

A Heat and Mass Balance Study of a Solar Still Investigating Ways to Improve its Performance

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ABSTRACT: This paper discusses the experimental work of heat and mass balance of Single Slope Solar Still and giving ways to improve its performance. Experiments conducted over solar still with slope 26.8° (i.e. latitude angle of the site) and of basin areas 1 m^2 under the weather condition of Jaipur, Rajasthan, India during the month of March. Heat balancing was done to analyze the heat involved, and its efficient utilization within the solar still along with the mass (vapor) loss. This paper also focuses on losses due to reflected solar radiation at glass cover, and their method of evaluation. Measurement of temperature at various points, solar intensities, feed water, and distilled water production, were taken for several days at different operating conditions. These experiments were performed using tap water as a feed water. It has found that 15% of incoming heat has lost from walls (excluding glass surface), out of which 6% loss are from the bottom, heat carried by lost vapor accounted as 4%, and 9% loss as incident solar radiation reflects from the outer surface of the glass cover.

KEYWORDS: solar still, solar desalination, heat balance, heat and mass balance, reflectivity.

I. INTRODUCTION

All over the world, owing to the inadequate freshwater resources in many of the countries, desalination industry has extensively grown within these countries. It has forecasted that the world-wide-desalinated water supply will become 54 billion metrics per year by 2020. As an account of this, there is an urgent need to clean, pure drinking water in many countries. Often water resources are brackish and containing harmful bacteria and therefore cannot be used for drinking purpose. On the same, there are many coastal locations where sea water is in abundant amount, but potable water is not available. Pure water is always needed in Hospitals, Schools and also in many production Industries. Solar distillation is one of many processes that used for water purification. Solar radiation from the Sun is the source of heat energy, where sea water is evaporated and condensed as in pure water.

There are numerous factors affecting the solar still productivity such as intensity of solar radiation, wind velocity, ambient temperature, glass – water temperature difference, water condensing surface, deepness of water, inlet water temperature, area of absorber plate and angle of glass cover. The intensity of solar radiation, wind velocity and ambient temperature cannot be controlled as they are metrological factors. The other parameters can be varied to increase the productivity of solar still. By considering the numerous factors affecting the solar still productivity, several modifications have been made to improve the productivity of solar still. Omara et al. [1] used the mirror as an internal reflector in a stepped type solar still, and on comparing its results with conventional solar still, found increment in its productivity by 75%. Kabeel et al. [2] used mirror as external and internal reflector on stepped type solar still and compared its result with conventional solar still, found 125% increment in its productivity. They had also estimated the cost of distilled per litre, i.e. 0.031\$ and 0.049\$ for stepped type solar still and conventional type solar still respectively. Rajaseenivasan et al. [3] used circular and square fins at its basin, and performed experiments by

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varying the depth of feed water at 1cm, 2 cm, 3cm, and 4 cm in the basin. The makeup water attained a maximum, i.e. 4.55kg/m². Bhardwaj et al. [4] have designed and analysed the performance of inflatable plastic solar still using passive condenser, which used to increase the condensing surface and attained the maximum productivity rate of 0.75 litre per hour.

Several integrations of solar still with other system have been made to improve the productivity of the solar still. Badran et al. [5] has integrated solar still with the conventional flat-plate collector, using feed water which first passes through collector, finally this heated feed water is supplied to solar still. As result of this, 231% increment was found in productivity of distilled water. Abdul-Wahab et al. [6] has integrated inverted solar still with a refrigeration cycle, and analysed its daily yielding at water depth of 8 cm, 6 cm, and 4cm for two different temperature (30, 35°C) of feed water, found more yielding for 30°C temperature. Panchal et al. [7] integrated vacuum tubes with the double basin solar still, and found the daily yielding of makeup water increased by 56%. Velmurugan et al. [8] integrated solar pond, stepped solar still, and conventional solar still all in a series, and carried out two experiments, one for its integration in series only, and another for its integration in series along with sponges used in basin of both solar stills, and found the increment of 80% in productivity for system of integration in series along with sponges. Now, in order to view its further improvement, we needed to analysis its detailed heat transfer losses so as to optimize energy losing areas.

