THERMAL MODELLING AND PERFORMANCE STUDY OF MODIFIED DOUBLE SLOPE SOLAR STILL

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Abstract

Solar distillation is a process of producing purified drinking water from brackish water by using the heat of solar radiation as the feed to evaporate the impure water which on condensation gives the pure water. It is independent of electricity, a major portion of which is generated from fossil fuel causing environmental pollution and relies completely on renewable source of energy like solar radiation, thus making it environment friendly. In this paper a modified double slope solar still (modified dsss) has been designed by using transparent acrylic and opaque fibre reinforced plastic (frp) as its body material with two toughened glass covers. The basin and north wall of modified dsss have been made by using frp of thickness (0.005 m), whereas, its three sides (east, west and south walls) are made of transparent acrylic sheet of thickness (0.003 m) equivalent to that of frp for the same heat loss, which results in increased input solar radiation inside the solar still and improved performance but with low cost. It is evident that, the inside space of solar still is filled with air and vapour molecules which can come in contact with inner surfaces of walls and glass covers. The vapour molecules close to the walls strike it due to molecular collisions and stick to it to release its heat for phase change from vapour to liquid during condensation process. Hence, five troughs (distillate collecting channels) have been placed at inside surfaces of all its walls and glass covers. The yield has been collected from all the sides of the solar still except north wall which acts heat absorber. The molecules which come in contact with north wall get additional heat from it and get evaporated. In this paper, a thermal model has been developed to predict theoretically the performance of mdsss for the climatic condition of mnnit, allahabad, india on 22nd may 2014. Expressions for water and glass temperatures and hourly yield for the modified double slope solar distillation system have been derived analytically. It has been found that the total yield obtained from the mdsss in a period of 24 hour is 16 kg of purified water from 25 kg of brackish water which is about twice of that obtained from conventional solar stills.

Keywords: *Equivalent Thickness, Molecular Collision, Double Slope Solar Still, Yield*

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1. INTRODUCTION

The availability of fresh water is gradually decreasing from the natural resources due to continually increasing water pollution and receding level of ground water .Various technologies like reverse osmosis (RO), multistage flash (MF) etc., have been developed to provide fresh water. But the major problem concerned with these technologies is that they rely upon electricity a major portion of which is generated from gas or coal based power plants, which also cause environmental pollution. Hence an environment friendly, economical and effective water purification technology like solar distillation is highly desirable for solving today's water scarcity problem.

The performance of solar distillation systems depends on various climatic parameters such as ambient temperature, solar radiation intensity etc., design parameters like inclination angle and operational parameters like orientation of solar still and brine water depth [1-4]. Dunkle [5] has developed several expressions for convective, radiative and evaporative heat transfer coefficients for the solar still. Tiwari et al. [6] have studied the effect of inclination of condensing cover on internal heat and mass transfer in a passive solar distillation system under indoor conditions. Dwivedi and Tiwari have developed a thermal model for double slope active solar still (DSASS) [7]. Shukla and Sorayan [8] have experimentally validated a thermal model of solar stills on the basis of heat transfer coefficients for both summer and winter conditions. Dev and Tiwari [9] have developed the characteristic equation for single slope passive solar still at different water depths and inclinations. Dev [10] has studied various passive and active solar stills to develop their modified thermal models and characteristic equations.

The aim of present work is to design a Modified Double Slope Solar Still (MDSSS) which replaces fiber reinforced plastic (FRP) by acrylic as the body material for the three side walls (East, West and South). The transparency of acrylic increases the input solar radiation in to the still. Hence, a thermal model has been developed to correlate the new design. It has been used to test theoretically the performance of MDSSS for the climatic condition of MNNIT,Allahabad India.

