Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Energy 33 (2008) 71–80
ENERGY
www.elsevier.com/locate/energy

Theory and experimental investigation of a weir-type inclined solar still

S.B. Sadineni*, R. Hurt, C.K. Halford, R.F. Boehm

Center for Energy Research, Department of Mechanical Engineering, University of Nevada, Las Vegas, 4505 Maryland Parkway, Las Vegas, NV 89154-4027, USA

Received 28 December 2006

Abstract

A weir-type solar still is proposed to recover rejected water from the water purifying systems for solar hydrogen production. This consists of an inclined absorber plate formed to make weirs, as well as a top basin and a bottom basin. Water is flowed from the top basin over the weirs to the bottom collection basin. A small pump is used to return the unevaporated water to the top tank. Hourly distillate productivity of the still with double- and single-pane glass covers was measured and the latter showed higher production rates. The average distillate productivities for double- and single-pane glass covers are approximately 2.2 and 5.5 l/m^2/day in the months of August and September in Las Vegas, respectively. Mathematical models that can predict the hourly distillate productivity are developed. These compared well with the experimental results. Productivity of the weir-type still with a single-pane glass was also compared with conventional basin types tested at the same location. The productivity of the weir-type still is approximately 20% higher. The quality of distillate from the still is analyzed to verify the ability of the still to meet the standards required by the electrolyzers.

Keywords: Solar still; Distillation; Hydrogen; Weir-type still; Renewable; Theoretical; Experimental; Electrolyzer; Double-pane glass

1. Introduction

The ever-increasing need for energy and environmental concerns has focused much attention on sustainable energy resources. An important drawback of renewable energy sources such as solar and wind is their intermittent nature. Making hydrogen, which can be stored and used on demand, using renewable sources allows the intermittent resources to be decoupled from the use. The University of Nevada, Las Vegas Center for Energy Research, is developing a hydrogen filling station at the Las Vegas Valley Water District (LVVWD). An electrolyzer is a component of this project, which makes hydrogen from water through electrolysis. Pure water needed for the electrolyzer is conventionally obtained from a water purifying system consisting of a de-ionizer (DI). The proposed project consists of a DI system, which rejects 8 l/h while using 1 l/h. Water is a precious commodity and recovering a significant portion of the rejected water is an important aspect of this project. A solar still can be used for this purpose.

Unlike other distillation methods, solar stills use solar energy to distill water in an environmentally friendly manner. These are broadly divided into passive and active types. Passive stills are further divided into basin and inclined types. Extensive research was reported on different methods to improve the productivity of these stills [1–10]. The important parameters affecting the performance of a still are also reported [11]. The level of water on the absorber surface has been shown to be an important factor affecting the productivity [11]. Still performance was shown to increase with thinner water films [11]. This can be achieved by different designs of the absorber surface. Common designs are inclined [2] and stepped [5] absorber surfaces. In an inclined still, water flows from the top to the bottom of the absorber surface. To maintain uniform thickness of water, a wick, which draws water through capillary effect, is used. Stills with inclined absorber surfaces are reported to have significantly higher productivity compared with basin-type stills [2,6,8]. A new design combining the advantages of both inclined and basin-type

*Corresponding author. Tel: +1 702 895 3422; fax: +1 702 895 3936.
E-mail address: ssb@egr.unlv.edu (S.B. Sadineni).

0360-5442/$ - see front matter
doi:10.1016/j.energy.2007.08.003

Nomenclature

A	area of the absorber plate (weirs) (m^2)
A_{Bbasin}	area of the bottom basin (m^2)
A_{TBasin}	area of the top basin (m^2)
b	breadth of the sill (m)
C_w	specific heat of water (J/kg K)
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
h_b	bottom loss coefficient from basin to the ambient ($W/m^2 K$)
h_{cw}	convective heat transfer coefficient from water surface to the glass cover ($W/m^2 K$)
h_{ca}	convective heat transfer coefficient from glass cover to the ambient ($W/m^2 K$)
h_{cb}	convective heat transfer coefficient from bottom to the ambient ($W/m^2 K$)
h_{ew}	evaporative heat transfer coefficient from water surface to the glass cover ($W/m^2 K$)
h_{cgi}	convective heat transfer coefficient between glasses of double-pane glass ($W/m^2 K$)
h_{rgi}	radiative heat transfer coefficient between sheets of double-pane glass ($W/m^2 K$)
h_{gi}	total heat transfer coefficient between glasses of double-pane glass ($W/m^2 K$)
h_{1w}	total heat transfer coefficient from water surface to the glass cover ($W/m^2 K$)
h_{rb}	radiative heat transfer coefficient from bottom to the ambient ($W/m^2 K$)
h_{rw}	radiative heat transfer coefficient from water surface to the glass cover($W/m^2 K$)
h_{1g}	total heat transfer coefficient from glass cover to the ambient ($W/m^2 K$)
H	length of the still (m)
I	solar radiation incident on the glass cover of the still (W/m^2)
k	thermal conductivity (W/m K)
L	characteristic length between glasses of double-pane cover (m)
l	latent heat of evaporation (J/kg)
L_i	thickness of insulation (m)
$\dot{m}_{ew}$	hourly distillate productivity (kg/h)
$\dot{m}_w$	mass flow rate of water over the absorber plate (kg/s)
m_{TBasin}	mass of water in the top basin (kg)
m_{BBasin}	mass of water in the bottom basin (kg)
$\bar{N}u$	average Nusselt number
Pr	Prandtl number
P_w	partial vapor pressure at water temperature (N/m^2)
P_g	partial vapor pressure at glass temperature (N/m^2)
Ra	Rayleigh number
T_a	ambient temperature (°C)
T_g	glass temperature (°C)
T_{gi}	inner glass temperature (°C)
T_{go}	outer glass temperature (°C)
T_w	water temperature (°C)
$T_{WTBasin}$	temperature of water in the top basin (°C)
$T_{WBBasin}$	temperature of water in the bottom basin (°C)
TDS	total dissolved solids (mg/l)
TOC	total organic carbon (μg/l)
t	time (s)
U_b	overall bottom heat loss coefficient ($W/m^2 K$)
U_L	overall heat loss coefficient ($W/m^2 K$)
U_t	overall top loss coefficient ($W/m^2 K$)
V	wind velocity (m/s)

