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Preliminary results from the testing of an advanced passive solar still incorporating a shielded condenser

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Abstract: An advanced passive solar still with separate condenser has been studied theoretically and experimentally. The system has one basin in the evaporation chamber and two basins (middle and upper) in the condenser chamber, with a glass cover over the evaporator basin and an opaque condensing cover over the upper basin. The evaporator, middle and upper basins form the primary, secondary and tertiary effects respectively. The top part of the condensing cover is shielded from solar radiation and heat. Water vapor from the primary effect condenses under the glass cover while the remainder of it flows into the condenser, by purging and diffusion, and condenses under the liner of the middle basin. Outdoor tests of the present solar still and a conventional system were conducted at the University of Strathclyde. The two systems are also simulated under the same meteorological conditions. It is found that the solar shield effectively keeps the condenser cover relatively cool. Under favorable weather conditions the present solar still produced up to 34% more distillate than the conventional type. Experimental and estimated results are in close conformity. It appears that the new solar still can be exploited within and outside the tropical region

1. Introduction

According to the United Nations (2007), the ability to provide affordable, clean drinking water in sufficient quantities will be one of the major challenges we have to address in order to sustain socio-economic development in many parts of the world. In 2006, 78 % and 96 % of the rural and urban populations, respectively, had access to safe drinking water on a global scale (World Health Organization, 2008). It is clear that a shortage of clean drinking water is worse in rural areas. This problem may be alleviated through the use of solar distillation.

One way of increasing the yield from solar distillation has been through the use of a separate condenser (Fath and Elsherbiny, 1993; El-Bahi and Inan, 1999a; El-Bahi and Inan,1999b). However, the condenser unit in the previous work is located in the shadow zone of the solar still (without a solar shield), which exposes the condenser cover to diffuse and ground-reflected components of solar radiation. Moreover, the sun is overhead and on either side of the latitude at a tropical site, thereby allowing the global solar radiation to reach and heat the exposed condensing cover, and significantly reduce the cover-water temperature difference. This curtails the thermal efficiency of the still.

Research being undertaken in the Energy Systems Research Unit at the University of Strathclyde aims to overcome this limitation through: a) identification of the governing parameters influencing the production of clean water from passive solar stills; b) formulation of a computational based decision support tool to be used for the design of an effective solar still for the climatic conditions of the site of operation; and c) develop an advanced prototype solar still for operation in meteorological conditions as found in tropical areas such as Malawi.

2. Materials and methods

2.1 System description and modeling

The advanced solar still has one basin in the evaporation chamber and two basins (middle and upper) in the condenser chamber, with a glass cover over the evaporator basin and an opaque condensing cover over the upper basin (Fig.1). The evaporator, middle and upper basins provide primary, secondary and tertiary productions of fresh water respectively. It should be mentioned that the middle and upper basins were stepped to minimize the mass of saline water in these basins. To enhance performance, the top part of the condensing cover is shielded from solar radiation and heat. Water vapor from the primary evaporation chamber condenses under the glass cover while the remainder of it flows into the condenser chamber, by purging and diffusion, and condenses under the liner of the middle basin. The condensed fresh water is channeled into a sealed collection vessel from where the water can be used.

A mathematical model is developed to predict the performance of a solar still with separate condenser. It is assumed that: a) the solar still is air-tight, b) purging and diffusion stop when the temperature of water in the middle basin exceeds that of the lower basin liner, and c) ground-reflected solar radiation does not reach saline water in the evaporator basin. With these assumptions, the heat balance equations for the present solar still (PSS) components are given as follows:

Glass cover (gc)

$$m_{gc}C_{p,gc}\frac{dT_{gc}}{dt}=A_{gc}F_{gc}G_{ef}+A_{wl}h_{gc}\left(T_{wl}-T_{gc}\right)-A_{gc}h_{c,gc-a}\left(T_{gc}-T_{a}\right)-A_{gc}h_{r,gc-sk}\left(T_{gc}-T_{sk}\right) \tag{1}$$

$$h_{gc}=\left(\frac{Rh_{c,wl-gc}}{1+R}+\frac{Rh_{e,wl-gc}}{1+R}+h_{r,wl-gc}\right) \tag{2}$$