2. EXPERIMENTAL SET UP

Fig. 1 shows the isometric view of experimental set up which is modeled using CATIA V5R18 software. MDSSS consists of a box shaped basin of base area 2m^2. The height of the solar still walls is 0.12 m at the East-West ends and 0.38 m at the centre. The base and North wall are made of FRP of 0.005m thickness which are painted black from inside to increase absorptivity of solar radiation. Three side walls (East, West and South) are made of acrylic of 0.003m thickness equivalent to that of FRP for same heat loss. Toughened glass is used as the building material for two glass covers of dimensions 1.03×1.03×0.004 m^3 to ensure reliable and harmless operation. Two glass covers are placed on the walls of the solar still with an inclination angle of 15°. This angle is maintained to allow maximum solar radiation to be incident on the glass covers when the sun is in either east or west direction and to guide the condensate under the combined effect of gravity, adhesion and cohesion forces. Brackish water is supplied in to the still through an inlet provided at the north wall. Five troughs have been placed at the inside surface of the walls and glass covers to collect the distillate and guide it in to the collecting jars placed outside. No condensate is obtained from north wall, as the vapour molecules striking it get additional heat from it.

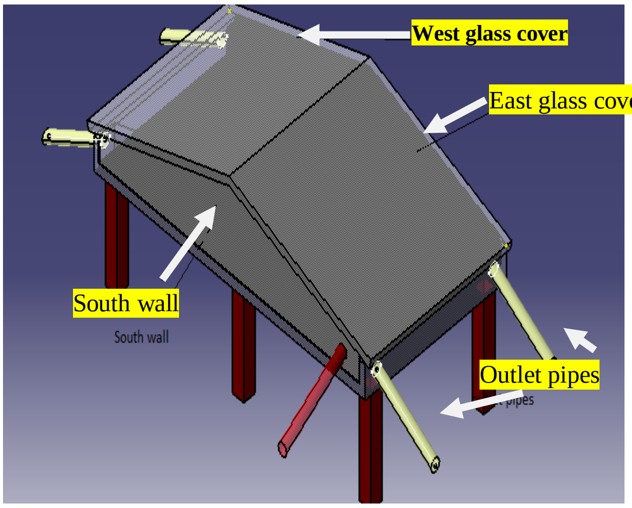

Fig.1. Isometric View of MDSSS

3. METHODOLOGY

Research methodology deals with detailed description of working principle (modified) and complete thermal model.

3.1 Working Principle

The space enclosed by the solar still consists of a large number of air and water vapor molecules. These molecules are in random motion and may come in contact with the inside surfaces of the walls and glass covers. Early in the morning when the sun rises solar radiation is incident on the water inside the still through the transparent acrylic walls. The temperature inside the still increases causing a rise in molecular kinetic energy. Hence, the molecules undergo rapid collision with each other. As a result the vapor molecules close to the walls stick to it and release heat through the process of condensation to undergo phase change from vapor to liquid state.

Hence, yielding starts very early unlike the conventional stills which produce distillate only when sufficient solar radiation is incident on the glass covers (due to opaque FRP walls). As the sun moves toward west due south, more solar radiation is incident on the walls and glass covers. A large fraction of this radiation is absorbed by the basin liner and the north wall due to high absorptivity. Heat is transferred from basin to water by convection which evaporates the water. The vapor molecules come in contact with the walls and glass covers through molecular collision and condensation process continues. The condensate is guided by the troughs to the collecting jars placed outside.

Various design and operational parameters have been listed in Table 1. Table 2 shows the instruments used for measuring temperature and solar radiation along with their specifications. The distillate obtained from the MDSSS has been calculated on hourly basis for the date of 22nd May, 2014 for the climatic condition of MNNIT, Allahabad, India.

3.2 Thermal Modeling

The energy balance equation for different components of MDSSS has been formulated based on the following assumptions.

[1]. MDSSS is vapor leakage proof and is in quasi steady state.

[2]. There is no temperature gradient in the water inside the basin.

[3]. Heat capacities of glass and basin material are negligible.

[4]. Temperature dependent heat transfer coefficients have been considered.

[5]. A hypothetical vapor surface is assumed inside the still from which all the heat interactions to the condensing surfaces take place.

Table 1: Design and operational parameters of MDSSS.