Greek letters

ε_{eff}	effective emissivity
ε	emissivity
σ	Stefan–Boltzman constant, 5.67×10^{-8} ($W/m^2 K^4$)
β	slope of the still
β^1	volumetric thermal expansion coefficient (K^{-1})
ν	kinematic viscosity (m^2/s)
α	thermal diffusivity (m^2/s)
γ	surface azimuth angle
γ_s	solar azimuth angle
τ_w	fraction of solar energy transmitted to water through glass cover
Δt	time-step

solar still was also proposed [7]. The performance of a stepped still is also reported to have higher productivity [5]. An important issue with these designs is the formation of scale on the absorber surface, which significantly effects the absorptivity of the surface and hence the productivity of the still. A weir-type still with a nylon wick, and a small circulation pump to recover sensible energy of water leaving the absorber plate is proposed in this project.

The temperature difference between the water and condensing surfaces is an important factor affecting the productivity of a solar still. A higher temperature difference between these surfaces yields higher productivity. To maintain this temperature difference, various methods were proposed [12,13]. Unlike solar collectors, a double-pane glass reduces the productivity of a solar still by reducing the temperature difference between the water and condensing surfaces. To verify this fact the productivity of the still with both single- and double-pane glass are compared. To predict the performance of different types of solar stills, various mathematical models are proposed. In the present study, a mathematical model was developed to compare with the experimental results based on the model proposed by Shukla et al. [14].

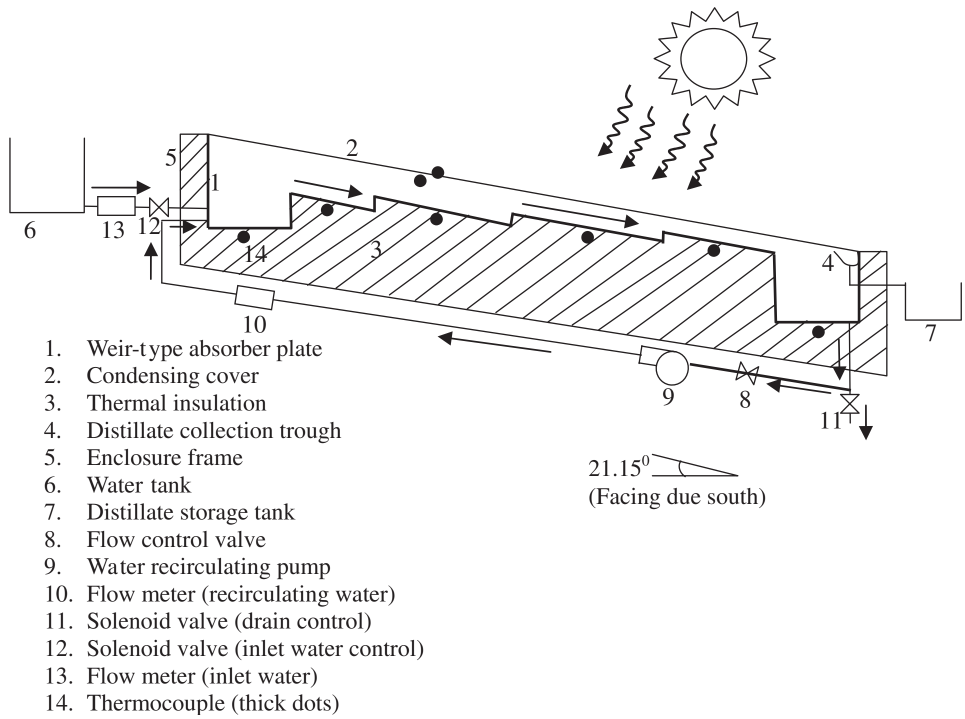

Fig. 1. Schematic of the weir-type solar still.

2. Design and construction of the weir-type still

A weir-type solar still is designed and constructed to test it under Las Vegas weather conditions. It is an inclined-type still, which consists of a weir-shaped absorber plate, cover/condensing glass, distillate collection trough, water circulation system and support structure. The still is well insulated to minimize any heat loss from the bottom and sides of the unit. A schematic of the still is as shown in Fig. 1. The smaller arrows in the figure show the water flow direction in the still.

The construction details of different parts of the still are as follows:

2.1. Absorber plate

The absorber plate is made from a 20 gauge galvanized steel (approximately 1 mm thickness) sheet, formed to make the top basin, weirs and the bottom collection basin. The details of the absorber plate with top and bottom tanks are as shown in Fig. 2. The step heights of the weirs were kept small ($\sim$1.6 mm) to reduce the depth of water on the absorber plate. The top tank helps to absorb any momentum transferred in with the circulating water. This helps to avoid the splashing of water on to the absorber plate. The top and bottom basins are made large enough to contain enough water for at least 1 day. The area of the absorber plate exposed to radiation (aperture area) was 1.7×0.57 m. Two side plates made of the same material are soldered to the absorber plate. To avoid any leakage in the soldered joints, high-temperature RTV silicone is applied. The absorber plate is painted black with a high-temperature spray enamel to improve its absorptivity. Water flows from the top basin over the weirs and collected in the bottom basin. The weirs help to distribute the water evenly and increase the time spent on the absorber surface. A vinyl window mesh (thickness and porosity are approximately 0.25 mm and 32%, respectively) is used as a wick to improve the distribution of water on the absorber plate. The small thickness of water on the weirs increases the water temperature and evaporation significantly. As shown in Fig. 1, the top and bottom tanks are also exposed to insolation and contribute to the productivity of the still.

