Theoretical Analysis of Solar Still incorporated with Pin Finned Wick, Water Sprinkler and Phase Change Material with Design Improvements

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Abstract

The dearth of potable water in developing countries accompanied with electricity shortfalls has led the scientific community to develop and continuously enhance means of purifying the available water. This is done while ensuring minimal energy requirements such as the solar still. In this paper, we aim to investigate the theoretical advantages of implementing improvements in the solar still. In the evaporator portion of the solar still, the utility achieved by using a pin finned wick is studied. In the condenser portion of the solar still, the added benefit of using Phase Change Material (PCM), Paraffin Wax in our case, is analyzed. Finally, an additional design advancement is offered where the collector plate is made parallel to the glass cover to maximize solar radiation yield. A detailed improvement analysis will be conducted in the context of the conditions prevalent in Pakistan to get an insight in the opportunity cost of making the aforementioned modifications.

Keywords

Solar still, pin finned wick, phase change material (PCM), design improvements, heat and mass transfer, theoretical analysis

Nomenclature

a	Dimensionless coefficient based on optical properties
b	Exergy power (W)
c	Specific heat capacity (J/mK)
D	Diffusivity (m2/s)
G	Solar irradiance (W/m2)
Gr	Grashof number
h	Convection heat transfer coefficient (W/m2K)
H	Distance from brine surface to glass cover inside the solar still (m)
I	Irreversibility (W/m2)
j	Mass flux per unit of area (kg/m2s)
k	hermal conductivity (W/mK)
m	Mass (kg)
M	Molecular mass (kg/kmol)
Nu	Nusselt number
P	Pressure (kPa)
Pr	Prandtl number
q	Heat flux (W/m2)
q	Heat flux (W/m2)
R	Universal gas constant (kJ/kmolK)
T	Temperature (˚C/K)
U	Global heat transfer coefficient (W/m2K)
V	Wind speed (m/s)
x	Thickness (m)
a	Ambient/air within the still
b	Interior surface of the bottom of the still
ca	Forced convective heat transfer from glass cover to surroundings
col	Collector (bottom inner part of the still)
colw	Heat convective transfer from collector to water
conv	Free convection
cw	Convective heat transfer for water vapor
dif	diffusion
ev	Evaporation heat transfer
g	Glass cover
ga	Convective and radiative heat transfer from glass cover to ambient
i	Initial
in	Input
ins	Insulation
max	Maximum
out	Output
ra	Radiation between glass cover and surroundings
rw	Radiation emission from water to surroundings
S	Solar radiation
source	Source
tot	total
w	Water (Brine)
wg	Interaction between brine and glass cover
α	Absorptance
β	Thermal Expansion coefficient (K−1)
Δ	Difference (Operator)
ε	Emissivity
λ	Enthalpy of evaporation
ρ	Reflectance
τ	Transmittance

1. Introduction

Solar stills are extremely attractive since they are not only inexpensive but are also very economical in terms of their energy requirements. However, their attractiveness gets limited due to the scarce amount of water they are able to collect. This is due to a number of reasons, including but not limited to the high latent heat required by water to evaporate and then condense on the glass plate, the heat that is lost i.e. not absorbed by water to evaporate and heat lost by water to the surroundings including the walls of the solar still.

A number of advancements and improvements have been incorporated in the design of the solar still in order to reduce the aforementioned losses and increase the amount of water per unit time that is collected by the still. Alaian et al [1] talk about the use of fins on the base surface made from aluminum in order to increase the conductivity and the surface area that comes into contact with the solar radiation. They further suggest wrapping the fins in wick as wick is porous and would hence absorb water allowing the surface area to increase drastically. This is similar to a sponge absorbing water in its pours. Sathyamurthy et al [2] discuss the use of Phase Change Materials (PCM) to improve the amount of heat that is stored. Since during phase changes, the heat absorbed or released is latent instead of sensible, the largest amount of heat can be absorbed or released without retarding the heat transfer due to temperature changes. Moreover, this can allow the still to work even after solar energy is not directly available.

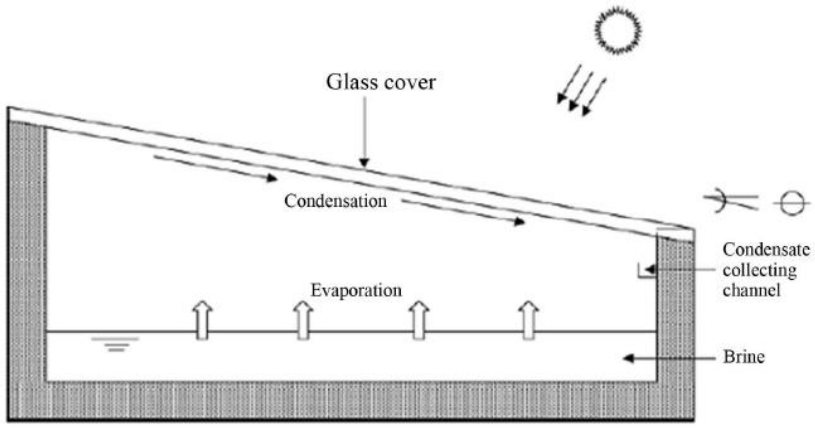
In this paper we will be analyzing the efficiency of both of these proposed methods. Moreover, we will attempt to replicate the results that have been published in the paper based on experimental studies analytically. The key parameters that will come under our analysis will be the rate of heat transfer, the amount of water collected per unit time, the heat that is provided by solar radiation and finally the efficiency of the entire system.

2. Analysis of a conventional solar still

2.1 Purification mechanism

The basic working principle of a conventional solar still is to collect condensed water vapors produced by heating the contaminated water. This condensed water is pure and can be consumed. The main source of the energy required for the functioning of a solar still is the sun. Modifications can be made to improve the evaporation and condensation processes.