Sl.no	Type	Specification	
1	location	MNNIT, Allahabad, India	
2	Specification of location	25 ° 23' N, 81° 52' E altitude 101m from sea level	
3	Climate	warm and humid	
4	Orientation	East – west	
5	Body material	Base and north wall made of FRP, other three walls of acrylic, east and west glass covers of	

		toughened glass	
6	Basin area and colour	2 m^2 , black	
7	Thickness of GRP	0.005m	
8	Thickness of acrylic	0.003m	
9	Height at ends	0.12m	
10	Height at centre	0.38m	
11	Toughened glass	1.03 x 1.03 x 0.004 m^3	
12	Quantity of glass	2	
13	Inclination angle	15^0	
14	Colour of north wall inside	Black	
15	Number of inlet to saline water	1	
16	No. of outlets connected with trough at ends	5	
17	Latent heat of vaporization (L)	2390 x 10^3 J/kg	
18	Water depth	1.25 cm	
19	Specific heat of water(C_w)	4200J/kgK	
20	Mass of water(M)	25 kg	
21	Wind velocity(v)	0-20 m/s	
22	K_{FRP}	0.351 W/mK	
23	K_g	0.78 W/mK	
24	K_{AC}	0.2 W/ mK	
25	α'_{bg}	0.8	
26	α'_g	0.1	
27	α'_{wg}	0.6	
28	ε_g	0.8	
29	ε_w	0.95	
31	U_{bw}	300 W/ mK	
32	α'_{bac}	0.77	
33	α'_{Ng}	0.7	

Table 2: Description of measuring instruments.

Instrument	Range
Solarimeter	Resolution 20 W/m^2 , range 0-1200 W/m^2
Digital temperature indicator	Resolution 0.1^{o}C,range -20^o to 450 ^{o}C
Calibrated mercury thermometer	Resolution 1 ^{o}C, range 0-120 ^{o}C
Calibrated thermocouples	Copper constantan(T type), measuring range -200 ^{o} to 450 ^{o}C
Measuring jar	Resolution 10 ml , range 0-100 ml

Energy balance equation for different components of MDSSS:

a. For inner surface of north wall

$$\alpha'_{Ng} \, . \, A_N.I(t)_{gN} = h_{Nv} \, .A_N. \, (T_{iN}-T_v) + h_{KFRP}. \, A_N \, (T_{iN}-T_{oN}) \quad \textbf{(1)}$$

b. For outer surface of north wall

$$h_{KFRP}. \, A_N \, (T_{iN}-T_{ON}) = h_o.A_N \, (T_{ON} - T_a) \quad \textbf{(2)}$$

For inner surface of south wall

$$\alpha'_S.A_S. \, I(t)_{acS} + h_{vS} \, .A_S.(\, T_v - T_{iS}) = h_{Kacr}.A_S. \, (T_{iS}-T_{oS}) \quad \textbf{(3)}$$

c. For outer surface of south wall

$$h_{Kacr}.A_S. \, (T_{iS}-T_{oS}) = h_o.A_S \, .(T_{oS}-T_a) \quad \textbf{(4)}$$

d. For inner surface of east wall

$$\alpha'_E.A_E. \, I(t)_{acE} + h_{vE} \, .A_E.(\, T_v - T_{iE}) = h_{Kacr}.A_E. \, (T_{iE}-T_{oE}) \quad \textbf{(5)}$$

e. For outer surface of east wall

$$h_{Kacr}.A_E. \, (T_{iE}-T_{oE}) = h_o.A_E.(T_{oE}-T_a) \quad \textbf{(6)}$$

f. For inner surface of west wall

$$\alpha'_W.A_W. \, I(t)_{acW} + h_{vW} \, .A_W.(\, T_v - T_{iW}) = h_{Kacr}.A_W. \, (T_{iW}-T_{oW}) \quad \textbf{(7)}$$

g. For outer surface of west wall

$$h_{Kacr}.A_W. \, (T_{iW}-T_{oW}) = h_o.A_W.(T_{oW}-T_a) \quad \textbf{(8)}$$

h. For inner surface of east glass cover

$$\alpha'_g.A_E. \, I(t)_{gE} + h_{vgE} \, .A_{gE}.(\, T_v - T_{giE}) = h_{Kg}.A_{gE}. \, (T_{giE}-T_{goE}) \quad \textbf{(9)}$$

i. For outer surface of east glass cover

$$h_{Kg}.A_{gE}. \, (T_{giE}-T_{goE}) = h_o.A_{gE}.(T_{goE}-T_a) \quad \textbf{(10)}$$