2.2. Condensing cover

Both single- and double-pane tempered glass covers are used in these experiments. The tempered glass panes are fixed in metal frames, which are secured firmly to the absorber plate using sheet metal screws. Weather stripping is used between these metal contacts to prevent the leakage of the vapor from the still.

2.3. Collection trough

A small collection trough is attached at the end of the absorber plate. The vapor is condensed on the inclined cover glass and flows down into the collection trough. From there the condensate drains through the outlet pipe into the collection tank.

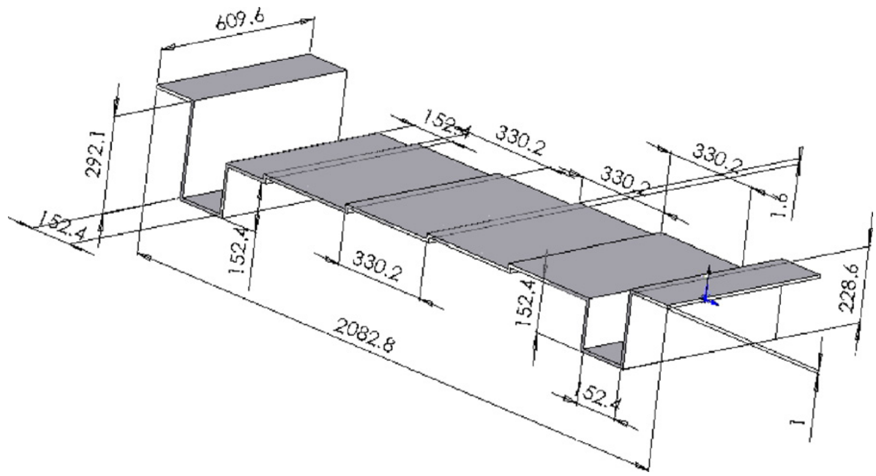

Fig. 2. Weir-type absorber plate with top and bottom basins (dimensions in millimeters).

2.4. *Insulation and frame*

Glass fiber insulation with a thickness of 15.24 mm (R-30), is placed at the bottom and sides of the still to reduce the heat losses to the surroundings from the absorber plate and the side plates. It is generally accepted that optimal year round performance of stills can be obtained by installing them at an inclination equal to the latitude of the location. To obtain the seasonal optimal performance stills are installed at latitude -15° for summer and latitude $+15^\circ$ for winter [1,11]. In the present study, the experiments are performed in the summer time and the summer optimal angle of inclination is considered. The still is mounted on a stand at an inclination of 21.15° (36.15°N latitude of Las Vegas—15°), facing due south.

2.5. *Water circulation system*

Water flows from the top basin, over the weirs and finally, to the bottom basin. A small pump, with a capacity of 0.7 l/min at 1 m elevation is used to return the unevaporated water to the top basin. The flow rate of circulating water is controlled by a valve in the system. The circulating water flow is set at 0.2 l/min. The velocity of the water flowing on each weir varies significantly, and hence so does the thickness of the water film. The maximum thickness of the water film on the weirs is less than 2 mm, including the thickness of the vinyl mesh, with the average being generally much smaller. The flow rate was set such that no portion of the absorber plate is ever left totally dry. This is done to avoid scale from forming on the absorber surface. These deposits are reflective and hence reduce the absorptivity of the absorber plate. Formation of scale is one of the major concerns in inclined type of stills.

2.6. *Data acquisition system*

Data were collected using a Campbell Scientific CR10x data logger with the Am16/32 multiplexer. Instrumentation consists of eight thermocouples to measure the temperature of the absorber plate at various locations, the top and bottom surfaces of the cover glass. In addition to this, the return water flow rate is also recorded. A weather station installed at the same location as the still is also connected to the logger. This station measures wind speed, solar flux, ambient temperature and relative humidity. A second pyranometer is also installed at the same inclination as the still.

3. Mathematical modeling

Mathematical models are developed for the still. Both single- and double-pane glass covers were modeled. The integrated hourly solar insolation, averaged hourly wind velocity and ambient temperatures were used in these calculations. The variation of water temperature along the absorber plate plays a significant role in the productivity for an inclined still. Hence the model considers the variation of water temperature along the flow direction. Due to the relatively large mass ($>24{,}000$ g) of water in the top and bottom basins the time-dependent term is included in the formulation of the model for these portions of the still. On the absorber surface, however, the relatively small mass of water present at any given time (<5 g/s) causes the response time to be much smaller than the data collection interval. For this reason, the time-dependent term is omitted in the model formulation for the absorber. This provides an adequate approximation and greatly simplifies the model. The equations used in the simulation are based on those developed by Shukla et al. [14] for a similar kind of inclined still. The simulations were carried out using MATLAB. The program calculates the variation of temperatures as well as distillate productivity as a function of the collected weather data.

The following assumptions were used in the development of mathematical models:

- The heat capacities of the glass cover and nylon mesh are negligible.
- There is no leakage of vapor from the still.

- Heat losses from the sides of the still are negligible.
- The flow of water on the absorber plate has a uniform thickness. The change of thickness at the weirs is neglected.
- Solar radiation after transmission through the condensing cover is completely absorbed by the water film.