A conventional solar still consists of a basin with a sloped transparent cover and a water collection system. Contaminated water is kept in the basin, the internal sides of which are usually colored black to absorb maximum amount of solar radiations. The external sides of the basin are insulated to prevent any heat loss. The transparent cover can be glass or a plastic sheet. The water is evaporated in the basin and condensed on the sloped cover from which it is directed to the collection system via gravity. The following figure shows a conventional solar still.



2.2 Conduction

Water evaporation and condensation are dependent on the efficiency of conduction of heat in a solar still. For smooth operation of the still the heat conduction through the transparent cover

a. *Dependence*

Heat transfer through a material due to conduction is dependent on the coefficient of conductivity of the material, the difference in temperature and distance between the considered end points. The relation can be mathematically modeled by Fourier's law of conduction.

b. Through transparent cover

The water vapors in contact with the cover need to lose heat as quickly and as efficiently as possible and convert to liquid water that can be directed to the collection system. It can be attained by using a thin sheet of a conductive transparent material and a large temperature difference between the internal and external side of the sheet. The heat through the transparent sheet can be modeled as:

$$q_{cond,g} = -\frac{k\Delta T}{x}$$

c. Through collector plate

It is crucial for the water vapors to lose their heat of condensation through the transparent sheet only and so we must minimize heat loss from any of the other sides. A major chunk of losses occurs through the collector plate which loses usable heat to the surrounding if poorly insulated. These losses can be minimized heavily insulating the exterior sides of the still and exposing it less and less to wind whenever possible. The heat losses can be modeled as:

$$q_{cond,c} = -\frac{k\Delta T}{x}$$

2.3 Convection

a. Dependence

Convention of any fluid depends on the temperature difference between surface and the fluid, the area of the contact surface and on the convective heat transfer coefficient 'h'. The relation is given as:

$$q_{conv} = hA\Delta T$$

b. From basin bottom to water surface

As the basin temperature rises due to radiation, natural convection starts in the contaminated water and it gets heated by convection currents. To maximize evaporation, it is important that convection takes place effectively. This convection can be modeled as:

$$q_{colw} = h_{colw}(T_{col} - T_{w)}$$

c. From water surface to glass cover

Water vapors rise from the surface of the contaminated water and move upwards till they reach the cover where they lose their heat of condensation and change phase to liquid. Malik et al. [1] proposed a limited range of temperatures for which the values of the physical properties of the fluid remain constant with the temperature. With the appropriate consideration of mass transport during evaporation they arrive to the generally accepted expressions:

$$q_{cw} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)}{268.9 \times 10^3 - P_w} \times (T_w + 273)\right]^{\frac{1}{3}} (T_w - T_g)$$

$$h_{cw} = 0.884\Delta T^{'\frac{1}{3}}$$

d. From glass cover to surroundings

The dominant heat losses from the outer surface of the glass cover to the surroundings are by convection due to the wind. The expression for heat transfer by convection from glass to the environment is:

$$q_{ca} = h_{ca}(T_g - T_a)$$

Wattmuff *et al*. [2] found the expression for convection coefficient as:

$$h_{ca} = 2.8 + 3V$$

2.4 Radiation

Radiation is a mechanism of heat transfer between two bodies. The main feature of radiation lies in the fact that there is no need of a participating medium between the source of the radiation and a receiver.

a. Dependence

Radiation is a phenomenon that depends on several parameters:

i. Intensity
ii. Wavelength
iii. Angle of the ray with respect to the normal of the surface of the source
iv. Optical properties of the material
v. Solid angle described by the bundle of rays
vi. Temperature of the source and the receiver

b. From sun to glass cover

The radiation intensity from the sun changes throughout the day and is decreased as it reaches the solar still because of the atmosphere. The expression for the final radiation reaching the solar still at a particular time can be written as:

$$G = \frac{G_{max}}{2}\left[\sin\left(\frac{\pi t}{12}\right)\right] + \left|\frac{G_{max}}{2}\left[\sin\left(\frac{\pi t}{12}\right)\right]\right|$$

The ambient temperature also varies throughout the day which can be expressed by an equation as:

$$T_a = A\sin\left(\frac{\pi t}{24}\right) + T_{a,i}$$

where t is the time in hours and $T_{a,i}$ is the ambient temperature at the beginning of the day in ˚C. Assumed in the model is the following:

i. All physical properties of materials are not affected by temperature differences
ii. Vapor-air mixture and insulation are not regarded as systems or participating media
iii. Brine and glass cover do not interact with incoming solar radiation
iv. The shape factor value between the collector and glass cover is 1
v. The solar still is a closed system
vi. There are no temperature gradients across brine depth, collector plate or glass cover

c. Radiation from water to transparent cover

Radiation inside the solar still accounts for the least dominant phenomenon for heat transfer. Radiations from water to the transparent cover can be categorized into long and short wavelength radiations. The short wavelength radiations are too insignificant and are hence ignored but the long wave radiations are taken into account by the following equation:

$$q_{rw} = \sigma\varepsilon(T_w^4 - T_g^4)$$

Dunkle [3] found that radiation accounted for only 10% from the overall energy budget in the still when using a value of 0.9 for water emissivity.

d. Radiation losses to surroundings

Similar to the previous case, only the long wavelength radiations will be considered that are being emitted back to the surroundings due to the reflectiveness of the glass cover and the still. A good solar still design would require the lowest possible value for reflectivity and absorptivity for the glass cover, so that most of the radiation is transmitted through the glass. The heat dissipated by the glass cover is expressed as following:

$$q_{ra} = \sigma\varepsilon(T_w^4 - T_a^4)$$

2.5 Energy balances in a solar still

Now that almost all the dominant heat transfer expressions in the solar stills have been accounted for, it is important to derive energy balance equations for different parts of the still for the sake of mathematical modeling. We have chosen three main parts of the still for this purpose:

a. the collector plate
b. the contaminated water
c. the transparent cover

The energy entering and exiting these parts is as following:

$$\underbrace{q_{ev} + q_{cw} + q_{rw} + a_g G}_{\text{in}} - \underbrace{\left(q_{ca} + q_{ra}\right)}_{\text{out}} = m_g c_g \frac{\mathrm{d}T_g}{\mathrm{d}t}$$

$$\underbrace{a_w G + q_w}_{\text{in}} - \underbrace{\left(q_{ev} + q_{cw} + q_{rw}\right)}_{\text{out}} = m_w c_w \frac{\mathrm{d}T_w}{\mathrm{d}t}$$

$$\underbrace{a_{col} G}_{\text{in}} - \underbrace{\left(q_{colw} + q_{ins}\right)}_{\text{out}} = m_{col} c_{col} \frac{\mathrm{d}T_{col}}{\mathrm{d}t}$$