II. EXPERIMENTAL SETUP

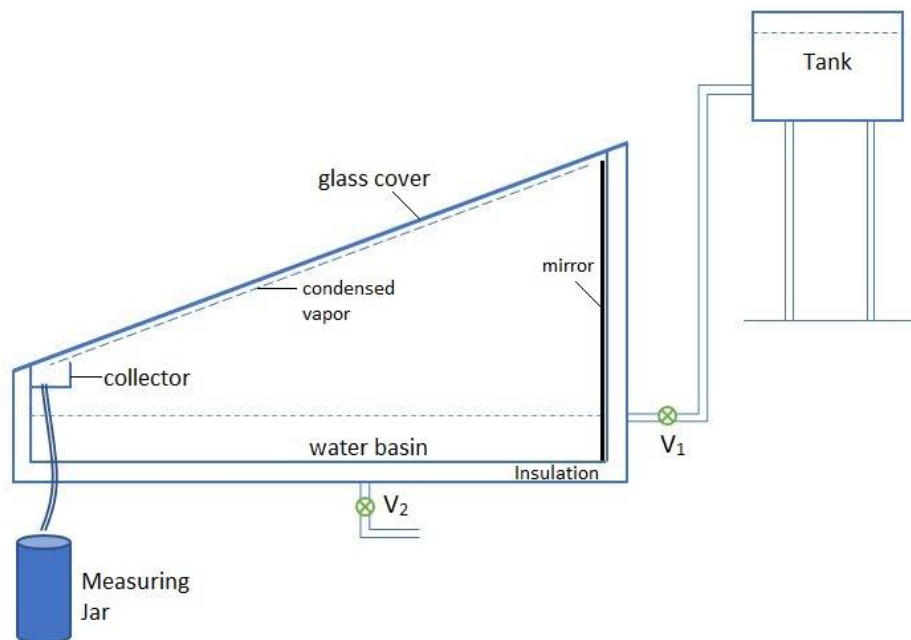


Figure 1: Schematic diagram of single slope solar still

The single slope–single basin passive solar still used, shown in Fig.1 in a schematic diagram, which also explain it's components. Galvanized Steel Sheet of 1.4 mm thickness used to fabricate solar stills. The size of the basin is 1 m² and height of 12.5 cm at front and 55.5 cm at rear end. This make an inclination of 26.8° with the horizontal plane, which is the latitude of Jaipur, Rajasthan, India. A window glass of 5mm thickness used as a transparent cover still. 10mm thick thermocol used as insulation to reduce the heat loss. A water storage tank with the capacity of 50 litres used to supply the saline water to the still as shown in Fig. 1. Control valve V₁ used to control the flow from the saline water storage tank to still.

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Figure 2(a): A photo to show internal reflector

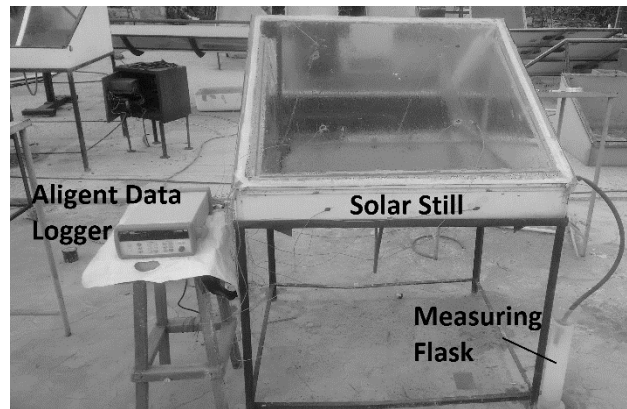


Figure 2(b): Photographic view of experimental setup of Solar Still

The mirrors placed on the three inner vertical sides of the solar still as internal reflectors, as shown in Fig. 2(a). These mirrors are placed to increase thermal energy inside the solar still, which was being absorbed by the walls. For the collection of condensate, collector provisioned below the lower edge of the cover. An outlet provided in collector to drain the water through pipe and to store in measuring jars of 1 litre. Provisions are made to supply raw water, draining of the basin water and inserting thermocouples at the outlet. Fig 2(b) is the photoreal view of the actual experimental setup, which shows the solar still installed with the thermocouples, which are connected to the Agilent data logger, and measuring flask that store distillate water. Before starting the experiment, the required water level is maintained in the still by opening the valve. As the water evaporates inside the still, the level of the water is reduced and added in the still within every hour.