3.1. Single-pane glass

Shukla et al. [14] solved for water temperature (T_W) as a function of location from the top of inclined absorber surface, which is given as

$$T_W = \left\{\frac{\tau_W}{U_L} I + T_a\right\}\left(1 - \exp\left(-\frac{U_L b x}{\dot{m}_w C_w}\right)\right) + T_{Wi} \exp\left(-\frac{U_L b x}{\dot{m}_w C_w}\right) \quad (1)$$

and the water temperature at the end of the absorber plate, $x = L$, $T_W = T_{Wo}$ evaluated as

$$T_{Wo} = \left\{\frac{\tau_W}{U_L} I + T_a\right\}\left(1 - \exp\left(-\frac{U_L A}{\dot{m}_w C_w}\right)\right) + T_{Wi} \exp\left(-\frac{U_L A}{\dot{m}_w C_w}\right). \quad (2)$$

Now the average water temperature obtained as

$$\overline{T}_W = \frac{1}{L}\int_0^L T_W \, \mathrm{d}x = \left\{\frac{\tau_W}{U_L} I + T_a\right\} \times \left(1 + \frac{\exp\left(-(U_L A)/(\dot{m}_w C_w)\right) - 1}{(U_L A)/(\dot{m}_w C_w)}\right) + \frac{T_{Wi}}{(U_L A)/(\dot{m}_w C_w)}\left(1 - \exp\left(-\frac{U_L A}{\dot{m}_w C_w}\right)\right). \quad (3)$$

The expression for the average temperature was obtained differently than those reported by Shukla et al. [14]. As can be seen from Fig. 1, the top and bottom basins are also exposed to the weather conditions. Hence the change in the temperature of water in the basins at the end of each time-step is calculated as

$$T_{WBBasin} = T_{WBBasin} + \frac{[I A_{BBasin} \Delta t] - [U_L A_{BBasin}(T_{WBBasin} - T_a)\Delta t]}{m_{BBasin} C_w}, \quad (4)$$

$$T_{WTBasin} = T_{WTBasin} + \frac{[I A_{TBasin} \Delta t] - [U_L A_{TBasin}(T_{WTBasin} - T_a)\Delta t]}{m_{TBasin} C_w}, \quad (5)$$

where Δt is time-step and $T_{WBBasin}$, m_{BBasin} are the water temperature and mass in the bottom basin, respectively. T_{TBasin}, m_{TBasin} are the water temperature and mass in the top basin, respectively. T_{TBasin} is the same as the temperature of water at the start of weirs.

The average water temperature at the end of each time-step in the bottom basin due to mixing of outlet water from the absorber plate can be modeled as

$$T_{WBBasin} = \frac{[m_{BBasin} T_{WBBasin} + \dot{m}_w \Delta t T_{Wo}]}{(m_{BBasin} + \dot{m}_w \Delta t)}. \quad (6)$$

Furthermore, the average water temperature at the end of each time-step in the top basin due to mixing of the circulated water from the bottom tank is modeled as

$$T_{WTBasin} = \frac{[m_{TBasin} T_{WTBasin} + \dot{m}_w \Delta t T_{WBBasin}]}{(m_{TBasin} + \dot{m}_w \Delta t)}. \quad (7)$$

In some of the above equations, same variables appeared on both sides of an equation. In those cases, the variables on the right-hand side corresponds to the previous time-step.

3.2. Double-pane glass

A similar procedure is followed to solve for the exit water temperature from the absorber plate and the average water temperature.

An energy balance on the inner glass of the double-pane glass cover is given as

$$h_{1w}(T_W - T_{gi}) = h_{gi}(T_{gi} - T_{go}). \quad (8)$$

The energy balance on the outer glass is given as

$$h_{gi}(T_{gi} - T_{go}) = h_{1g}(T_{go} - T_a). \quad (9)$$

The energy balance for the water flowing on the absorber plate, for a small elemental length dx and constant width b, is given as

$$\left[\tau_W I - h_{1w}(T_W - T_{gi}) - h_b(T_W - T_a)\right] b \, \mathrm{d}x = \dot{m}_w C_w \left(\frac{\mathrm{d}T_W}{\mathrm{d}x}\right) \mathrm{d}x. \quad (10)$$

From Eq. (8), T_{gi} can be found as

$$T_{gi} = \frac{(h_{1w} T_W + h_{gi} T_{go})}{(h_{1w} + h_{gi})}. \quad (11)$$

From Eq. (9), T_{go} can be found as

$$T_{go} = \frac{(h_{gi} T_{gi} + h_{1g} T_a)}{(h_{gi} + h_{1g})}. \quad (12)$$

Substituting Eq. (11) in Eq. (12) yields T_{go} as

$$T_{go} = \frac{h_{gi} h_{1w} T_W + h_{1g}(h_{1w} + h_{gi}) T_a}{(h_{1w} + h_{gi})(h_{gi} + h_{1g}) - h_{gi}^2}. \quad (13)$$

Rewriting Eq. (8)

$$h_{1w}(T_W - T_{gi}) = U_t(T_W - T_a) \quad (14)$$

where

$$U_t = \frac{h_{1w} h_{gi} h_{1g}}{h_{1w} + h_{gi} + h_{1g}}.$$

Substituting the Eq. (14) in Eq. (10) and reducing provides

$$[\tau_W I - U_L(T_W - T_a)]b\,\mathrm{d}x = \dot{m}_w C_w \left(\frac{\mathrm{d}T_W}{\mathrm{d}x}\right)\mathrm{d}x, \quad (15)$$

where $U_L = U_t + h_b$

Solving Eq. (15) for initial condition, $T_W|_{x=0} = T_{Wi}$, results in the same equations as in the case of single-pane glass (Eqs. (1)–(3)). The equations for average water temperatures in top and bottom basins are also the same as those obtained in the case of single-pane glass (Eqs. (4)–(7)).