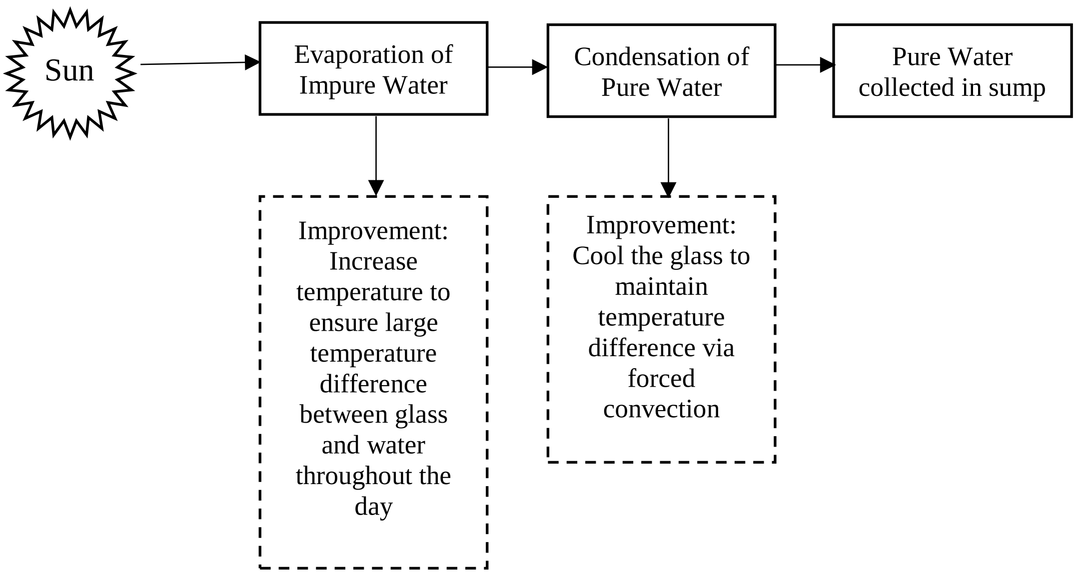
where,

$$a_g = \alpha_g \left(1 - \rho_g\right)$$

$$a_w = \alpha_w \tau_g \left(1 - \rho_g\right)\left(1 - \rho_w\right)$$

$$a_{col} = \alpha_{col} \tau_g \tau_w \left(1 - \rho_g\right)\left(1 - \rho_w\right)\left(1 - \rho_{col}\right)$$

3. Improvements in evaporation



3.1 Phase Change Material (PCM)

Conventional solar stills have water absorb the thermal energy provided by the sun which naturally leads to rise in the sensible heat and hence the temperature. Not only is sensible heat a poor means of getting energy but it also retards the heat transfer process. In order to solve this issue, we need to utilize the latent heat of materials in the evaporator region of the solar still.

For this purpose, it is necessary that the material we use as our phase changer has a boiling point at the normal working conditions of the solar still. This will allow the phase change material to absorb the heat provided by solar radiation and change phase, i.e. store up the provided energy in the form of latent heat and allow the solar still to work even after the sun is not available by using the stored energy in the PCM. For our purpose, we have used paraffin wax as our PCM.

Paraffin wax properties:

Property	**Value**
Melting ^oC	40-60
Specific heat in Solid/Liquid kJ/kgK	2.95/2.51
Density solid/liquid kg/m^3	818/760
Thermal conductivity (k) W/m^{o}C	0.24/0.24
Heat of fusion kJ/kg	226

Governing equations for convection and evaporation coefficient.

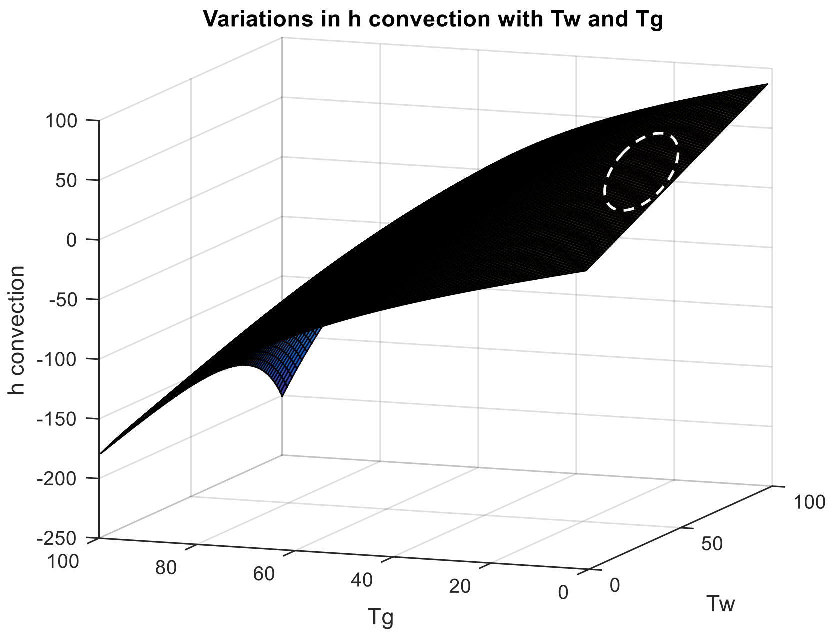
T_w = Temperature of water, T_g = Temperature of glass, P_w =Partial Pressure at water, P_g= partial pressure at glass

$$h_{conv} = 0.884\left[(Tw - Tg) + \frac{(Pw - Pg)(Tw + 273.15)}{268900 - Pw}\right]$$