Table 1: Accuracy of various measuring instruments

SL. No.	Instrument	Accuracy	Range	Error %
1.	T-type Thermocouple	-	0-200°C	0.01
2.	Fluke Oil-bath Calibrator	± 0.0001	0-100°C	0.001
3.	Agilent data logger	± 0.1°C	0-500°C	-
4.	Solarimeter	± 1 W/m ²	0-2000 W/m ²	2.5
5.	Anemometer	± 0.1 m/s	0-15 m/s	10
6.	Measuring Jar	± 10 ml	0-1000 ml	10

Table 1: shows the list of instruments that used in the experimental Setup of the solar still. The temperatures measured with help of the T-type thermocouples arranged at the following locations: two at basin plate, two for water at the basin, two for the vapor hang inside, four at inner and outer surfaces of glass each, three at side surfaces, four at the

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back surface, two at the front surface, and two at the bottom surface. Solar intensity is measured using the Solarimeter and velocity of wind by an anemometer.

III. EXPERIMENTAL PROCEDURE

Over this experimental set up, several experiments have performed for three quantity of feed water i.e. 10ltrs, 15ltrs, 20ltrs. Every experiment carried out for 24 hours Before starting the experiment, valve V_2 has opened for the 1 hour in order to empty the water basin fully. Measured quantity of feed water has supplied through the valve V_1 to the basin of Solar Still. Switch ON the data logger to record the temperatures, data logger was setup for an interval of 15min. During experiment, solar intensity and produced distilled water are being recorded for an interval of 1 hour till 6pm and after that only distilled water is being measured in next morning for whole night produced distilled water. Now the next early morning remaining feed water in the basin is being measured and evaluate the amount of the mass of water which was accounted as vapor loss.

Now brief experimental analysis which is being done, for the mass balance - noted total mass of feed water poured to basin of solar still which is equal to total distilled water produced, mass of the water lost in the form of vapor, and the remained feed water at basin in next morning. For the heat balance – measured solar intensity fall on the effective area of the glass cover which is consider as the solely energy source for the solar still which is equal to energy used in evaporating of feed water, heat losses from all the surfaces, amount of solar intensity which is being reflected by the glass cover, and unaccounted heat.

IV. THEORETICAL ANALYSIS

The energy balance for the stills is carried out with the following assumptions for simplification: (a) absorptivity of glass cover is neglected; (b) neglecting forced convection heat loss the side heat loss from the solar still; (c) water level in the basin of the solar still is kept constant; (d) angle of incident while passing from rear medium to glass medium is same for radiation passing from outer and inner surface of glass. For energy balance or heat balance, solar still considered as system i.e. amount energy goes inside the solar still will be equal to the amount energy come out.