The distillate productivity in both single- and double-pane cases can be obtained from the temperatures as

$$\dot{m}_{ew} = \frac{h_{ew}\left\{A(\bar{T}_W - T_g) + A_{TBasin}(T_{WTBasin} - T_g) + A_{BBasin}(T_{WBBasin} - T_g)\right\}}{l} \times \Delta t, \quad (16)$$

where T_g is replaced by T_{gi} (inner glass temperature), in the case of double-pane glass.

3.3. Transmittance of the glass covers (τ_w)

The transmittance of the glass cover varies with incidence angle (θ) of the beam radiation. This angle is dependent on the location and local time. The hourly position of the sun for Las Vegas (latitude 36.175°N, longitude115.136°W, elevation P 618 m) was calculated using a MATLAB program called "sun_position.m" developed by National Renewable Energy Laboratory (NREL) [19]. This program calculates the zenith (θ_z) and solar azimuth (γ_s) angles for each hour. Using the program output, the angle of incidence (θ) is calculated as [17]

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma). \quad (17)$$

The orientation of the still is due south. Because of this the surface azimuth angle (γ) is zero. The solar transmittances of single- and double-pane glass (refractive index 1.526) covers for the corresponding angle of incidence are obtained from the results presented by Hottel and Woertz as reported in [17].

3.4. Convection coefficient between the glass panes (double-pane)

The convective heat transfer coefficient between the panes of the double-pane glass cover ($H/L \approx 220$ and $\beta = 21°$) can be obtained from the average Nusselt number, which is given as [18]

$$\bar{N}u_L = \frac{h_{cgi}L}{k} = 1 + 1.44\left[1 - \frac{1708}{Ra_L \cos\beta}\right] \times \left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra_L \cos\beta}\right]^* + \left[\left(\frac{Ra_L \cos\beta}{5830}\right)^{1/3} - 1\right]^* \quad \text{for} \begin{bmatrix} \frac{H}{L} \geqslant 12 \\ 0 < \beta \leqslant 70 \end{bmatrix}. \quad (18)$$

The notation [ ]* implies that, if the quantity in the brackets is negative, it must be set equal to zero. Where the Rayleigh number is calculated as [18]

$$Ra_L = \frac{g\beta^1(T_{gi} - T_{go})L^3}{\alpha v}. \quad (19)$$

The radiation coefficient between the panes can also be calculated from the standard relation given as [16]

$$h_{rgi} = \varepsilon_{eff}\sigma\left[(T_{gi} + 273)^2 + (T_{go} + 273)^2\right][T_{gi} + T_{go} + 546]. \quad (20)$$

The total heat transfer coefficient between the panes is calculated as

$$h_{gi} = h_{cgi} + h_{rgi}. \quad (21)$$

All the other heat transfer coefficients and variables used are as following:

$h_{1w} = h_{rw} + h_{cw} + h_{ew}$ [16]

$$h_{rw} = \varepsilon_{eff}\sigma\left[(T_W + 273)^2 + (T_g + 273)^2\right] \times [T_W + T_g + 546] \text{ [16]},$$

$h_{1g} = 5.7 + 3.8V$ [16],

$$h_b = \left[\frac{1}{K_i/Li} + \frac{1}{h_{cb} + h_{rb}}\right] \text{ [16]},$$

$$h_{cw} = 0.884\left[T_W - T_g + \frac{(P_w - P_g)(T_W + 273)}{268.9 \times 10^3 - P_w}\right]^{1/3} \text{ [16]},$$

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}\frac{(P_w - P_g)}{T_W - T_g} \text{ [15]},$$

$$P(T) = \exp\left(25.317 - \frac{5144}{T + 273}\right) \text{ [16]},$$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g}\right]^{-1} \text{ [16]}.$$

4. Experimental uncertainty

Uncertainties associated with the experimental measurements are presented here. The distillate productivity was measured using a graduated cylinder marked in 10 ml increments. Hence the associated uncertainty is ±5 ml. Weather data were measured using instrumentation from Campbell Scientific. The uncertainties associated with these measurements are ±5% (maximum) or ±3% (typical) for the pyranometer, ±0.3 m/s for the anemometer, and ±0.5 °C for the temperature probe. The water temperature was measured using J-type thermocouples from Omega with an uncertainty $\pm 0.5\,^{\circ}C$.

5. Results and discussion

The weir-type inclined solar still was installed and tested at the University of Nevada, Las Vegas. Theoretical models are developed to predict the effects of various design and weather parameters on the productivity of the still.

5.1. Performance of the still with a single-pane glass cover

The weir-type still with a nylon wick is tested on September 8, 2006. Typical measured temperatures and productivity of the still are presented along with the corresponding weather data. The measured values are compared with the theoretically calculated values as shown in Figs. 4 and 5. The corresponding weather data are shown in Fig. 3. The temperatures shown in Fig. 4 are the average values for the measured water temperatures and predicted water temperatures. The total distillate productivity of the still was $5.5\,l/m^2/day$ including 450 ml overnight productivity. By considering the fact that the convective heat transfer coefficients cannot be modeled accurately (can vary up to 30%), the temperature and distillate productivity predicted by the model is in good agreement with the experimental results. The models are more sensitive to the solar radiation as can be seen from the variations in temperatures and productivity at time 15 h (Figs. 4 and 5).