Lower basin liner (bl)

$$m_{bl}C_{p,bl}\frac{dT_{bl}}{dt}=A_{wl}\left\{F_{bl}G_{ef}-h_{c,bl-wl}\left(T_{bl}-T_{wl}\right)-U_{bo}\left(T_{bl}-T_{a}\right)\right\} \tag{3}$$

Water in lower basin (wl)

$$m_{wl}C_{P,wl}\frac{dT_{wl}}{dt}=A_{wl}\left[F_{wl}G_{ef}+h_{c,bl-wl}\left(T_{bl}-T_{wl}\right)\right]-\dot{m}H_{wl}-A_{wl}h_{wl}\left(T_{wl}-T_{gc}\right)-A_{sl}U_{sw}\left(T_{wl}-T_{a}\right) \tag{4}$$

$$h_{wl}=h_{c,wl-gc}+h_{e,wl-gc}+h_{r,wl-gc} \tag{5}$$

$$\dot{m}=D\left(\mathrm{A}_{\mathrm{ec}}/x_{ec}\right)\left(\varphi_{ve}-\varphi_{vc}\right) \tag{6}$$

Middle basin liner (bm)

$$m_{bu}C_{p,bm}\frac{dT_{bm}}{dt}=A_{wl}h_{pu}\left(T_{wl}-T_{gc}\right)+\dot{m}H_{wl}-A_{bm}h_{c,bm-wm}\left(T_{bm}-T_{wm}\right) \tag{7}$$

$$h_{pu}=\frac{h_{c,wl-gc}}{1+R}+\frac{h_{e,wl-gc}}{1+R} \tag{8}$$

Water in the middle basin (wm)

$$m_{wu}C_{p,wm}\frac{dT_{wm}}{dt}=A_{bm}h_{c,bu-wm}\left(T_{bm}-T_{wm}\right)-A_{wm}h_{wm}\left(T_{wm}-T_{bu}\right)-A_{sm}U_{sw}\left(T_{wm}-T_{a}\right) \tag{9}$$

$$h_{wm}=h_{c,wm-bu}+h_{e,wm-bu}+h_{r,wm-bu} \tag{10}$$

Upper basin liner (bu)

$$m_{bu}C_{p,bu}\frac{dT_{bu}}{dt}=A_{wm}h_{wm}\left(T_{wm}-T_{bu}\right)-A_{bu}h_{c,bu-wu}\left(T_{bu}-T_{wu}\right) \tag{11}$$

Water in upper basin (wu)

$$m_{bu}C_{p,wu}\frac{dT_{wu}}{dt}=A_{bu}h_{c,bu-wu}\left(T_{bu}-T_{wu}\right)-A_{wu}h_{wu}\left(T_{wu}-T_{co}\right)-A_{su}U_{sw}\left(T_{wu}-T_{a}\right) \tag{12}$$

$$h_{wu}=h_{c,wu-co}+h_{e,wu-co}+h_{r,wu-co} \tag{13}$$

Rate of condensation (dw)

$$\frac{dm_{dw}}{dt}=\frac{h_{e,wl-gc}\left(T_{wl}-T_{gc}\right)}{H_{wl}}+\frac{A_{wm}h_{e,wm-bu}\left(T_{wm}-T_{bu}\right)}{A_{wl}H_{wm}}+\frac{A_{wu}h_{e,wu-co}\left(T_{wu}-T_{co}\right)}{A_{wl}H_{wu}}+\frac{\dot{m}}{A_{wl}} \tag{14}$$

The distillate yield (m_{dw}) in a time interval of (t_2-t_1) is calculated as follows:

$$m_{dw}=\int_{t_1}^{t_2}\left[\frac{h_{e,wl-gc}\left(T_{wl}-T_{gc}\right)}{H_{wl}}+\frac{A_{wm}h_{e,wm-bu}\left(T_{wm}-T_{bu}\right)}{A_{wl}H_{wm}}+\frac{A_{wu}h_{e,wu-co}\left(T_{wu}-T_{co}\right)}{A_{wl}H_{wu}}+\frac{\dot{m}}{A_{wl}}\right]dt \tag{15}$$

A computer program was written in MATLAB to solve the above system of non-linear equations using the Gauss-Seidel iterative method (Burden and Faires, 1985), with a temperature tolerance of 0.5K and time step of 20s. Based on this numerical study, a conventional solar still (CSS) and PSS were constructed and tested outdoors at the University of Strathclyde (51^{o} 52′ N, 4^{o} 15′ W). The systems were mounted outdoors on steel frames on top of a horizontal roof 35 m above the ground to reduce shading from tall structures. Basins were filled with 20 kg of tap water, and topped up once in the morning on a test day.