j. For inner surface of west glass cover

$$\alpha'_g.A_{gW}. \, I(t)_{gW} + h_{vgW} \, .A_{gW}.(\, T_v - T_{giW}) = h_{Kg}.A_{gW}. \, (T_{giW}-T_{goW}) \quad \textbf{(11)}$$

k. For outer surface of west glass cover

$$h_{Kg}.A_{gW}. \, (T_{giW}-T_{goW}) = h_o.A_{gW}.(T_{goW}-T_a) \quad \textbf{(12)}$$

l. For vapour

$h_{wv}. \, A_b \, . \, (T_w - T_v) + h_{Nv} \, . \, A_N \, (T_{iN} - T_v) = h_{vS} \, . \, A_S(T_v - T_{iS}) +$

$h_{vE}.A_E.(T_v - T_{iE}) + h_{vW}.A_W.(T_v - T_{iW}) + h_{vgE}.A_{gE}.(T_v - T_{giE}) + h_{vgW}.A_{gW}.(T_v - T_{giW})$ **(13)**

n. For water

$\alpha'_{wg}.A_b.\{I(t)_{gE} + I(t)_{gW}\} + \alpha'_{wac}.A_b.\{I(t)_{acE} + I(t)_{acW} + I(t)_{acS}\} + h_{bw}.A_b.(T_b - T_w) = (MC)_w.\frac{dT_w}{dt} + h_{wv}.A_b.(T_w - T_v) + h_s.A_s.(T_w - T_a)$

(14)

o. For basin

$\alpha'_{bg}.A_b.\{I(t)_{gE} + I(t)_{gW}\} + \alpha'_{bac}.A_b.\{I(t)_{acE} + I(t)_{acW} + I(t)_{acS}\} = h_{bw}.A_b.(T_b - T_w) + h_{ba}A_b(T_b - T_a)$ **(15)**

Solution of the above equations gives a differential equation for water temperature as given below.

$$\frac{dT_w}{dt} + aT_w = f(t)$$

(16)

Solving the above equation we get the expression for water temperature:

$$T_w = \frac{\overline{f(t)}}{a}.(1 - e^{-at}) + T_{wo}.e^{-at}$$

(17)

From T_w the expressions for vapor temperature and west wall temperature have been derived as follows:

$$T_v = -\frac{A_1}{A_2} + \frac{T_w}{A_2}$$

(18)

$$T_{iW} = \left(\frac{R_4}{U_4} - \frac{h_{vW}.A_1}{U_4.A_2}\right) + \frac{h_{vW}}{U_4.A_2}T_w$$

(19)

Similar expressions for other temperatures have been obtained .

The hourly yield from West wall of the solar still can be calculated with the help of the following equation

$$\dot{M}_{evW} = \frac{\dot{q}_{evW} \times 3600}{L} = \frac{h_{evW} \times 3600}{L}$$

(20)

Where h_{evW} is the evaporative heat transfer coefficient between vapor and West wall, and L is the latent heat of water. Similarly the yield from other two walls and glass covers are obtained and their summation gives the total yield. Total yield in the period of 24 hour is calculated as per the following equation,

$$\sum_{i=1}^{24}\dot{M}_{evE} + \sum_{i=1}^{24}\dot{M}_{evW} + \sum_{i=1}^{24}\dot{M}_{evS} + \sum_{i=1}^{24}\dot{M}_{evgE} + \sum_{i=1}^{24}\dot{M}_{evgW}$$

(21)

3. RESULTS AND DISCUSSION

Fig.2 shows the hourly variation of incident solar radiation on East and West glass Cover. It is evident from the figure that, the incident solar radiation on East and West glass cover nearly remains same during noon hours (from 11:00 AM to 1:00 PM). Before noon the East glass cover is subjected to more solar radiation. As sun moves towards west incident radiation on west glass cover increases. The maximum solar radiation incident on East and West glass cover are 1083.7W/m^2 and 1181W/m^2 respectively.

