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SIMULATION AND EXPERIMENTATION OF HEAT TRANSFER IN A SOLAR DISTILLATION STILL

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ABSTRACT

This paper deals with a simple and inexpensive solar desalination configuration. The performance of a simple solar still operating under Maltese climatic conditions is analysed both theoretically and experimentally. The internal and external heat transfer modes of the distillation unit are examined. This paper concludes that the distillation rate in a simple solar distiller increases with ambient temperature and solar radiation, even though the condensation capacity of the glass is reduced. A higher wind speed decreases the evaporation and condensation processes. The energy fractions within the solar still have also been analysed. The simulations and the experiments conclude that the glass components handle the bulk of the heat transferred in a solar still namely radiation, evaporation and condensation and thus the distillation efficiency is enhanced by improving the thermal and optical properties of the glass.

INTRODUCTION

Energy and water supply are two of the challenges being faced by mankind in the twenty first century. Whereas fresh water availability is decreasing due to widespread droughts around the world, the demand is on the increase. It is estimated that by 2025, two-thirds of the world's population will be living under water-stressed conditions and around 1.8 billion people will face absolute water scarcity [1]. Using fossil fuel energy, desalination offers a solution to offset this problem by desalting sea or brackish water. However in view of the energy crisis and given that water and energy are closely related, it is envisaged that water shortages will worsen the energy situation. This in turn will have a negative effect on fresh water availability. In addition, environmental and climate change considerations should also be taken into account.

One of the possible solutions to satisfy the problems and conditions mentioned is renewable desalination. Renewable energy is used as the primary source to desalinate seawater. One of the most promising renewable desalination couplings is solar desalination due to the fact that countries that are arid and lack fresh water supplies have an abundant supply of solar energy.

NOMENCLATURE

h	[W/m^{2}K]	Heat transfer coefficient
T	[K]	Temperature
P	[Pa]	Pressure
A	[m^2]	Surface area
θ	[°]	Angle of inclination of the top cover
α		Solar absorptivity
ρ		Solar reflectivity
I	[W/m^2]	Solar irradiance
MC	[J/K]	Thermal capacity
k	[W/mK]	Thermal conductivity
C,n		Nusselt number constants
Gr		Grashof number
Pr		Prandtl number
d	[m]	Mean distance between water and glass cover
$\dot{m}$	kg/s	Distillation rate
h_{fg}	J/kg	Latent heat of vaporisation

Subscripts

c	Convective heat transfer coefficient
e	Evaporative heat transfer coefficient
r	Radiative heat transfer coefficient
t	Total heat transfer coefficient
bsn	Basin
gls	Glass
sw	Seawater
sa	Saturated air
wg	From water to glass
ga	From glass to air
ba	From basin to air
wa	From water to air

SOLAR DISTILLATION OVERVIEW

Solar stills, which make passive use of solar energy, are the main constituents of direct solar desalination plants. Solar irradiation is used to generate the necessary heat transfer mechanisms in order to replicate the green house effect and the natural water cycle within an enclosed volume. A transparent glass cover which encloses the solar distillation unit, serves as a condensing surface against which distillate is formed and collected. The distillation process involved is governed by heat transfer mainly radiation and convection. Passive solar stills use heat from the still itself for the evaporation processes. On the other hand, active stills make use of external sources such as solar collectors or waste heat from other industrial processes. Solar stills are mainly used where the freshwater demand is lower than 200m^3/day [2].

The high latent heat of vaporisation of water, which is dissipated into the air by condensation, limits the production capacity of single effect solar distillation. Single-effect solar stills reach a low thermal efficiency of 35-40% with a production rate of around 5 l/m^2/day [2]. As the name implies, a single effect solar still uses solar energy to evaporate water and dissipates the latent heat of condensation to air, making no re-use of this energy. Basin type stills can be single-slope or double-slope. The latter can absorb more radiation but heat losses by radiation and convection are higher. Research has shown that single slope stills are better for cold climate [2].

METHOD

In order to analyse the heat transfer characteristics within a solar distillation still, a software program was written using MATLAB® to simulate the temperature profiles of the various components of a simple still and thus calculate the amount of distillate produced. A prototype was constructed and tested under natural conditions for over six months. The results of the simulation and the experiments were then compared.

Mode of Operation

A solar distillation still was constructed using fibre glass reinforced plastic (FGRP) panels, glass covers and expanded polystyrene insulation as shown in Figure 1.

