apparent that small differences in the daily performance between the models led to significant differences in terms of yearly output of such systems. Although the effect of single slope solar still geometric factors on the performance of solar still was considered in some of the models, this was not universal. It is foreseeable that these factors would influence the convective heat transfer coefficient which directly leads to different mass transfer performance.

In order to improve the different thermal models existing in the literature, there is a need to critically investigate the effect of the different designs and geometrical factors such as aspect ratio, cover slope and characteristic length on solar still performance. Doing this will lead to better predictions of the annual production from these devices and their successful implementation in practical applications.

Nomenclature

A_{abs}: Absorber area (m^2)

A_g: glass cover area (m^2)

A_R: Aspect ratio = L/B

B: Base (m)

Cp_w: Specific heat of water (J/kg K)

Cp_g: Specific heat of the glass (J/kg K)

Cp_{abs}: Specific heat of the Absorber (J/kg K)

$C_{p_{mix}}$: Specific heat capacity of the water vapour-air mixture (J/kg K)

Gr: Grashof number

h_{abs-w}: Convective heat transfer coefficient from absorber to water (W/m^{2}K)

h_{cv} : Convective heat transfer from water surface to cover (W/m^{2}K)

h_{ew}: Evaporative heat transfer from water surface to cover (W/m^{2}K)

$h_{r\,w-g}$: Radiative heat transfer from water surface to cover (W/m^{2}K)

h_b: Heat transfer coefficient by conduction through the bottom of the absorber (W/m^{2}K)

$h_{cv\,g-a}$: Convective heat transfer coefficient from glass to ambient (W/m^{2}K)

$h_{r\,g-a}$: Radiative heat transfer from cover to ambient (W/m^{2}K)

I_T: Total radiation (W/m^2)

L: Characteristic length (m)

Le: Lewis number

M_w: Water mass in solar still (Kg)

M_v: Molecular weight of water vapour (g/mol)

M_{abs}: Absorber mass (Kg)

M_g: Glass mass (Kg)

M_{mix}: Molecular weight of water vapour air mixture (g/mol)

$\dot{m}$: Hourly water production (Kg/s)

Nu: Nusselt number

P_w: Pressure at evaporation surface (pa)

P_g: Pressure at inner cover surface (pa)

$P_{(a)w}$: Partial pressure of dry air at the basin (pa)

$P_{(a)g}$: Partial pressure of dry air at the glass cover (pa)

$P_{(a)LM}$: Log mean of the air partial pressure (pa)

Ra: Rayleigh number

Ra': Modified Rayleigh number

T_w: Water temperature (K)

t: Time (s)

T_{abs}: Absorber temperature (K)

T_w: Water temperature (K)

T_g: Cover temperature (K)

T_a: Ambient temperature (K)

τ_g: Glass transmission coefficient

α_w: Absorption coefficient of water

τ_w: Glass transmission coefficient

α_{abs}: Absorption coefficient of absorber

α_g: Absorption coefficient of the glass

$\Delta T'$: defined as $\left[\left(T_w - T_g\right) + \frac{(P_w - P_g)*(T_w + 273.15)}{268.9*10^3 - P_w}\right]$

λ_w: Latent heat of vaporization (J/kg)

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