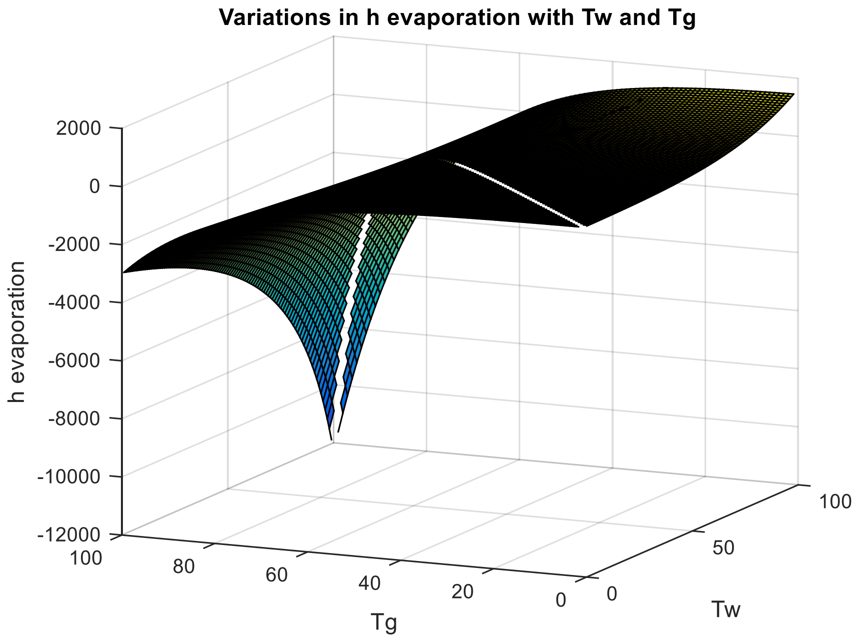
$$h_{evap} = 0.01627 h_{evap}\left[\frac{Pw - Pg}{Tw - Tg}\right]$$

$$P = e^{\left(25.317 - \frac{5144}{Tw + 273.15}\right)}$$

We can put this mathematical model with Tw and Tg as the independent variables and produce surface plots for h_{conv} and h_{evap}.



Here we see that the coefficient achieves maximum value when the difference between the temperatures is the highest. We lie on the marked spot on the graph.



The above graphs show us that large temperature differences lead to large values in coefficients for both convection and for evaporation. Moreover, we realize that the coefficient of evaporation is significantly larger than the coefficient of convection [45].

Assuming unit width of our solar still.

The dimensions of the PCM = 0.05 x 0.06 x 1

The maximum energy PCM can absorb:

$$Q\ total\ absorbing\ capacity = L \times m = 226000 \times 818 \times 1 \times 0.05 \times 0.06 = 554604\,J$$
$$Q_{solar} = I \times A \times T$$

The average intensity is 800W/m^2, we will take the average value of solar radiation and find the energy by multiplying it with the time the sun is up. However not all of this energy is taken up by the PCM since some of it is lost and other absorbed by water.

$$Q_{solar} = 800\ \times 0.05 \times 11 \times 60 \times 60\ = 1584000\,J$$

Hence 1386000 J of energy is supplied by the sun in total but water absorbs most of this during the time the sun is available. This head is transferred to the PCM via convection of water and conduction of the surface (pin finned wick) Since water is stagnant we can model it as conduction and hence;

$$Q\ conduction\ through\ water = \frac{kAdT}{dx} = 0.63 \times 0.1 \times 1 \times \frac{10}{0.06} \times 11 \times 60 \times 60 = 415800\,J$$

The heat transfer will mostly be retarded due to water hence we need not take the aluminum plate in our calculations.

$$Q\ solar\ absorbed\ by\ PCM =\ 415800$$

In order to calculate the heat absorbed by water to evaporate

$$heat\ absorbed\ by\ water = 2260000 \times mass\ of\ water\ collected = 2260000m_w$$

Some of the energy is also recorded back by the PCM as the condensed water releases heat back to the PCM to cool down to the normal temperature and from solar radiation. This can be found via:

$$Q_{condenced} = m_w c_p(Tg - Tw)$$

Tg-Tw varies during the day from 0 to 16 degrees. We will check for the average case.

$$Q_{condenced} = m_w \times 4180 \times 10 = 41800m_w$$

Saline water is kept at a height of 60mm hence the volume of water available is

$$Volume\ of\ water = 0.1 \times width \times 0.06 = 0.006w\ m^3$$
$$Mass\ of\ water = 0.006w \times 1000 = 6w\ kg$$

Therefore, assuming that all of the PCM is charged during the day, we can calculate the extra amount of water it can evaporate by discharging during the night.

$$Q_{condensed\ water\ cooling} + Q_{solar\ radiation} = 2260000m_w$$
$$415800 + 554604 + 41800m_w = 2260000m_w$$

Solving for m_w

$$m_w = 0.437\ kg$$
$$V_w = 420\ ml$$

Our research paper shows an increase in yield of:

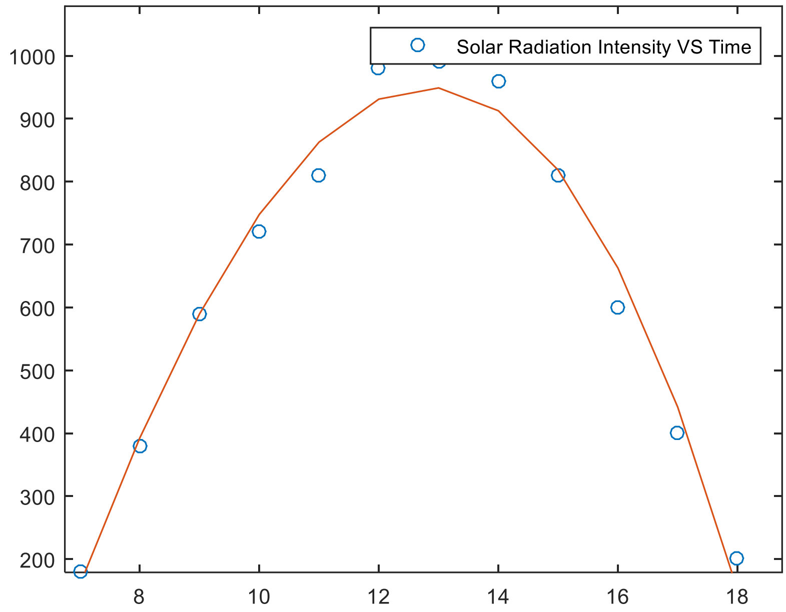
$$Experimental\ Increase\ in\ yeidl = 1600 - 1100 = 500ml$$

And hence our analytical results and experimental results are in harmony.