A solar still uses solar radiation directly to heat and evaporate seawater in an enclosed chamber. Most of the evaporated water vapour is condensed against the top glass cover. However, some condensate is also formed against the glass sides. The water produced is channelled and collected.

The FGRP absorber is painted black in order to increase the solar absorptivity and the convective heat transfer between the absorber and the seawater in the basin. Apart from the top cover, the front and side covers are also made of glass in order to increase the solar radiation transmitted to the absorber. As the temperature of the water in the basin is increased, the difference between the temperatures of the water surface and the glass covers induces heat transfer, predominantly by convection. The naturally induced convective currents develop evaporative heat transfer which is the mechanism used in solar stills to distil seawater. The evaporative heat transfer also depends on the partial pressure difference created between the surface of the water in the basin and the volume near the internal surface of the glass covers. Since the partial pressure is a function of temperature, the evaporation and distillation rates are proportional to the difference generated between the seawater and glass temperatures.

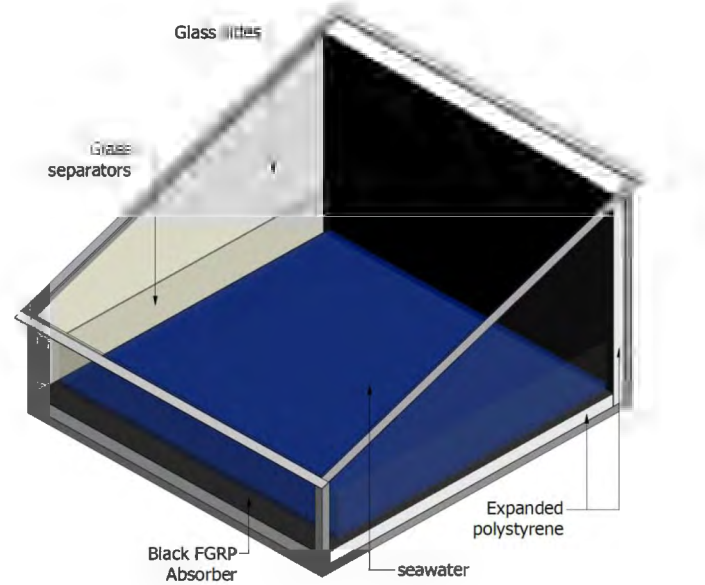

Figure 1: Simple Distillation Still

The solar irradiation absorbed by the glass covers added to the latent heat dissipated by condensation increase the temperature of the glass. This in turn reduces the temperature difference between water and glass and hence eventually the distillation rate levels out. The glass covers transfer heat by convection and radiation to ambient. The higher the wind speed, the higher the heat lost by convection and thus the higher the condensation-capacity of the glass cover.

Simulation

The analytical model of the thermal behaviour of a solar still is based on thermal balances of the main three components: Basin, seawater in the basin, glass covers.

The heat transfers of a solar still are depicted in Figure 2 and are as follows:
1. Solar irradiation incident on vertical sides.
2. Solar irradiation absorbed by the vertical sides.
3. Solar irradiation transmitted through the vertical sides.
4. Solar irradiation incident on the inclined glass panel.
5. Solar irradiation absorbed by the inclined glass panel.
6. Solar irradiation transmitted through the inclined glass panel.
7. Solar irradiation incident on the horizontal water surface.
8. Solar irradiation absorbed by the water in the basin.

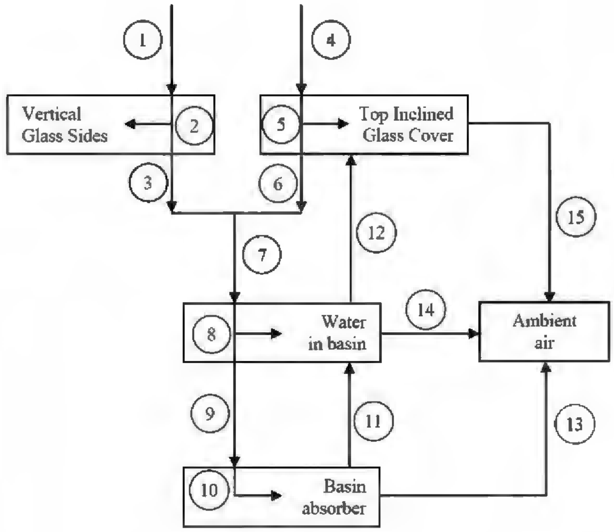

Figure 2: Schematic diagram of heat transfers of a solar still

9. Solar irradiation transmitted through the water thickness and incident on the absorber surface.
10. Solar irradiation absorbed by the basin absorber.
11. Convective heat transfer between the absorber surface and the water in the basin.
12. Convective, evaporative and radiative heat transfer between the waster surface and the inner glass surface.
13. Energy lost through the insulation beneath the absorber by conduction and convection from the basin to air.
14. Energy lost through the vertical sides by conduction and convection from the water to air.
15. Energy lost by convection and radiation from the top inclined glass cover to air.