5.2. Performance of the still with a double-pane glass

In order to measure the performance differences between single- and double-pane covers, experiments were carried out with a double-pane glass. The measured temperatures and productivity of the still are presented along with the corresponding weather data. The measured temperatures and productivity of the still are also compared with the

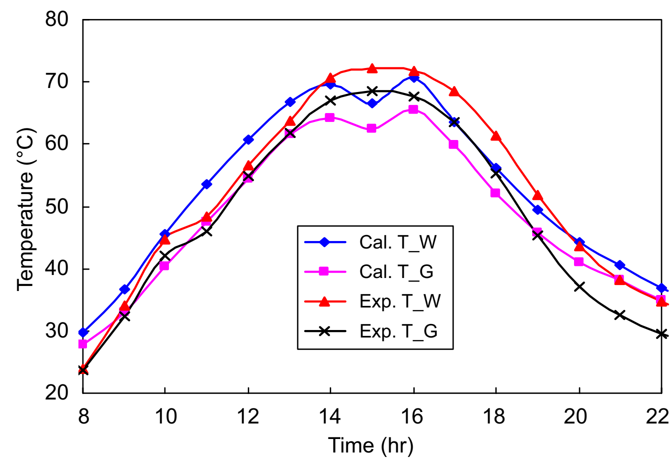

Fig. 4. Comparison of experimentally measured and theoretically calculated temperature variations of water and glass for a single-pane cover system, September 8, 2006.

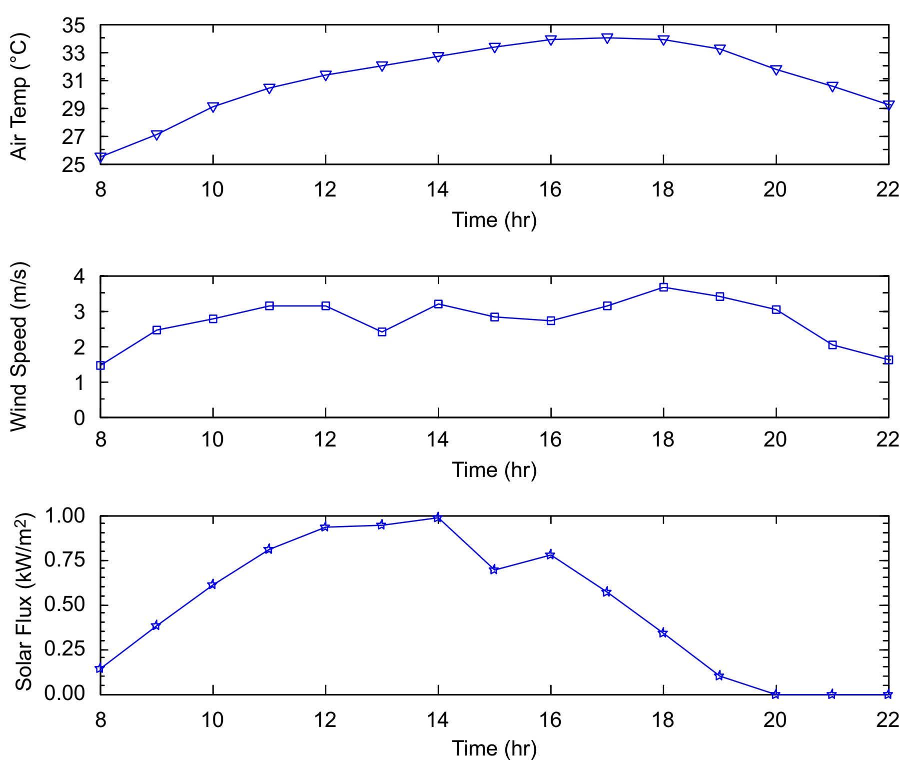

Fig. 3. Variation of air temperature, wind speed and solar flux on September 8, 2006.

theoretically calculated values as shown in the Figs. 7 and 8 and the corresponding weather data are shown in Fig. 6. The total distillate productivity of the still was approximately 2.2 l/m^2/day including 300 ml overnight productivity. The temperatures shown in Fig. 7 are the average values for the measured water temperatures and predicted water temperatures. As can be seen in Fig. 7, in the early hours of the day the temperature of condensing glass is same as the water due to the trapped heat between the glass panes. Hence the distillate productivity in that time period is zero. As the day progressed the increase in glass temperature is less compared with water due to the higher heat losses from the glass to the ambient.

5.3. Comparison of the performance of the still with single- and double-pane glasses

The developed theoretical models are used to predict the productivity of the still with double- and single-pane covers at similar weather conditions. Comparison of distillate productivity of the still with single- and double-pane glass covers for August 9, 2006 weather data is presented in the Fig. 9.

As was expected the productivity of the still with the double-pane glass is significantly lower than the single-pane glass even though the temperature of water in the case of double-pane glass is higher. Thus, it is demonstrated

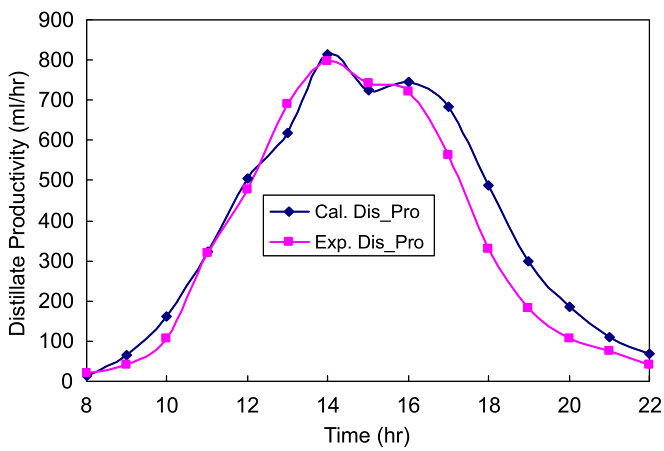

Fig. 5. Comparison of experimentally measured and theoretically calculated distillate productivity of the still with a single-pane cover, September 8, 2006.