Accumulated yield with PCB = 1600ml/day = 1600kg/day
Accumulated yield without PCB = 1100ml/day = 1100kg/day

$$\eta_D = \frac{\Sigma m_d * L}{I_t * A_b}$$

Latent heat of vaporization= 2.23kJ
Energy absorbed by water with PCM = $\frac{1600}{1000000} \times 997 \times 2230 = 3557\ J$
Energy absorbed by water without PCM = $\frac{1050}{1000000} \times 997 \times 2230 = 2334\ J$
Basin Area = 0.8x1.25 = 1m^2



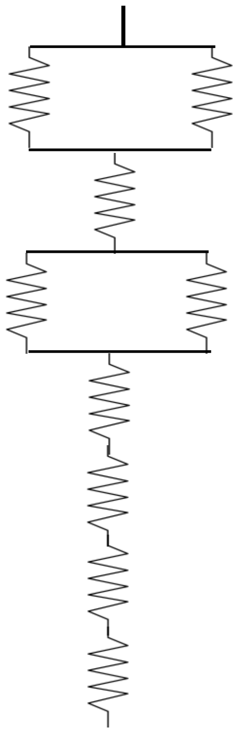
Energy via solar radiation = $\int Intensity * Area * \ dt = 7430 \ \times 1 = 7430J$

$$\eta_{with\ PCM} = \frac{3557}{7430} = 0.478$$

$$\eta_{with\ no\ PCM} = \frac{2334}{7430} = 0.314$$

$$\%_{Increase\ in\ efficiency} = \frac{0.48 - 0.31}{0.31} \times 100 = 52.7\%$$

3.1.1 Resistance model of solar still



$R_{\text{atmospheric convection}} \parallel R_{\text{atmospheric radiation}}$

$R_{\text{glass conduction}}$

$R_{\text{solar still air convection}} \parallel R_{\text{solar still air radiation}}$

$R_{\text{water conduction}} + R_{\text{wick conduction}} + R_{\text{aluminum conduction}} + R_{\text{PCM}}$

3.2 Pin Finned Wick

We have discussed how we can increase the area of the evaporator bed to improve heat transfer and also how we can increase the surface area to enhance the evaporation process of water. The next step is to combine the two improvements so that they complement each other.

In order to do this, we cover the aluminum fins with black colored wick. The black color is necessary as it allows absorbance of solar radiation and hence lets the aluminum fins absorb the heat and thus heat from the sun is transferred on the evaporation bed while maintaining the increased surface area for water to help with evaporation.

Theoretically, the water collected based on the evaporative and convective heat transfer the yield of water is calculated by using the experimental temperatures with the following equations [5]:

$$h_{conv} = 0.884\left[(Tw - Tg) + \frac{(Pw - Pg)(Tw + 273.15)}{268900 - Pw}\right]$$

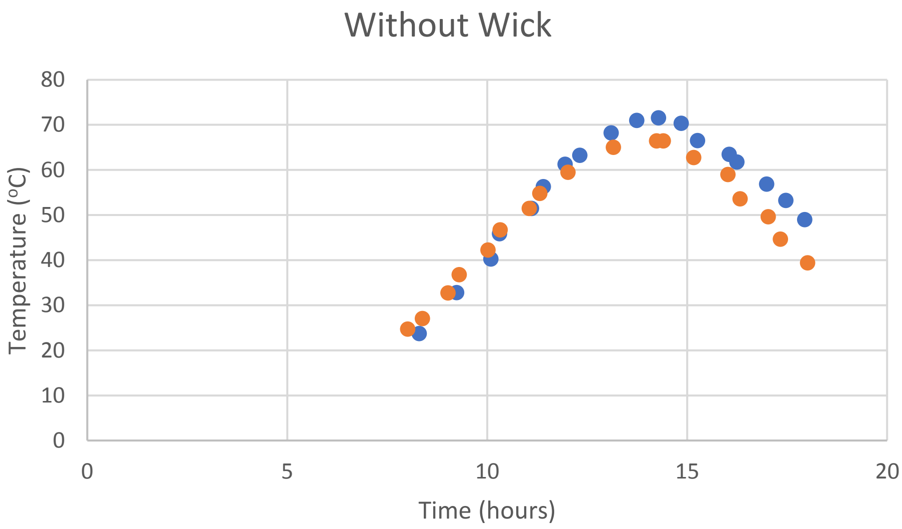
$$h_{evap} = .016273\ h_{conv}\frac{(Pw - Pg)}{Tw - Tg}$$

$$P = e^{\left(25.317 - \frac{5144}{Tw+273.15}\right)}$$

$$\frac{dm_c}{dt} = h_{evap}\frac{Tw - Tg}{h_{fg}}$$

3.2.1 Without wick

T_w reaches a maximum of 71.578 °C. We take average values for T_w=50.369 °C and T_g=49.08°C for calculations