By calculating the absorptivity and the transmissivity for the four glass sides, the total radiation falling on the absorber plane was found. Hence the following thermal energy balances were applied. The thermal capacity of the basin absorber and the glass and the temperature difference across the glass thickness were considered negligible. The Dunkle method [3] was used to calculate the evaporation rate based on modified convective characteristics [4].

For the top glass cover:

$$h_{t_{wg}} A_{bsn}(T_{sw} - T_{gls}) + \alpha_{gls} I_{gls} A_{gls} = h_{t_{ga}} A_{gls}(T_{gls} - T_{amb}) \quad (1)$$

Since $A_{bsn} \approx A_{gls} \cos\theta$,

$$T_{gls} = \frac{h_{t_{wg}} T_{sw} \cos\theta + h_{t_{ga}} T_{amb} + \alpha_{gls} I_{gls}}{h_{t_{ga}} + h_{t_{wg}} \cos\theta} \quad (2)$$

For the basin absorber:

$$I_{abs}(1 - \rho_{sw} - \alpha_{sw}) = h_{t_{bw}}(T_{bsn} - T_{sw}) + h_{t_{ba}}(T_{bsn} - T_{amb}) \quad (3)$$

$$T_{bsn} = \frac{I_{abs}(1 - \rho_{sw} - \alpha_{sw}) + h_{t_{bw}} T_{sw} + h_{t_{ba}} T_{amb}}{h_{t_{bw}} + h_{t_{ba}}} \quad (4)$$

For the water in the basin

$$I_{abs}(1 - \rho_{sw})\alpha_{sw} + h_{t_{bw}}(T_{bsn} - T_{sw})$$
$$= h_{t_{wg}}(T_{sw} - T_{gls}) + h_{t_{wa}}(T_{sw} - T_{amb})\frac{As}{A_{bsn}} + (MC)_{sw}\frac{dT_{sw}}{dt} \quad (5)$$

$$h_{t_{bw}} = h_{c_{bw}} \quad (6)$$

$$h_{t_{wg}} = h_{c_{wg}} + h_{e_{wg}} + h_{r_{wg}} \quad (7)$$

$$h_{t_{ga}} = h_{c_{ga}} + h_{r_{ga}} \quad (8)$$

$$h_{e_{wg}} = 16.273\text{x}10^{-3}\ h_{c_{wg}}\ \frac{P_{sw} - P_{gls}}{T_{sw} - T_{gls}} \quad (9)$$

$$h_{c_{wg}} = \left(\frac{kC(Gr.\Pr)^n}{d}\right)_{sa} \quad (10)$$

$$P = e^{\left(25.317 - \frac{5144}{T}\right)} \quad (11)$$

$$\dot{m}_e = \frac{h_{e_{wg}}\left(T_{sw} - T_{gls}\right)}{h_{fg_{sw}}} \quad (12)$$

The thermophysical properties of the water in the basin are calculated for seawater having a specific salinity and temperature [5]. The thermophysical properties for air saturated with water vapour are calculated as per [6].

Experimental Setup

The performance of a solar still under weather conditions was measured by monitoring the temperature at various locations inside the still and measuring the distillate produced. Type T Thermocouples (±0.5°C) were used to measure the temperatures Tn at the locations indicated in Figure 3. A tipping bucket was used to measure the distilled water flow rate D1. The basin was automatically washed and filled with 20mm of fresh seawater at 03:00am.