2.3 Data acquisition and analysis

Kipp & Zonen pyranometers (model CM 11, error of 3 %) were used to measure global and diffuse solar radiation intensity on a horizontal surface. For diffuse radiation, a Kipp & Zonen shadow ring (model CM 121B) was fitted over the pyranometer and the recorded data was corrected for the shadow ring (Kipp & Zonen, 2004). The temperature of water and other components were measured using T-type thermocouples (±0.5 K) while wind speed was measured by a Vector Instruments anemometer (model A100L2, error of 1 %) for the duration of the experimental period. All of these sensors were connected to a Delta-T Devices Ltd data logger (model DL2e). The root mean square error (RMSE) was computed according to Tripathi and Tiwari (2004).

3 Results

3.*1 Irradiance and selected temperature profiles*

Fig.2 shows the variation of irradiance on a horizontal surface and temperature profiles for the ambient air (T_a) and condenser cover T_{co}) on 17th October 2007. It is observed that irradiance was intermittent especially around solar noon. Nevertheless, a maximum of 532 W m^{-2} was recorded at 13:22hrs, which is satisfactory for a site at high altitude in autumn.

It is seen that T_{co} is lower than T_a from 7:00hrs to around 16:00hrs. After 16:00hrs, T_{co} is higher than T_a, probably due the heat transfer by convection and radiation from water in the upper basin to the condenser cover which proceeds even after sun set due to the effect of thermal storage. The maximum observed difference between T_a and T_{co} was 1.6K. El-Bahi and Inan (1999b) found a maximum value of T_{co}= 433 K when T_a=309 K, which indicates that their condenser was significantly hotter than ambient air.

3.*2 Distillate productivity*

In this paper, the reported distillate productivity for the PSS is the sum of the contributions from all the three distillation effects. Fig.3 shows the variation of hourly distillate productivity of the CSS and PSS on 17th October 2007. It is seen that in the morning (up to about 11:00hrs), the measured distillate productivity is extremely low for both stills. This is expected because production starts when air inside the still is saturated with water vapor. From about 11:00hrs, the productivity of the CSS is lower than that of the PSS. On the daily basis, the PSS produced 0.426 kg m^{-2}, 34% more distillate water than the CSS on this test day. The average improvement for four test days with some sunshine was 19%. The observed levels of production are commensurate with the prevailing weather conditions. Under favorable weather, the daily productivity of a CSS is about 3- 4 kg m^{-2}, (Al-Kharabsheh and Goswami, 2003). El-Bahi and Inan (1999b) reported a daily distillate productivity of 4 kg m^{-2} for a double-glazed solar still with separate condenser and reflector, operated under maximum irradiance exceeding 800Wm^{-2} around solar noon. So, it is expected that the PSS would yield higher distillate on sunny days.

It is observed that the estimated hourly distillate productivity is slightly higher than the measured productivity for the PSS. This is probably due to distillate leakage from the solar still and measurement errors. The root mean square (RMSE) is 13 %, based on 4 days with favorable weather. Tripathi and Tiwari (2004) reported a RMSE of 32.13 % in a study of a conventional solar still by solar fraction. It appears therefore that the performance of the present model is satisfactory.

4. Concluding remarks

Analysis of the test results has shown that the solar shield is effective in keeping the condenser relatively cool, marginally above ambient temperature. Under favorable weather conditions, the comparative tests demonstrated the advanced solar still produced up to 34% more distillate than the conventional type. Experimental and simulated results are in close conformity, giving confidence in the modeling of solar still devices. Initial performance evaluation of the advanced solar still suggests that it can be exploited within and outside the tropical regions.