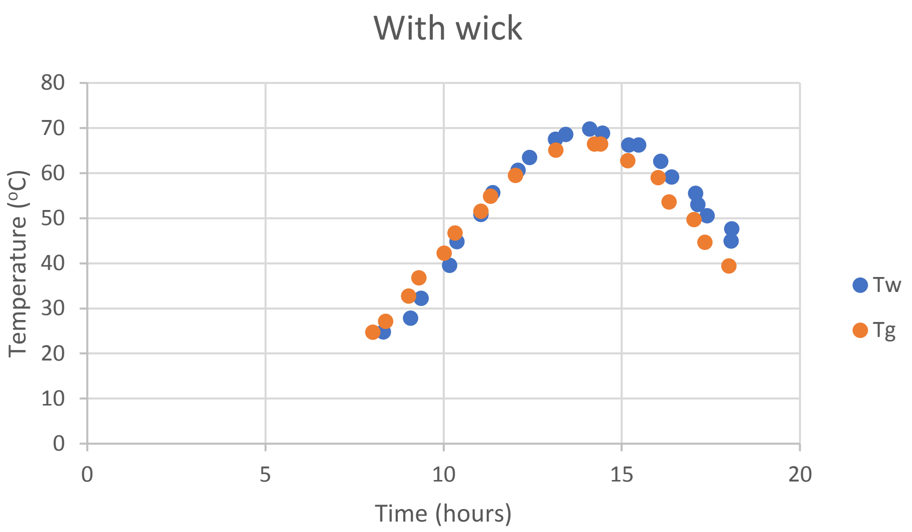
$$h_{conv} = 1.19\ W/m^2\ {}^oC$$

$$h_{evap} = 11.89\ W/m^2\ {}^oC$$

Amount of water collected without wick = 1.13 kg

3.2.2 With wick

Here we note the maximum temperature is reduced for the wick however the average T_w increases. Tw reaches a maximum of 67.8 °C. We take average values for T_g=49.08 °C and T_w=52.1 °C and calculate the heat transfer coefficients to estimate the water collected.



$$h_{conv} = 1.39\ W/m^2\ {}^oC$$
$$h_{evap} = 13.38\ W/m^2\ {}^oC$$

Amount of water collected with wick = 1.59 kg
Increase in theoretical yield of water = 460 mg

There is a theoretical increase of about .46 kg of water production in the solar still. This theoretical increase is higher than the experimental values as observed experimentally.

Accumulated yield with pin finned wick = 3290ml/day
Accumulated yield without pin finned wick = 2950ml/day

$$\eta_D = \frac{\Sigma m_d * L}{I_t * A_b}$$

Total solar radiation = I_t = 14.74 MJ/m^2
Latent heat of vaporization= 2.23kJ
Basin Area = 0.8x1.25 = 1m^2

$$\eta_{with\ wick} = \frac{(2950)(2230)}{(14740000)(1)} = 0.4463$$

$$\eta_{with\ no\ wick} = \frac{(3290)(2230)}{(14740000)(1)} = 0.4907$$

$$\%_{Increase\ in\ efficiency} = \frac{0.4907 - 0.4463}{0.4463} \times 100 = 9.949\ \%$$

Increase in yield due to pin finned wick = 340 ml/day = 340 mg/day

4. Improvements in condensation

Enhanced condensation may be achieved through the following two methods [7].

- Decreasing the temperature of glass cover as much as possible.
- Decreasing the temperature of the space above the water level and below the glass plate.

4.1 Decreasing the temperature of glass cover

This means that we should pick a glass having maximum thermal diffusivity which implies more transmittance and less storage of heat.

$$Thermal\ Diffusivity = \frac{Heat\ Conducted}{Heat\ Stored}$$

$$\propto = \frac{k}{\rho C}$$

In this way, the temperature of the glass plate will not rise and all the solar radiations will be transmitted through the pane into the basin containing water. This also helps keep the pane’s temperature low. The outside as well as inside temperature of glass cover can be decreased by sprinkling water on the outside of the glass plate. This removes heat from the glass panel. It expedites the condensation process such that when water vapours reach the inner surface to glass panel, the greater temperature difference (due to sprinkled water) caused heat to be removed more rapidly from vapours for a given mass flow rate and hence rate of condensation is increased significantly.

4.2 Decreasing the temperature of the space above water level

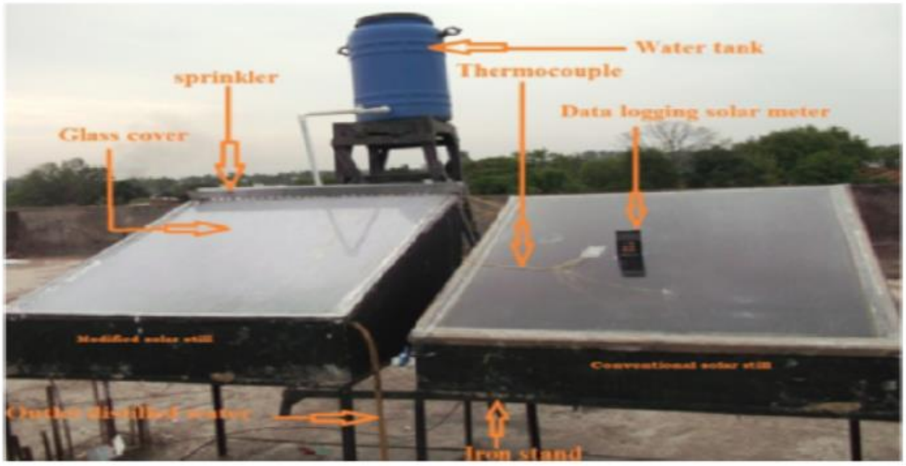
This space can be maintained at comparatively lower temperature by painting the side walls white. This allows the radiations to get reflected away from this region and the side walls are maintained at lower temperature and there is lesser heat transfer through convective currents in this region.

4.3 Comparison

For the comparison purposes, we will take two stills. One is conventional having black painted vertical walls and no water flow above the plate while the modified one has black painted walls upto the water level and above the water level, the walls are painted white. The modified still also has a water sprinkler on its top surface.