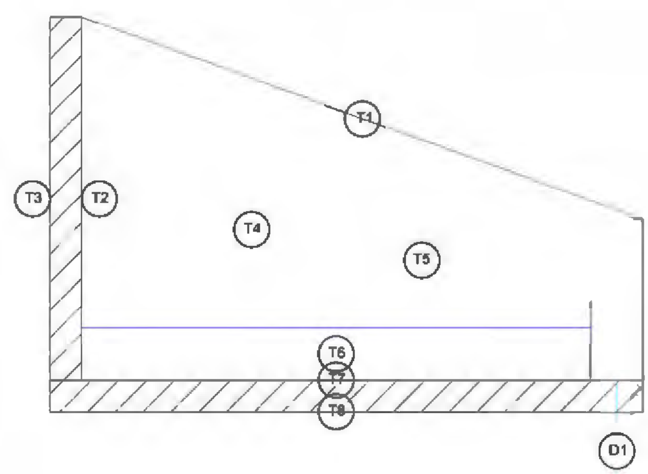

Figure 3: Location of sensors installed

Sensor	Measurand
T1	Glass temperature
T2	Vertical surface (inner) temperature
T3	Vertical surface (outer) temperature
T4	Air + water vapour temperature -1
T5	Air + water vapour temperature -2
T6	Seawater temperature
T7	Horizontal surface (inner) temperature
T8	Horizontal surface (outer) temperature
D1	Distillation rate

Table 1: Schedule of sensors

A weather station was also installed to monitor the micro climatic conditions. The following parameters were measured: solar irradiation, ambient temperature, humidity and pressure, wind speed and direction, and precipitation. The sensors were connected to a data logger which was programmed to take a sample reading every second. The average value of each parameter was recorded every minute.

Figure 4 shows the experimental setup including the simple still and the weather station installed on the roof of the Reverse Osmosis Plant of Water Services Corporation in Pembroke, Malta.

Figure 4: Experimental setup

RESULTS AND DISCUSSION

Effect of simulated climatic parameters on heat transfer

The performance of the solar distillation still was simulated using specific input conditions. The insolation was varied from 10 to 30 MJ/m^2/day, in order to cover the whole range from winter to summer. Similarly the ambient temperature and the wind speed were varied from 10 to 30°C and from 1 to 5 m/s respectively. For these simulations, both ambient temperature and wind speed were kept constant throughout the whole simulated day. The solar irradiation used in the simulation was as measured on specific days having the indicated insolation values. The results are plotted in Figure 5. Figure 6 shows how the amount of distilled water produced varies with insolation and temperature at a given wind speed of 1 m/s.

It is evident that the distillation rate increases with ambient temperature. This is because the average temperature of the seawater in the basin is increased and so, since the latent heat of evaporation decreases with temperature, for the same energy input more water is evaporated and distilled. Condensation occurs against the top covering glass. When the solar irradiation and ambient temperature are high, the glass