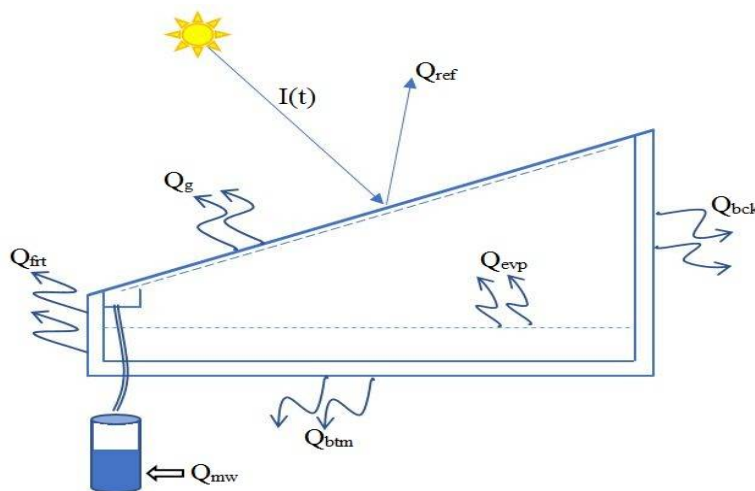


Figure 3: Heat transfer mechanism in solar still

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The heat transfer mechanism in the solar still is given in Fig.4. Solar radiation that falls on the glass area enter solar still i.e. heat input, is equal to heat goes out of it i.e. heat transfer losses from its surfaces to the ambient/sky, heat transferred to evaporate the makeup water as well as to evaporate the unaccounted water which lost in form of vapor, heat transferred carried by the makeup/distilled water at temperature higher than that of feed water, and the amount of solar radiation which get reflected from the outer surface of the glass.

Heat balance for the solar still

Heat In = Heat Out

Heat In: Incident solar radiation

Heat Out: Reflected solar radiation + Surfaces heat transfer loss + heat transfer in Evaporation of distilled water + heat carried by the distilled water

1) Incident Solar Radiation (Q_{in}):

$$Q_{in} = I(t) \cdot A_g ; \text{ where } A_g, \text{ is area of the glass cover}$$

2) Surfaces heat transfer loss:

heat transferred from the surfaces of solar still – glass surface, and other five walls (front, rear/back, right, left, and bottom) enclosing surfaces of Still.

a) Heat transfer from glass surface to sky; Q_g

i) Convective mode of Heat transfer b/w glass and sky; Q_{cg}

$$Q_{cg} = h_{cg} \cdot A_g \cdot (T_g - T_{sky})$$

whereas, h_{cg} taken from [9],

$$h_{cg} = 5.7 + 3.8 \times V_a$$

The sky temp. taken from [9],

$$T_{sky} = T_a - 6.0$$

ii) Radiative mode of heat transfer b/w glass and sky; Q_{rg}

$$Q_{rg} = \epsilon_g A_g \sigma ((T_g + 273)^4 - (T_{sky} + 273)^4)$$

b) Heat transfer from other five surfaces of the Still to its ambient;

Whereas, five surfaces – left side wall, right side wall, front wall, back wall, and bottom surface.

i) For left side wall heat transfer through convective mode; Q_{cL}

$$Q_{cL} = h_{cL} A_L (T_L - T_a)$$

whereas, h_{cL} is calculate through the Nusselt no. (N_u), i.e.; $h_{cL} = \frac{N_u \cdot k}{L_c}$

now to calculate N_u , Nusselt no.;

For vertical plate;

$$N_u = \begin{cases} 0.59 R_a^{1/4} & ; 10^4 < R_a < 10^9 \\ 0.1 R_a^{1/3} & ; 10^9 < R_a < 10^{13} \end{cases}$$

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For horizontal plate:
If upper surface is of hot plate;

$$N_u = \begin{cases} 0.54 R_a^{1/4} & ; 10^4 < R_a < 10^7 \\ 0.15 R_a^{1/3} & ; 10^7 < R_a < 10^{11} \end{cases}$$

If lower surface is of hot plate;

$$N_u = 0.27 R_a^{1/4} ; 10^5 < R_a < 10^{11}$$

whereas, R_a is Raleigh no. which was calculated by;

$$R_a = G_r \cdot P_r = \frac{g \cdot \beta \cdot (T_L - T_a) \cdot L_c^3}{\nu^2} \cdot P_r$$

ii) For left side wall heat transfer through radiative mode; Q_{rL}

$$Q_{rL} = \varepsilon_L A_L ((T_L + 273)^4 - (T_a + 273)^4)$$

whereas, A_L is the area of the left side walls, T_L is the instantaneous temperature which is being recorded for every 15 min, ε_L is the emissivity of left side wall surface.