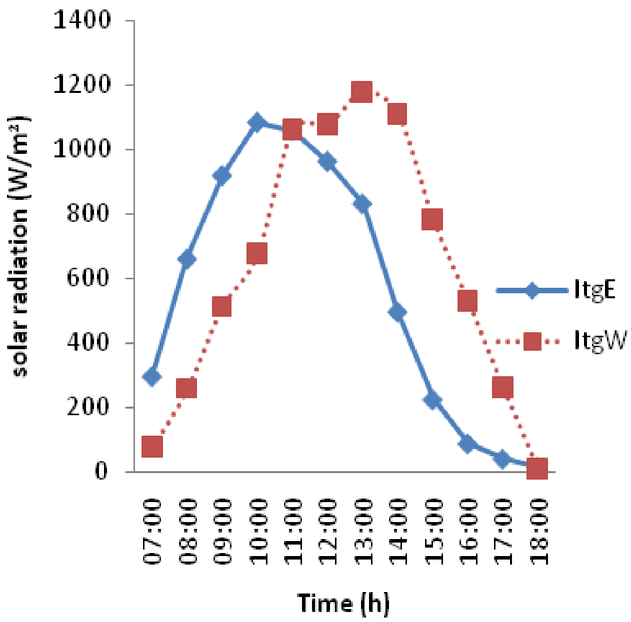

Fig. 2. Solar Flux variation on East and West glass cover on May 22, 2014, at MNNIT,Allahabad

Fig. 3 shows hourly variation of water, ambient and vapor temperature. The water temperature is always greater than the vapor temperature which is more than the ambient temperature.

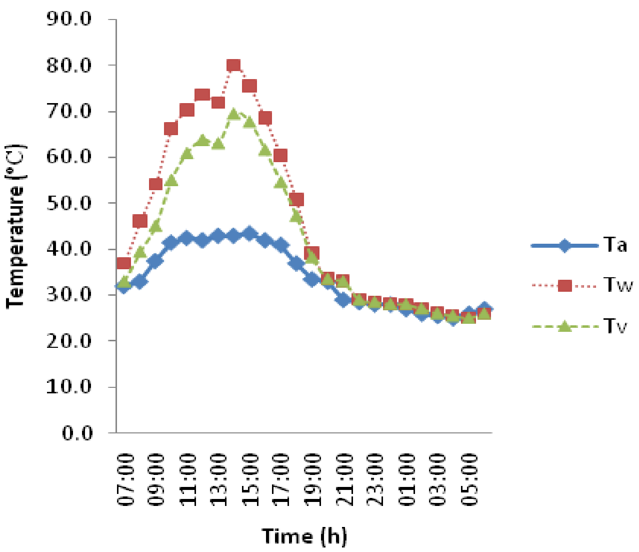

Fig.3. Hourly variation of water, ambient and vapor temperatures on May 22,2014 at MNNIT,Allahabad

Fig.4 shows the hourly variation of total distillate obtained from walls and glass covers of MDSSS for a water depth of 1.25 cm. From the figure we can observe that amount of yield obtained gradually increases, becomes maximum during noon hour and then decreases. The total yield obtained from the MDSSS (from walls and glass covers) for a water depth of 1.25 cm in a period of 24 hours is 16 Kg, which is more than that obtained from conventional solar stills with FRP walls.

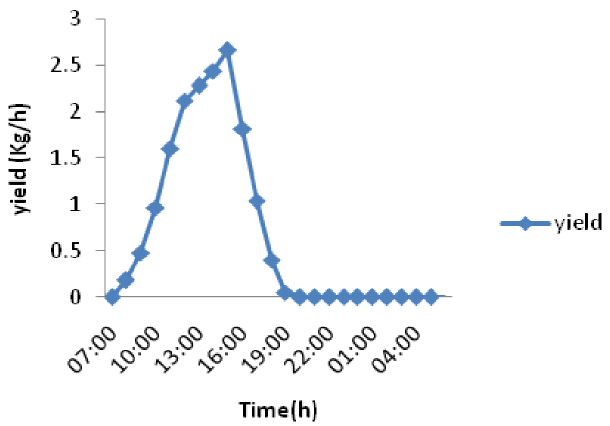

Fig.4. variation (hourly) of distillate on May 22, 2014 at MNNIT,Allahabad

4. CONCLUSION

On the basis of above analysis, it is being observed that more yield has been achieved after modifying the conventional double slope solar still (replacing opaque FRP walls by transparent acrylic walls of equivalent thickness). The hourly variation of inner surface temperature of walls and glass covers, and total yield have been found similar to that of conventional stills (9-11). The thermal modeling designed for MDSSS can be used to test its performance for different operational and climatic parameters.