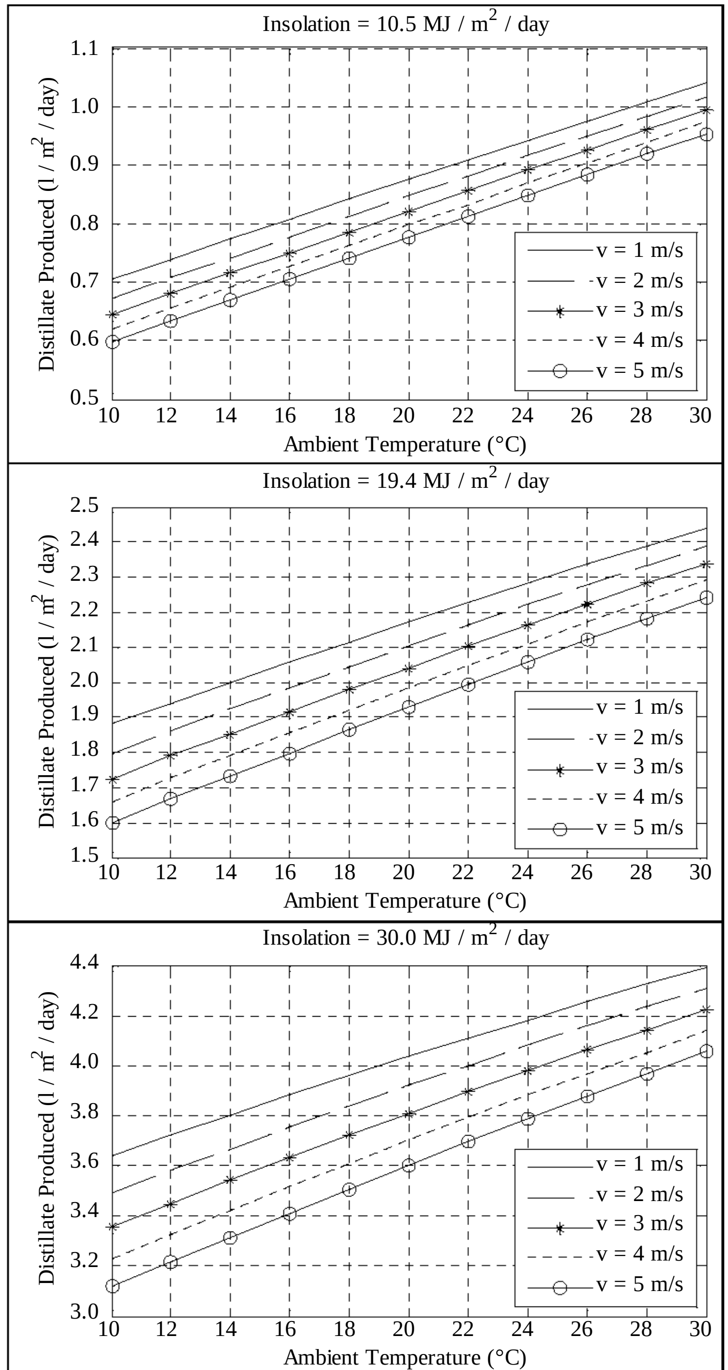

Figure 5: Distillate Production with varying insolation, wind speed and ambient temperature

temperature is high. However from the graphs one can conclude that this does not have an adverse effect on the distillation rate. The distillation rate increases with the difference between the temperatures and partial pressures of the water vapour above the seawater surface and that of the glass. When the ambient temperature is increased, the temperature difference is decreased.

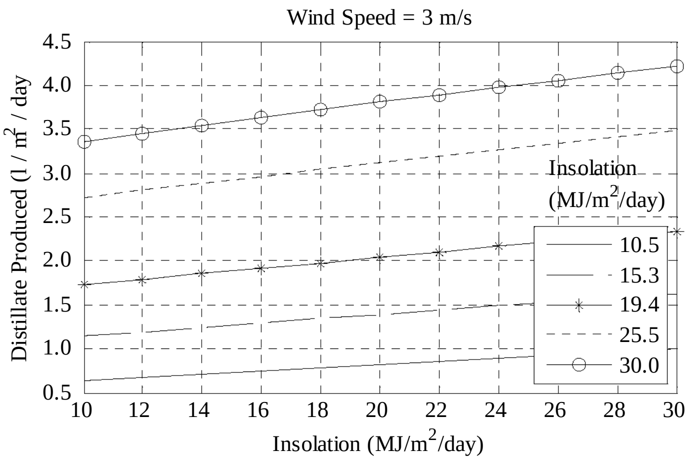

Figure 6: Distillate Production with varying insolation

However, since the partial pressure varies exponentially with temperature, when the ambient temperature, and thus the average operating temperature of the solar still is increased, the pressure difference has a net increase. This in turn results in a higher distillation rate. Figure 7 shows how the energy fractions vary with ambient temperature, wind speed and insolation. The energy fraction is defined as the ratio of the respective heat transfer to the total energy input in the solar still (summation of irradiation 1 and 4 indicated in Figure 2). It is interesting to note that although the distillation rate is increased with ambient temperature, the heat transfer ratios remain more or less constant. This means that for example out of the total amount of radiation incident on the solar still, the amounts of heat transferred (by convection, evaporation and radiation) from the water to glass and from the glass to air throughout the day are of around 20% and 30% respectively. Since this does not vary much with ambient temperature, it is concluded that the distillation rate is increased due to a lower latent heat of evaporation caused by a higher seawater temperature.

When the wind speed is increased, the total amount of water produced per day is decreased. A higher wind speed increases the heat lost by convection from the glass covers and the bottom and back sides of the still. Since the basin is insulated with 50mm of expanded polystyrene, the heat lost by convection is not affected much by higher wind speeds. However the average operating temperature of the still is decreased due to the heat lost from the uninsulated glass covers. This is observed when the wind speed is high and the ambient temperature is low. The convective heat transfer coefficient and the temperature difference between the glass and the atmosphere are increased at high wind speeds and low ambient temperatures. At an ambient temperature of 10°C, when the wind speed is increased from 1 to 5 m/s, the amount of water produced is decreased by 15%. However, at 30°C, the reduction is halved to 8%. Although the condensation capacity of the top covering glass is increased at higher wind speeds, the specific humidity inside the solar still is lowered due to lower water and water vapour temperatures and higher latent heat of evaporation. Hence the distillation rate is decreased.