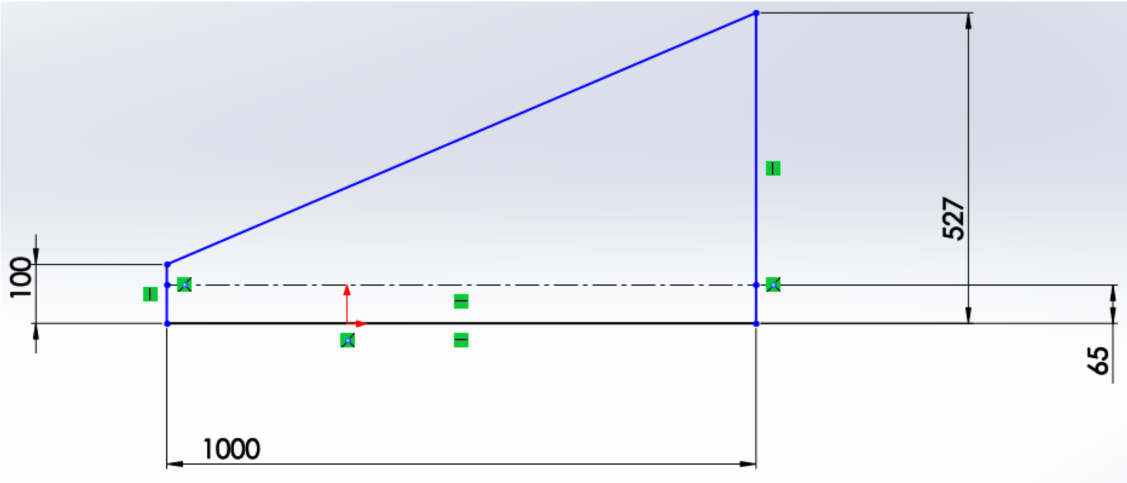
4.4 Solar Still Set up

Both the solar stills were fabricated in similar way and identical in geometry. These have basin area of 1 m2, height of back-side wall is 527 mm and height of front-side wall is100 mm. Basins of stills are made from galvanized iron sheet having a thickness 1 mm. The bottom and the side walls are insulated with layer of glass wool (20 mm thickness) to reduce the heat loss from the solar still to atmosphere. Ply-wood of 15 mm thickness is used for making outer layer of solar still. The top of both the stills have been covered by glass of 4 mm thickness. It is inclined at $23^\circ$to the horizontal which is latitude of the place where experiment was being carried out.



4.5 Incident Solar Energy Calculations

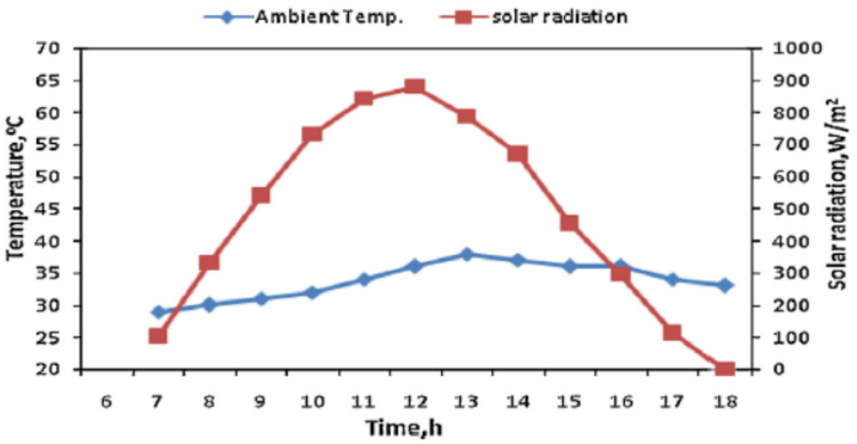
The Solar Intensity vs time plot is given below. The values were recorded experimentally. From this data, we obtain the total amount of solar radiation incident on the walls. For this particular case, we are assuming that the whole of the incident radiation falls on the surface under consideration (the side walls above the water level).



The level of water is assumed to be constant at 65mm. The area under consideration is:

$$Area = 1000 \times (100 - 65) + 1000 \times (527 - 65)$$
$$Area = 0.497m^2$$

The plot of Solar Radiation and Ambient Temperature vs time is given:



From the plot, we get radiation as a function of time as:

$$y = 0.4864x^4 - 22.689x^3 + 354.22x^2 - 2076.5x + 3890.3$$

where y is the radiation intensity and x is the hours. For our calculations, we consider the timeframe of 10 to 14 hours.So total energy incident during this time frame is given as

$$Q = \int_{t1}^{t2} \dot{q}(t)Adt$$

$$Q = \int_{10}^{14} (0.4864x^4 - 22.689x^3 + 354.22x^2 - 2076.5x + 3890.3) \times 0.497 \times 3600dt$$

$$Q = 5.757MJ$$

4.6 CASE 1 (Side walls are completely painted black)

The absorptivity of a new galvanized iron plate is 0.64 while that of a dirty galvanized iron plate is 0.92. So, working with the mean of these two values, we have absorptivity of the black painted galvanized iron as 0.78 [8].

The portion of the energy absorbed by the plate is given as

$$Absorptivity\ of\ black\ galvanized\ iron\ plate = 0.78$$

$$Q_{absorbed} = 0.78Q_{incident}$$
$$Q_{absorbed} = 4.49MJ$$
$$Q_{reflected} = 1.267MJ$$
$$Emissivity = \in = 0.38$$

Assuming all other factors remain the same the energy emitted by the black painted plate is proportional to its emissivity [9]. Hence,

$$Q_{emitted} = 1.706MJ$$

So net energy balance becomes,

$$Q_{released} = 2.973MJ$$
$$Q_{retained} = 2.784MJ$$

4.49MJ of absorbed energy will cause increase in temperature of the side wall above the water level and will contribute to the heating of the air above the water which is of no use to us, rather it halts the condensation process. 1.267MJ of energy is reflected and contributes to the heating of basin plate.