NOMENCLATURE

A_b	Basin area (m^2)
A_{gE}	Area of the East glass cover (m^2)
A_{gw}	Area of the west glass cover (m^2)
A_E	Area of East wall (m^2)
dt	Small time interval (s)
A_W	Area of West wall (m^2)
A_S	Area of South wall (m^2)
A_N	Area of North wall (m^2)
$I(t)_{gN}$	Solar intensity on north wall (W/ m^2)
$I(t)_{gE}$	Solar intensity on east glass cover(W/ m^2)
$I(t)_{gW}$	Solar intensity on west glass cover(W/ m^2)
$I(t)_{acE}$	Solar intensity on east wall (W/ m^2)
$I(t)_{acW}$	Solar intensity on west wall (W/ m^2)
$I(t)_{acS}$	Solar intensity on south wall (W/ m^2)
K_g	Thermal conductivity of glass cover (w/ mk)
Kac	Thermal conductivity of acrylic wall (w/ mk)
K_{FRP}	Thermal conductivity of FRP wall (W/ mk)
L_g	Thickness of glass cover (m)
L_{acr}	Thickness of acrylic wall (m)
L_{FRP}	Thickness of FRP wall (m)
T_a	Ambient air temperature (°C)
T_v	Vapor temperature (°C)
T_w	Water temperature (°C)
T_b	Basin temperature (°C)
T_{iE}	Inner wall temperature of east side (°C)
T_{iW}	Inner wall temperature of west side (°C)
T_{iS}	Inner wall temperature of south side (°C)
α'_g	Solar flux absorption factor for toughened glass
α'_E	Solar flux absorption factor for East wall
α_W	Solar flux absorption factor for west wall
C	Specific heat of water (J/Kg °C)
dt_w/dt	Change in water temp. In small time (°C/s)
h_{ba}	Conductive heat transfer coefficient from basin to ambient (W/m^2 °C)
h_{bw}	Convective heat transfer coefficient from basin to water (W/m^2 °C)
h_{go}	Combined convective and radiative heat transfer coefficient from inner surface of glass cover to ambient (W/m^2 °C)
h_{aco}	Combined convective and radiative heat transfer coefficient from inner surface of acrylic wall to ambient (W/m^2 °C)
h_{Kg}	Conductive heat transfer coefficient of glass cover (W/m^2 °C)
h_{Kacr}	Conductive heat transfer coefficient of acrylic wall (W/m^2 °C)
h_{KFRP}	Conductive heat transfer coefficient of FRP (W/m^2 °C)
h_s	Heat transfer coefficient of side wall (W/m^2 °C)
h_o	Total convective and radiative heat transfer coefficient from wall and glass cover to ambient (W/m2 °C)
h_{vW}	Total internal heat transfer coefficient from vapor to west wall (W/m^2 °C)

h_{vS}	Total internal heat transfer coefficient from vapor to South wall (W/m^2 °C)
h_{vgE}	Total internal heat transfer coefficient from vapor to east glass cover (W/m^2 °C)
h_{vgW}	Total internal heat transfer coefficient from vapor to west glass cover (W/m^2 °C)
h_{evE}	Internal evaporative heat transfer coefficient from vapor to east wall (W/m^2 °C)
h_{vE}	Total internal heat transfer coefficient from vapor to east wall (W/m2 °C)
T_{giW}	Inner glass cover temperature of west side (°C)
T_{wo}	Water temperature at time t=0 (°C)
v	Wind velocity (m/s)

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BIOGRAPHIES

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Mr. Rahul Dev is currently working as assistant professor in depart of mechanical engineering in Motilal Neheru National Institute of Technology. He is an eminent researcher in the field of solar energy and Solar thermal technology. He has completed his Phd. from IIT Delhi in 2012. He is involved in so many research projects (govt undertaking and also consultancy). His area of research includes Solar Energy Applications, Renewable Energy, Solar Passive Architecture etc.