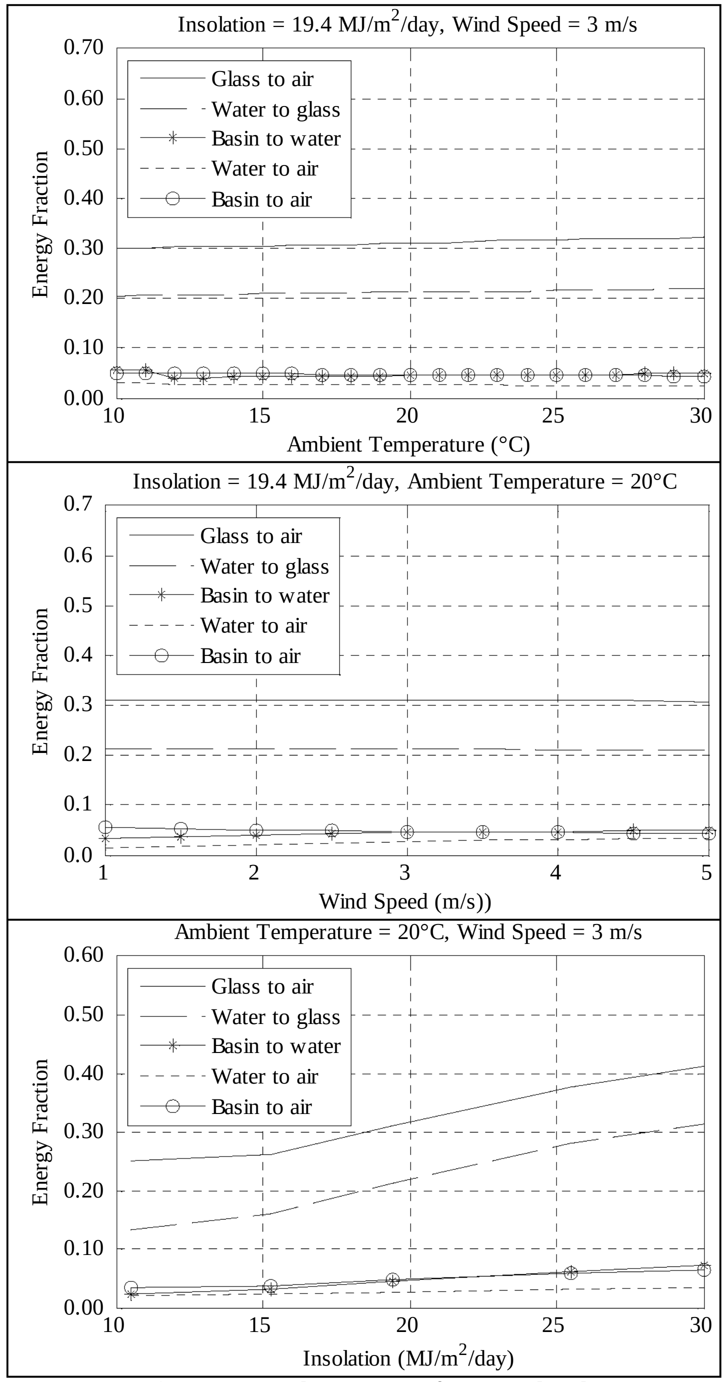

Figure 7: Total Heat Transfer normalised per total energy input in the solar still (simulations)

As expected, when the insolation is increased, the total amount of water produced is increased. The temperatures of all the components of the solar still are increased, and thus the heat losses are increased. The amount of solar energy absorbed by the glass covers is increased and their temperature is also increased. This reduces the ability of the glass covers to condense the water vapour formed. However, since the average operating temperature is increased, the distillation efficiency is improved due the exponential relationship between the temperature and partial pressure of water vapour. The ratio of heat transfers to input irradiation also increases with insolation as shown in Figure 7.

For a given wind speed, the evaporation and condensation processes are improved when the ambient temperature and insolation are increased. However at a higher insolation day the efficiency is also increased. From Figure 6, one can note that as the insolation increases from 10 to 30 MJ/m^2/day, at an ambient temperature of 20°C, the amount of distillate produced increases by more than threefold, in fact it increases by 4.6 times. This shows that the efficiency is enhanced by more than 50%.