So, total heat transferred from the left side wall is, $Q_L = Q_{cL} + Q_{rL}$

Similarly, calculation for heat transfer through convective or radiative mode of other remaining four walls (i.e. Q_R , Q_{bck} , Q_{btm} , Q_{fnt}) would be same as per their respective areas, temperatures, orientation, and emissivity.

3) Heat transfer in Evaporation:

Heat transferred in the evaporation of the distilled water as well of water which accounted as vapor loss; Q_{evp}

Total mass of water which undergoes evaporation = mass of distilled water + mass of vapor loss

$$M_w = m_w + m_v$$

$$Q_{evp} = M_w \cdot h_{fg}$$

whereas, h_{fg} is taken from [9]; $h_{fg} = 2335$ kJ/kg,

4) Heat carried by the distilled water:

Heat transferred to distilled water at higher temperature than as it was in its initial feed water temperature; Q_{mw}

$$\Delta Q_{mw} = \Delta m_w \cdot C_w (T_w - T_{fw})$$

whereas, T_{fw} is the initial temperature of feed water, and T_w is the instantaneous temperature of the distilled water which is been recorded within every 15 min.

$$Q_{mw} = \sum_{\text{initial state}}^{\text{final state}} (\Delta Q_{mw})$$

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5) Reflected Solar Radiation; Q_{ref}

Amount of reflected incident solar radiation from outer surface of glass, which is been evaluated using Fresnel equations for reflectance. In the evaluation of amount of reflected radiation, some of the incident radiation are parallel and some of the incident radiation are perpendicular, so there two equations for both one is called as reflectance of s-polarized (for perpendicular) and another is called p-polarized (for parallel). Some radiation reflects from the outer surface and remain gets refracted through the glass inside the solar still. Similarly, some of these radiation remains inside and some get refracted out from the solar still after incidenting on inner surface of glass cover, so such concept is applied to calculate the total reflection from the glass surface, with some assumptions like – interface between the media is flat, media is homogeneous, and incident radiation to be in a plane wave.

Fresnel equation for the reflectance is:

Reflectance for s-polarized light, R_s

Reflectance for p-polarized light, R_p

$$R_s = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2$$

$$R_p = \left| \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right|^2$$

whereas, n_1, n_2 are the refractive index air and glass respectively, and θ_i, θ_t are angle of incident and refracted ray respectively, and θ_t is calculated by the Snell's Law, i.e., $n_1 \sin \theta_i = n_2 \sin \theta_t$

And angle of incidence (θ_i) of the Sun on a surface tilted at an angle from the horizontal (β), when the surface is tilted towards the latitude of site (facing south in the northern hemisphere)

$$\cos \theta_i = \cos \delta \cos(\phi - \beta) \cos \omega + \sin \delta \sin(\phi - \beta)$$

where, δ is deflection angle, ϕ is latitude angle (i.e. 26.8°), β is the surface tilted angle (i.e. 26.8°) and ω is an hour angle which we have to calculate further for every hour according to IST.

Reflection of incident radiation from outer surface of glass is given by, R

$$R = \frac{R_s + R_p}{2}$$

Heat lost due the reflection, Q_{ref}

$$Q_{ref} = \sum_{initial}^{final} \bar{I} \bar{R} ; \text{ whereas } \bar{I} \text{ is an average solar intensity fall on the surface of glass for an hour, } \bar{R} \text{ is average reflectivity for an hour.}$$

Now, all the heat which are evaluated will use to perform the heat balance;

$$Q_{in} = Q_g + Q_L + Q_R + Q_{bck} + Q_{btm} + Q_{frt} + Q_{evp} + Q_{mw} + Q_{ref} + Q_{un}$$

V. RESULTS AND DISCUSSION

Fig 4(a). shows the global solar intensity throughout the day, along with the ambient temperature, on march 6, 2017. Solar intensity reached at its maximum at 12 noon, i.e. 820 W/m² and almost constant till 1 pm at 800 W/m². It is being measured by the Solarimeter in an interval of an hour, and recorded from 8am to 6pm. And with the end of the day total solar radiation incident over the Still is of 5.365 kWh/m². Ambient temperature curve is being carried out by averaging of the ambient temperature at two locations, one is at the back, and another hanged under the bottom surface of the