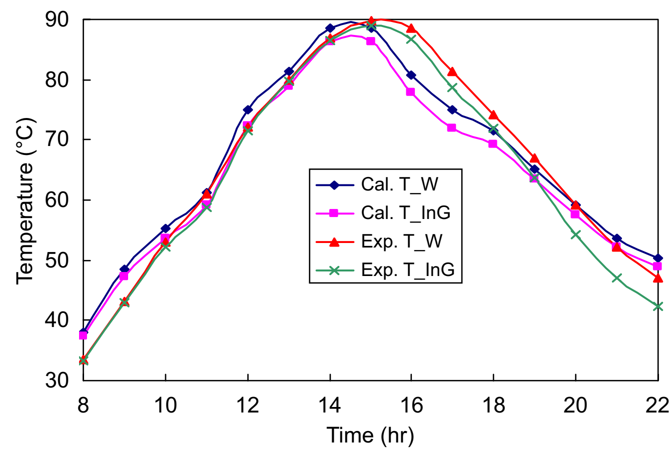

Fig. 7. Comparison of experimentally measured and theoretically calculated temperature variations of water and glass for a double-pane cover, August 9, 2006.

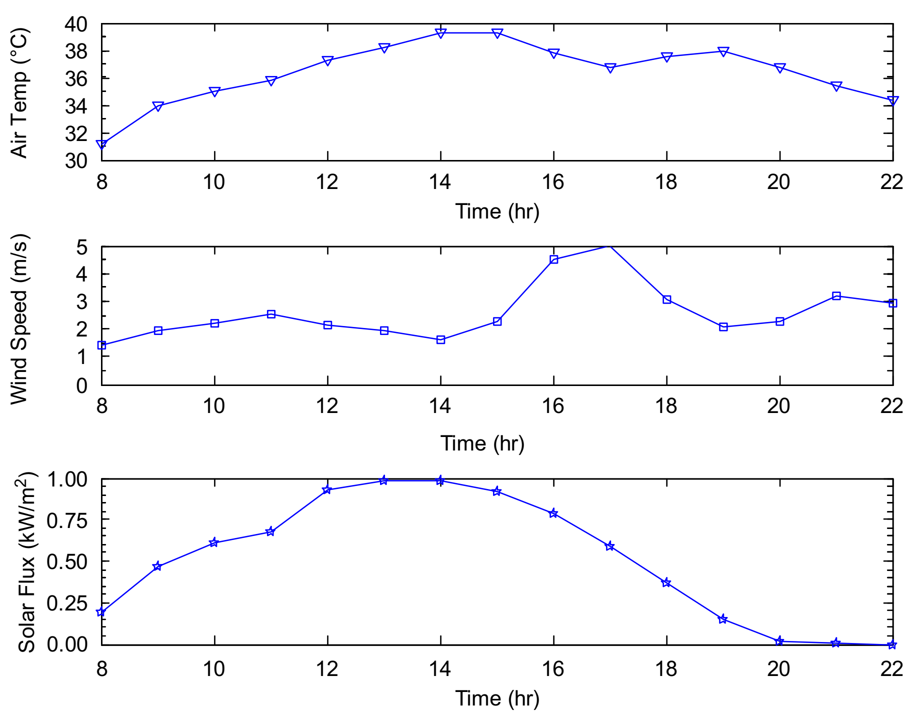

Fig. 6. Variation of air temperature, wind speed and solar flux on August 9, 2006.

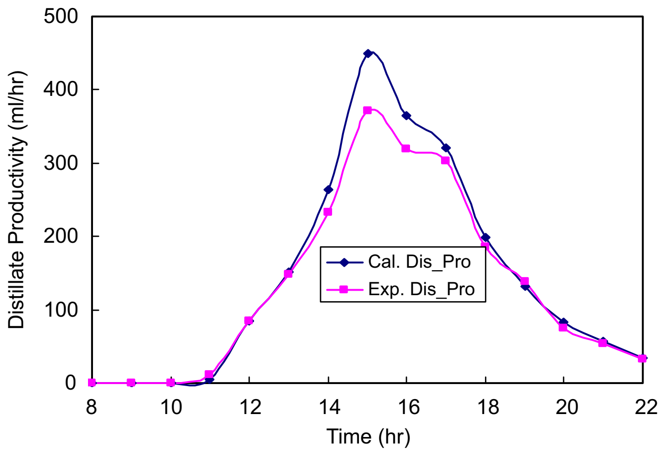

Fig. 8. Comparison of experimentally measured and theoretically calculated distillate productivity of the still with a double-pane cover, August 9, 2006.

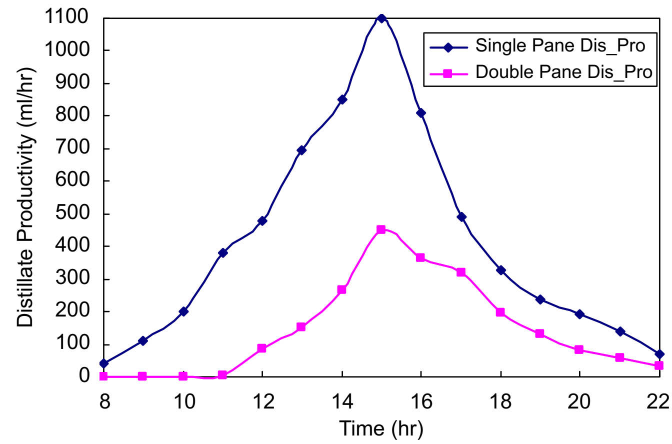

Fig. 9. Comparison of distillate productivity from the still with single- and double-pane glasses.

that the driving factor for higher productivity is the temperature difference between the water and condensing surface. It is also demonstrated that a double-pane glass used both as transparent cover and condensing surface for a solar still reduces the productivity significantly.