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Nomenclature

A	area (m^2)
A_{ec}	area across the entrance from the evaporator to condenser chamber (m^2)
C_p	specific heat capacity at constant pressure ($J\ kg^{-1}\ K^{-1}$)
D	coefficient of diffusion mass transfer of water vapor in air ($=2.56 \times 10^{-5}\ m^2\ s^{-1}$)
F	absorption factor (dimensionless)
G	irradiance (Wm^{-2})
h	coefficient of heat transfer ($W\ m^{-2}\ K^{-1}$)
H	specific latent heat of vaporization ($J\ kg^{-1}$)
m	mass (kg)
$\dot{m}$	rate of vapor diffusion ($kg\ s^{-1}$)
R	ratio of evaporator to condenser chamber volume
t	time (s)
T	temperature (K)
U	coefficient of heat loss ($W\ m^{-2}\ K^{-1}$)

Subscripts

a	air/ambient
bo	bottom
bu	upper basin liner
c	convective
dw	distilled water
e	evaporative
ef	effective
r	radiative
sk	sky
sl	side wall around lower basin
sm	side wall around middle basin
su	side wall around upper basin
sw	side wall

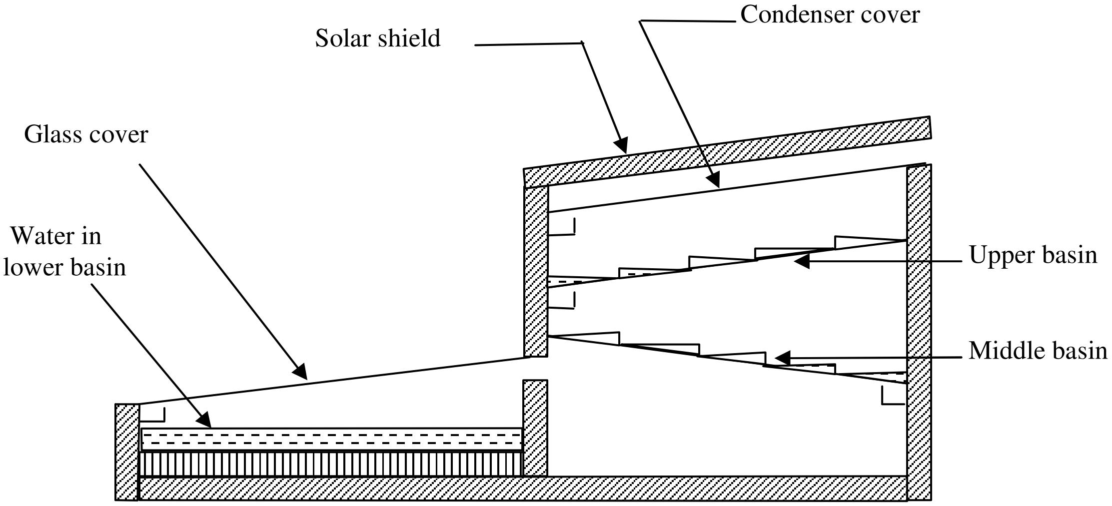

Fig.1: Cross-sectional view of the present solar still (PSS).