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Still. In actual all temperatures recorded for an interval of 15mins but here in graphs averaging is being done to show them for an interval of one hour. Fig 5. also shows the reflectivity of the solar radiation that fall on the inclined surface of glass, i.e. the percentage of reflected solar radiation at that instant for that angle of incident. It is being calculated by considering hourly change in the angle of incident, and remain constant for that hour. And also varies from day to day as in its calculation angle of deflection of sun is included. On account of this reflectivity, it is being found that 9% of the total solar intensity reflected by the glass surface, which is account as heat lost due to reflectivity.

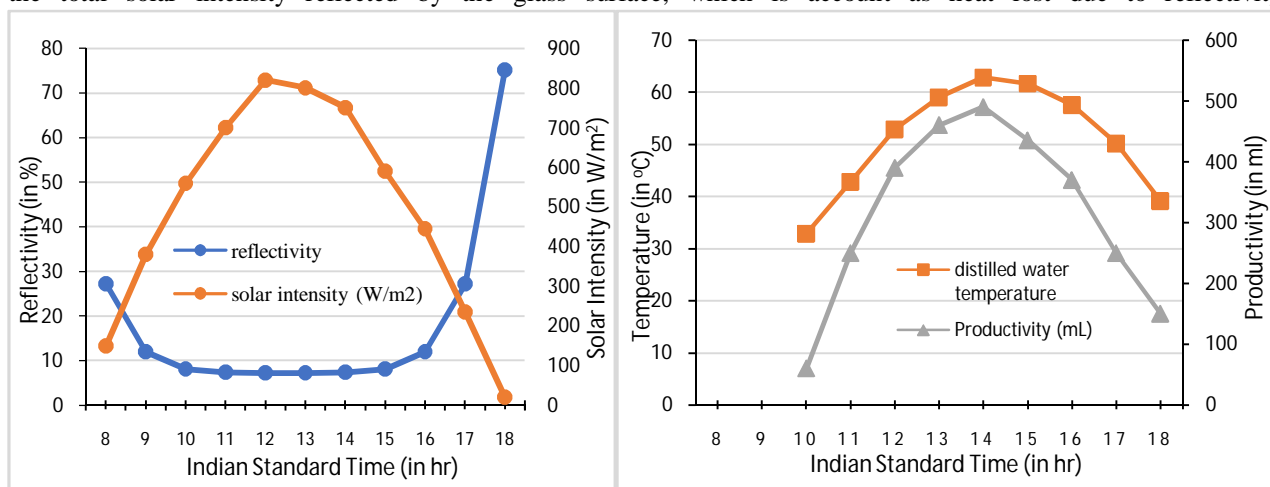


Figure 4(a): Hourly variation of solar intensity and reflectivity

Figure 4(b): Hourly productivity of distilled water and its temperature

Fig 4(b). shows temperature of the distilled water measured at the outlet of the Still, along with an hourly produced distilled water. This shows that rate of productivity is directly proportional to the temperature of the distilled water. It also shows the amount of heat carried by the distilled water is increasing with its rate of production. With the help of this, total amount of heat carried by makeup water is being calculated as 3%.