This results from the fact that a higher fraction of heat is transferred from the water to the glass (which includes evaporative heat transfer) and from the glass to air (heat transferred by condensation). Since both these rates of heat transfer are increased, and since the average operating temperature of the solar still is increased, the distillation efficiency is also enhanced. Since the overall temperature is higher, less heat is required to evaporate the water from the basin or in other words, for the same energy input more vapour is produced.

Effect of actual climatic parameters on heat transfer

Solar radiation, ambient temperature and wind speed data measured using the weather station, in conjunction with the software model, were used to simulate the temperatures reached inside the solar still. The distillation rate was also simulated using the theoretical energy balances described above. Typical daily plots are shown in Figure 8. The bottom charts show the theoretical and experimental temperature profiles of the seawater (SW) and the glass (Gls) and the distillation rate respectively.

One can observe that both the temperature and distillation profiles are very similar. These graphs were plotted for every day for over six months. The amount of heat transferred between the key components of the solar still were calculated and plotted as shown in Figure 9. The irradiation falling on the water in the basin was found by finding the radiation transmitted through the vertical and top glass covers. The resultant radiation component is as shown in the graph.

The total heat transferred is found by numerically integrating the curves obtained. The normalised quantities are plotted as shown in Figure 10. Month 1 represents January 2011. It is

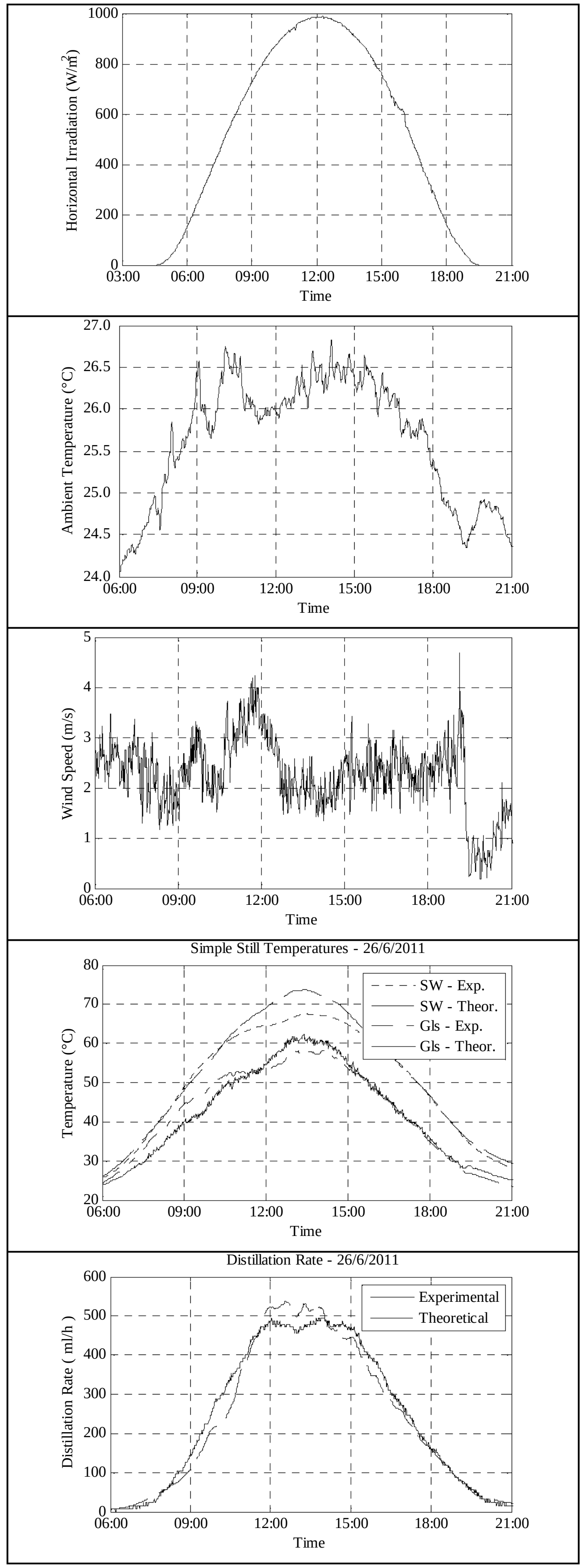

Figure 8: Simulated and experimental results for 26 Jun11

noted that the heat lost directly from the basin and from the water to ambient is quite constant throughout the testing period, with an average of about 5% each. This corresponds perfectly with that calculated and shown in Figure 7. On the other hand, the amount of radiation reaching the water in the basin doubles from 20% to over 40%. This is because in summer the solar altitude is higher and so, the radiation transmitted through the top inclined glass cover increases. This results in more radiation incident and absorbed by the water in the basin. Adding to this, in summer, the ambient temperature increases and the average wind speed decreases. As described above, these increase the operating temperature of the solar still. In turn, the heat transferred to and from the glass is increased as illustrated in Figure 10. This matches very well with what was predicted when the performance of the still was simulated on constant values.