4.7 CASE 2 (Side walls are painted black upto the water level):

Now if we paint the walls white above the water level,

$$Absorptivity\ of\ white\ washed\ galvanized\ iron\ plate = 0.22$$
$$Q_{absorbed} = 0.22Q_{incident}$$
$$Q_{absorbed} = 1.266MJ$$
$$Q_{reflected} = 4.491MJ$$
$$Emissivity = \in = 0.31$$

Assuming all other factors remain the same the energy emitted by the black painted plate is proportional to its emissivity. Hence,

$$Q_{emitted} = 0.392MJ$$

So net energy balance becomes,

$$Q_{released} = 4.883MJ$$
$$Q_{retained} = 0.874MJ$$

So we see that a significant amount of energy is reflected in this case, which may now be absorbed by the basin plate and hence will contribute to the evaporation process. Moreover, lower temperature of the side walls above the water level also facilitate the condensation process.

So, the percentage increase in the available amount energy which may be absorbed by the basin plate is

$$Percentage\ incraese = \frac{4.883 - 2.973}{4.883} \times 100 = 39.1\%$$

Hence, we should expect a theoretical increase in efficiency the value of which, the paper under discussion suggests to be 21%.

4.8 Effect of sprinkling water:

We will compare the mass flow rate of condensate with and without the sprinkled water.

The dimensions and properties of the glass plate are:

Length	1.088m
Width	1.000m
Thickness	0.004m
Thermal Conductivity	0.8 W/mK

The time frame for our analysis is from 10:00 am to 2:00 pm. The water vapors colliding with the inner surface of glass plate have an average temperature of 60℃. To condense them to liquid state, energy equal to heat of vaporization must be removed from them. At 100℃ the enthalpy of vaporization is 2160KJ/Kg and at 37℃ it is 2410KJ/Kg. So at the average temperature of 60℃ , it would be around 2318KJ/Kg (Using linear interpolation).
So in the absence of the sprinkler water, the heat transfer process is governed only by conduction.

$$\dot{Q} = \frac{0.8 \times 1.088 \times (60 - 35)}{0.004}$$
$$\dot{Q} = 5440W$$

So, the condensation rate comes out to be:

$$\dot{m} = \frac{\dot{Q}}{Q}$$
$$\dot{m} = 2.346g/s$$

This roughly approximates to 84.45l/day of distillate. This is of course the ideal maximum condensation rate possible. This was calculated assuming:

1. Continuous supply of water vapours at all times
2. Condensation to take place uniformly at the entire area of the plate
3. Temperature difference to remain constant throughout the day
4. Assuming 10 hours of operation

This ideal value serves our purpose since we only want to observe the effect of sprinkled water on the maximum condensation rate.
Now we consider the water flows from the sprinkler at a velocity of 1m/s and is at a temperature of 25℃. Now to account for the convection, we do following calculations

$$T_f = \frac{35 + 30}{2} = 32.5℃$$

The properties of water at this film temperature are

Prandtl Number	5.01
Density	995Kg/m^3
Thermal Conductivity	0.62 W/mK
Kinematic Viscosity	0.769 × 10^-3

$$Re = \frac{\rho V L}{\mu}$$
$$Re = 1.407 \times 10^6$$
$$Nu = (0.037Re^{0.8} - 871)Pr^{1/3}$$
$$Nu = 3761.33$$
$$h = \frac{Nu \times K}{L}$$
$$h = 2143.4$$

Now from the resistance model, we get:

$$R_{cond} = \frac{L}{kA}$$
$$R_{conv} = \frac{1}{hA}$$
$$R_{Total} = R_{cond} + R_{conv}$$
$$R_{Total} = 5.389 \times 10^{-3}$$
$$\dot{Q} = \frac{(60 - 25)}{R_{Total}}$$
$$\dot{Q} = 6495W$$

So, the condensation rate comes out to be:

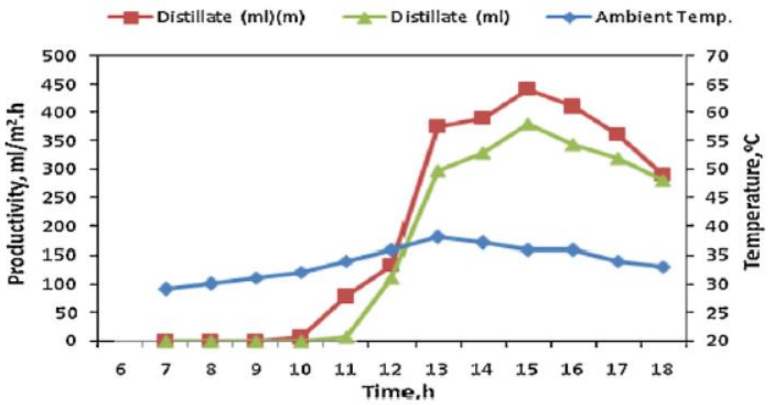
$$\dot{m} = \frac{\dot{Q}}{Q}$$
$$\dot{m} = 2.80g/s$$

This approximates to roughly 100.8 l/day of distillate.

This shows a percentage increase of 19.3% in the ideal maximum condensation rate. Practically the use of sprinkler increased the distillate from 2.94l/day to 3.541l/day which is 20% increase.

4.9 Results

1. By sprinkling water on the outer glass plate surface, the rate of condensation can be significantly increased. In our case, we observed a theoretical increase of 19.3% against the actual increase of 20%.
2. By painting the walls white above the water level, we increase the amount of reflected energy and hence roughly 39% more energy is available for the basin plate to absorb. Also, the space above the water can be maintained at a lower temperature by reducing the heat transfer by convection currents due to the comparatively lower sidewall temperature.



Conclusion

Evaporation was improved by integrating PCM (allowing functionality after the sun has set) and pin finned wick (increasing surface area). Condensation was improved by sprinkling water on the exterior of the glass cover (decreasing cover temperature and allowing efficient heat transfer from water vapors). The overall design of the solar still was improved by making the absorber plate parallel to the glass cover.

Theoretical analysis was done on above mentioned improvements and satisfactory results were accomplished. These analytical results also satisfied the experimental data obtained from reviewing research papers on similar topics.

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