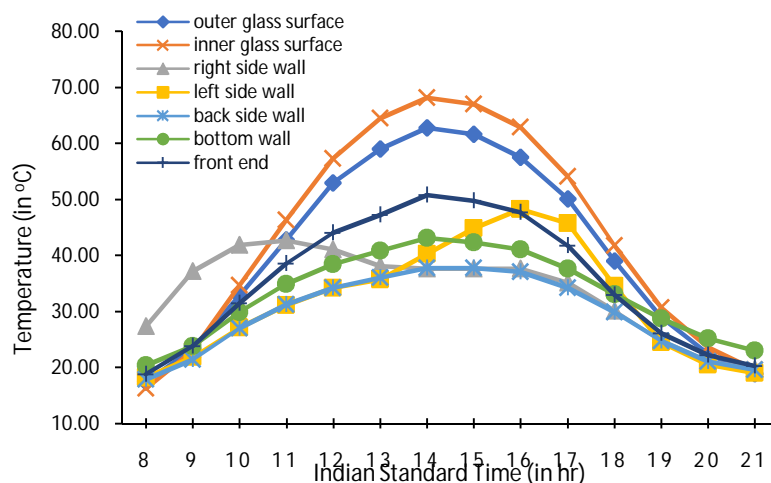


Figure 5: Hourly variation of surface temperature of solar still

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Fig 5. shows the mean temperature curve for different surfaces i.e. outer glass, inner glass surface, left, right side, front, back wall, and bottom surface. In these temp curves, the inner glass temp is higher, as the water vapor, which is generally of higher temp than inner glass surface, condensed at it and loss its heat. Water basin temp. has not shown in this but there was a maximum difference b/w water basin temperature and inner glass surface of 6°C , which means as this difference increased, productivity of distilled water will also increase. There is another 6°C fall from inner to outer glass surface this is because of the poor glass conductivity. In Fig 7. Left side and right walls surface temperature are showing some variation, i.e. from 8am right wall temp. curve at much higher temperature it is because of the solar intensity is falling on the right wall at that time, and similarly after noon this is being shown at left side wall.

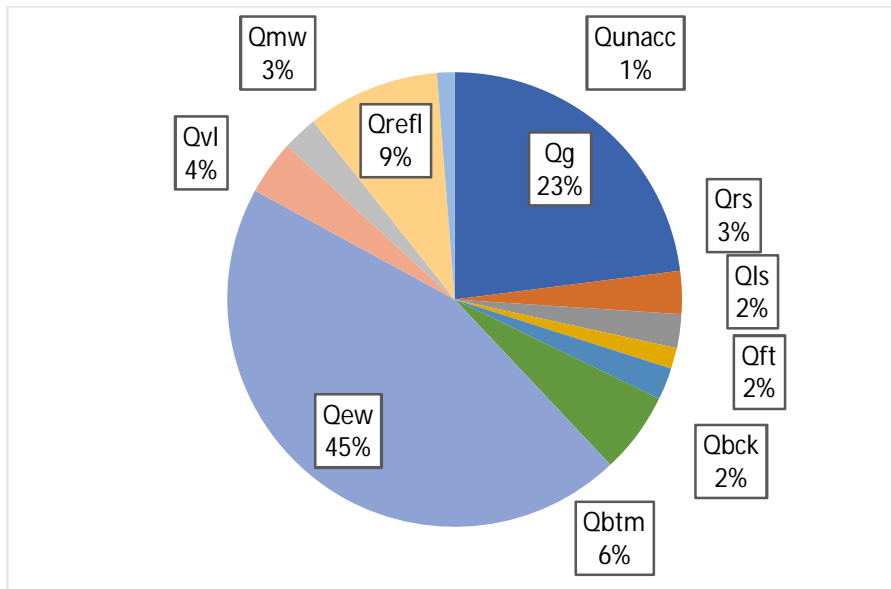


Figure 6: Overall heat balance of single slope solar still

Fig 6. shows the heat balanced pie – chart, showing how the total amount of heat, entered inside the Still during the Sun, is being dispersed out from it, i.e. in the form the evaporation, heated distilled water, vapor loss, and surface losses. Starting from the glass surface to sky heat loss which is 23%, heat loss from right side, left side, front, back, and bottom wall are 3%, 2%, 2%, 2%, and 6% respectively, heat transferred in the evaporation of feed water and of unaccounted vapor loss is 45% and 4% respectively, heat carried by the makeup water is 3%, and losses due to the reflection of the solar radiation from inclined glass surface is 9%, and 1% of unaccounted heat is being noticed, which considered as limitation of experimental work.