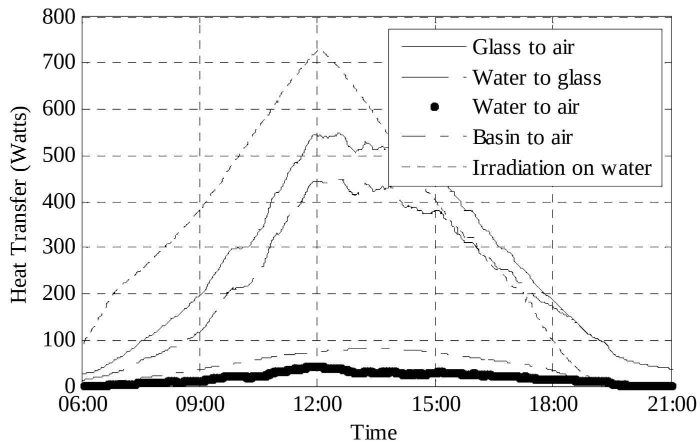

Figure 9: Daily heat transfer profiles

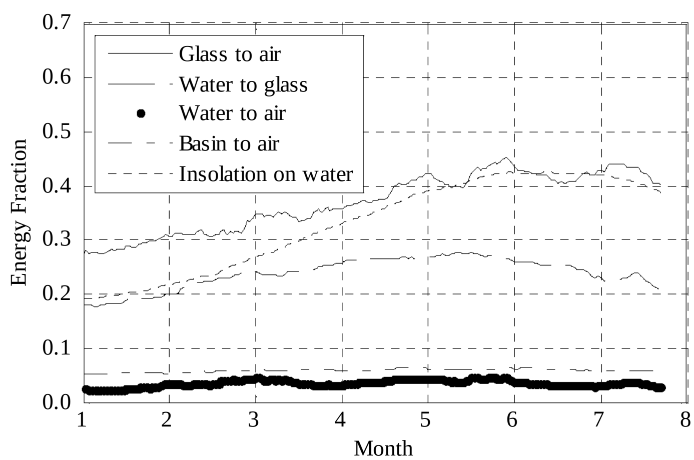

Figure 10: Daily total heat transfer normalised per total energy input in the solar still (calculated from actual weather data)

From Figure 10 one can observe that the glass covers handle the majority of the heat transferred to and from the solar still. The glass covers act as a radiation transmitter and as a condenser. All the radiation used inside the unit is transmitted through the glass and so its optical and thermal properties highly affect the performance of the distiller. However, the evaporation and condensation processes are also governed by the heat transferred to and from the glass. In summer, over 40% of the total energy input is transferred by convection and radiation to atmosphere. This depends on the convective, evaporative and radiative heat transfer between the water surface and the inner surface of the glass.

CONCLUSION

The theoretical heat transfer characteristics of a solar still were investigated analytically and experimentally. The performance of solar still distillation simulated on specific solar radiation, ambient temperature and wind speed was calculated. It is concluded that:

- The distillation rate increases with ambient temperature due to an increase of the overall temperature of the whole unit. The seawater-glass temperature difference is decreased, but due to the exponential relationship of the partial pressure of water vapour with temperature, operating at a higher temperature results in a higher pressure difference, and so the evaporation rate is increased.
- The distillation efficiency is improved when the insolation is increased, resulting in more distillate production.
- A higher wind speed decreases the temperature of the solar still and so the distillation rate is decreased, even though the condensation capacity of the glass is increased.

From the calculations based on data measured experimentally, it was concluded that the simulation is in very good agreement with the results obtained experimentally.. From the analysis of the energy fractions within the solar distiller it is concluded that:

- The glass covers transfer the bulk of the energy exchanged in a solar still.
- The pressure difference required for evaporation highly depends on the temperature of the seawater in the basin and the seawater-glass temperature difference.
- The evaporation and condensation processes, and thus the distillation rate are affected by the optical and thermal properties of the glass covers, due to the fact that their temperatures create the driving forces for both phase changes.

ACKNOWLEDGEMENTS

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