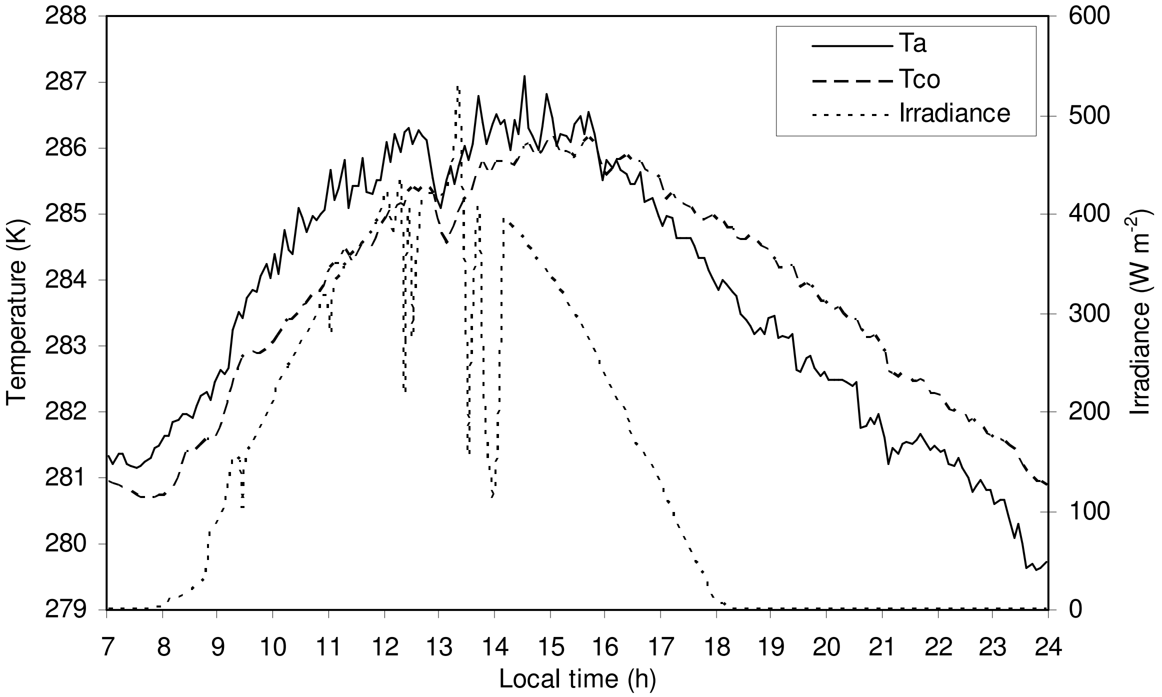

Fig.2: Variation global irradiance on a horizontal surface, and ambient (Ta) and condenser cover (Tco) temperatures.

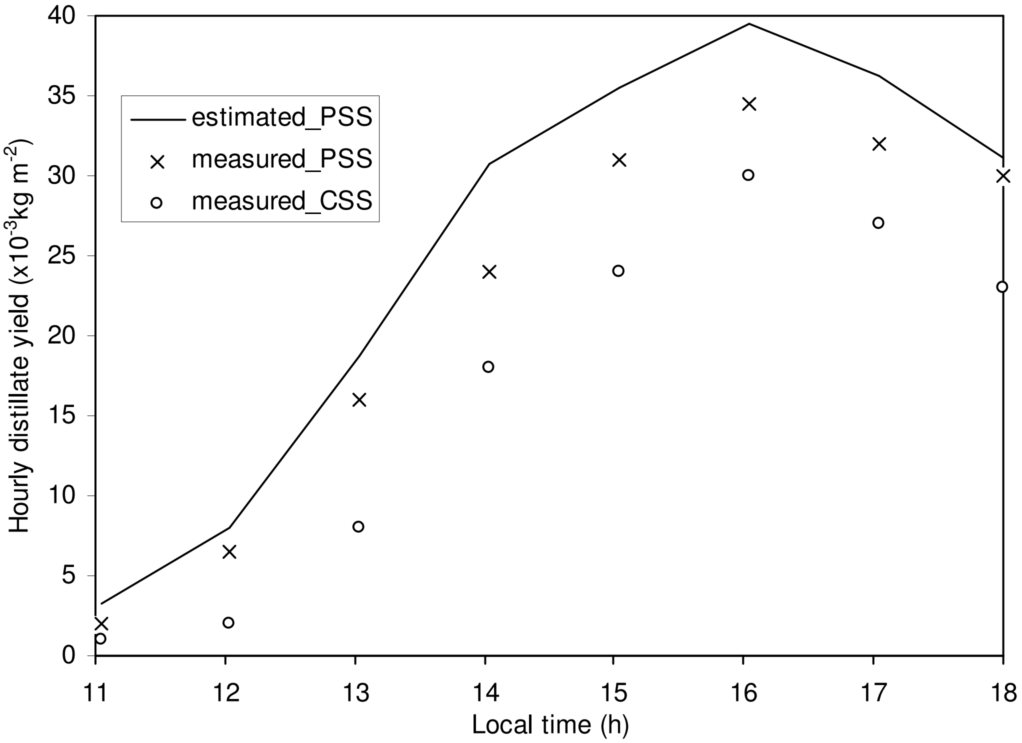

Fig.3: Variation of hourly production for the conventional solar still (CSS) and present solar still (PSS) on a typical day, 17 October 2007.