VI. CONCLUSIONS

Performance improvement areas for the single slope passive solar still are investigated in this work. Through the above results, we can conclude that some of the areas are there which can be further improved – like bottom surface, i.e. 6% heat loss, which is much more as compare to other surface loss that can be minimum by using more or better insulating material, as to trap this heat in it to allow more evaporation of feed water. Next, vapor losses from the solar still which accounts 4% of total heat, can be covered by improving its packing so as to trap these vapor with in the solar still. Another area of improvement is the reflectivity of the glass i.e. 9% loss, that can be minimize by using anti – reflective

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coated glass, which enable more to surpass the inclined radiation through the glass and allow more heat to enter the Still, which will increase the productivity Solar Still.

Nomenclatures

A	area, m ²
Gr	Grashof no.
g	acceleration due to gravity, m/s ²
h _{fg}	enthalpy of evaporation, J/kg
I(t)	solar radiation on inclined surface, W/m ²
L _c	characteristic length, m
M	total mass, kg
m	mass, kg
Pr	Prandtl no.
Q	heat transfer rate, W
V	velocity, m/s

Subscript

a	air transfer
c	convective mode of heat
g	glass surface
r	radiation mode of heat transfer
v	vapor
L	left surface
R	right surface
bck	back surface
btm	bottom surface
evp	evaporation
ref	reflection
mw	distilled water
vl	vapor loss
un	unaccounted

Greek

ε	emissivity
β	volumetric expansion coefficient, /K
ν	kinematic viscosity, m ² /s
σ	Stefan boltzmann constant, 5.67 W/m ² K ⁴

REFERENCES

- [1] Omara Z.M., Kabeel A.E., Younes M.M., "Enhancing the stepped solar still performance using internal reflectors", Desalination 314 (2013): 67–72.
- [2] Kabeel A.E., Omara Z.M., Younes M.M., "Enhancing the stepped solar still performance using internal and external reflectors", Energy Conversion and Management 78 (2014): 876–881.
- [3] Rajaseenivasan T., and Srithar K., "Performance investigation on solar still with circular and square fins in basin with CO₂ mitigation and economic analysis", Desalination 124 (2015): 89-97.
- [4] Bhardwaj R., Kortenaar M.V., and Mudde R.F., "Inflatable plastic solar still with passive condenser for single family use", Desalination 398, (2016): 151-156.
- [5] Badran A.A., Al-Hallaq A.A., Eyal Salman I.A., and Odat M.Z., "A solar still augmented with a flat-plate collector", Desalination 172, (2005): 227-234.
- [6] Abdul-Wahab S.A., and Al-Hatmi Y.Y., "Study of the Performance of the Inverted Solar Still Integrated with a Refrigeration Cycle", Procedia Engineering 33, (2012): 424-434.
- [7] Panchal H.N., "Enhancement of distillate output of double basin solar still with vacuum tubes", Journal of King Saud University – Engineering Sciences 27, (2015): 170-175.
- [8] Velmurugan V., Pandiarajan S., Guruparan P., Subramanian L.H., Prabakaran C.D., and Srithar K., "Integrated performance of stepped and single basin solar stills with mini solar pond", Desalination 249, (2009): 902-909.
- [9] Sharshir S.W., Peng G., Yang N., Eltawil M.A., Ahmed-Ali M.K., and Kabeel A.E., "A hybrid desalination system using humidification-dehumidification and solar stills integrated with evacuated solar water heater", Energy Conversion and Management 124, (2016): 287–296.
- [10] Patel N. S., Shah R.R., Patel N.M., Shah J.K., and Bhatt S.B., "Effect of various parameters on different types of solar still: case study", International Journal of Innovative Research in Science, Engineering and Technology Vol. 2, (2013): 1726-1731.
- [11] Alaudeen A., Johnson K., Ganasundar P., Abuthahir A.S., and Srithar K., "Study on stepped type basin in a solar still", Journal of King Saud University – Engineering Sciences 27, (2015): 143-150.
- [12] Appadurai M., and Velmurugan V., "Performance analysis of fin type solar still integrated with fin type mini solar pond", Sustainable Energy Technologies and Assessments 9, (2015): 30-36.