5.4. Distillate productivity of the weir-type solar still

The distillate productivity of the proposed weir-type regenerative still with single-pane glass is measured for a week's period in September. The average productivity of the still is approximately 5.5 l/m^2/day. The productivity of the conventional basin-type still measured at the same location and time period is also measured [20]. The average productivity of the conventional basin-type still is approximately 4.5 l/m^2/day. The daily productivities of both the stills for the second week of September 2006 are compared in Table 1. This amounts to a 20% gain in the productivity for the proposed still compared with basin type.

Table 1
Distillate productivity from the conventional basin- and weir-type (single-pane) stills, September 2006

Day	Distillate productivity (l/m^2/day)	
	Conventional basin-type still	Weir-type still (single-pane)
8 September	4.6	5.5
9 September	5.1	6.3
10 September	4.3	5.2
11 September	4.8	5.6
12 September	4.9	5.8
13 September	4.2	5.0
14 September	3.4	4.1

5.5. Quality analysis of distillate productivity for use in electrolyzers

The quality of the distillate is analyzed to determine whether the Type I/II standards set by the American Society for Testing and Materials (ASTM) had been met. These are the minimum purity levels required by Proton Inc. for use in their electrolyzers. Proton Inc. is one of the leading manufacturers of the electrolyzer systems in USA. Some preliminary analyses are completed. Different distillate samples obtained on different days from the still are tested. The measured values of electrical conductivity and pH at 25 °C of water temperature are 7.5 μs/cm and 7.08, respectively. The measured value of total dissolved solids (TDS) is 0.6 mg/l. These show some basic estimates on the quality of the distillate that can be produced. The other required standards such as maximum allowable total organic carbon (TOC), sodium, silica and chloride are so small that the available facilities at the university and at the local facilities could not accurately measure.

6. Summary and conclusions

A weir-type regenerative solar still is proposed for the industrial production of distilled water. The proposed still can be used with the solar hydrogen projects. A large fraction of the rejected water from the de-ionization system could be distilled and recovered in a still of this type. Distillate productivity of the still was tested at the University of Nevada, Las Vegas with local tap water. Performance of the still was also tested using double- and single-pane glass. Productivity of the still was also compared with the productivity of the conventional basin-type still tested at the same location. Quality of the distillate is analyzed for possible use in the electrolyzers. The following conclusions are made from the project:

- There is a significant reduction in the performance with a double-pane glass compared with a single-pane glass. Due to the reduced temperature difference between the evaporating water and condensing glass in a still with double-pane glass used both as transparent cover and condensing surface, the productivity reduced significantly.

- It was also observed that the proposed design is superior in productivity (20% improvement) compared with a conventional basin-type solar still.
- Scale formation on the absorber surface in the case of an inclined still with conventional wicks is avoided by using the weir-type design and a small recirculation pump.
- Preliminary tests on the quality of distillate have proved the possible use of solar stills in the solar hydrogen projects to render more yield to an electrolyzer system.

Acknowledgment

This project is supported by the US Department of Energy through the Golden Field Office, Doug Hooker contract monitor.

References

[1] Samee MA, et al. Design and performance of a simple single basin solar still. Renew Sustain Energy Rev 2007;11:543–9.
[2] Aybar HS, Egelioglu F, Atikol U. An experimental study on an inclined solar water distillation system. Desalination 2005;180:285–9.
[3] Al-Hayek I, Badran OO. The effect of using different designs of solar stills on water distillation. Desalination 2004;169:121–7.
[4] Murase K, et al. Experimental and numerical analysis of a tube-type networked solar still for desert technology. Desalination 2006;190: 137–46.
[5] Radhwan AM. Transient performance of a stepped solar still with built-in latent heat thermal energy storage. Desalination 2004;171:61–76.
[6] Ohshiro K, Nosoko T, Nagata T. A compact solar still utilizing hydrophobic poly(tetrafluoroethylene) nets for separating neighboring wicks. Desalination 1996;105:207–17.
[7] Minasian AN, Al-karaghouli AA. An improved solar still: the wick-basin type. Energy Convers Manage 1995;36:213–7.
[8] Janarthanan B, Chadrasekaran J, Kumar S. Performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover. Desalination 2006;190:51–62.
[9] Tiwari GN, Kupfermann A, Aggarwal S. A new design for a double-condensing chamber solar still. Desalination 1997;114:153–64.
[10] Yousif A, Ahmad F. Theoretical and experimental investigation of a novel multistage evacuated solar still. J Sol Energy Eng 2005;127: 381–5.
[11] Safwat A, et al. Parameters affecting solar still productivity. Energy Convers Manage 2000;41:1791–809.
[12] Fath HES, Elsherbiny S, Ghazy A. A naturally circulated humidifying/de-humidifying solar still with a built-in passive condenser. Desalination 2004;129:149–69.
[13] Mink G, et al. Design parameters, performance testing and analysis of a double-glazed, air-blown solar still with thermal energy recycle. Sol Energy 1998;64:265–77.
[14] Shukla SK, Sorayan VPS. Thermal modeling of solar stills: an experimental validation. Renew Energy 2005;30:683–99.
[16] Tiwari GN. Solar energy fundamentals, design, modeling and applications. New York: CRC press; 2002.
[17] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: Wiley; 1991.
[18] Incropera FP, DeWitt DP. Introduction to heat transfer. New York: Wiley; 1985.
[19] Reda I, Andreas A. Solar position algorithm for solar radiation application. National Renewable Energy Laboratory (NREL) Technical report NREL/TP-560-34302, 2003.
[20] James D, et al. Development and evolution of free-convection double-basin solar still with increased condenser area. ASES solar conference, Cleveland, OH, 7–13 July 2007.