Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Performance investigation of combined solar desalination and hot water system

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Abstract

Water treatment using solar thermal energy is more attractive for rural and remote communities as both desalination and detoxification can be carried out effectively in a single unit. In the present investigation, a hybrid solar still which has the capability to generate both potable water and hot water has been proposed and its performance has been simulated using transient mathematical modeling. The proposed still incorporates both inclined still and conventional basin type still and is ease of construction. The distillate yield from the proposed system is nearly 107 % higher than conventional inclined type solar still. The optimum gap between evaporating and condensing surface is 0.10 m. The optimum thickness of fluid film and depth of water in the basin is 0.001 m and 0.01 m. The unit is capable of generating 7.12 kg/d of distillate. The average temperature of hot water generated by the unit during summer and winter is 56.28 ˚ C and 45.09 ˚ C, respectively. The average overall efficiency of the unit is around 67.018 % and 59.61 % during summer and winter, respectively. The unit is found to meet the drinking water and hot water requirements of remote and rural communities.

Keywords: *solar distillation, hybrid still, hot water, potable water*

1. Introduction

Rapid growth in population and change in life style of human beings along side with industrialization has increased the demand for fresh water. Available limited fresh water bodies are being polluted continuously making them unfit for human consumption. The increasing demand of fresh water can be met by desalination of saline water which is available in plenty (Tabrizi et al., 2010a). Large number of desalination units fueled by conventional energy sources is being operated throughout the world but their negative impacts on atmosphere and marine environment makes their sustainability questionable (Younos and Tulou, 2005; Jijakli et al., 2012). Nearly, 40% of the mother earth's land is arid and semi-arid; supplying treated water from decentralized distillation units to these regions is found to uneconomical. But, these regions are blessed with abundant solar energy which can be used as a source to desalinate saline water for human consumption and domestic usage (Mink et al., 1998).

Solar basin type stills have been widely studied and depth of water in the evaporation basin plays a major role in their yield (Mathioulakis and Belessiotis, 2003; Khalifa and Hamood, 2009). Compared to basin stills, inclined solar stills are cheap, portable and can produce more distillate for the same absorber area (Sodha et al., 1981). Different techniques have been adopted by researchers around the globe to enhance the yield of inclined stills. Techniques like reduction of feed water mass flow rate (Aybar et al., 2005), shading of glass cover (Deniz, 2013), use of external reflectors (Tanaka and Nakatake, 2009; Tanaka, 2009), construction of weirs for increasing the residence time of water in the absorber plate (Ziabari et al., 2013) and lining of absorber plate with wicks (Hansen et al., 2015) have helped to enhance the yield of inclined stills. Phase change materials based storage units have also been integrated with inclined stills for their distillate yield

doi:10.18086/swc.2015.10.47 Available at http://proceedings.ises.org

enhancement. Phase change material based units are costly and are recommended only for cloudy weather conditions (Tabrizi et al., 2010b). It could be seen that the productivity of conventional basin type stills and vertical stills have been enhanced to large extent by making them to operate under active mode (Sampathkumar et al., 2010; Sharon and Reddy, 2015).

However, the work associated with enhancement of distillate yield from inclined stills by active mode operation is very scarce in literature and is available as a gap. Distillation units capable of producing both potable water and hot water would be of great beneficial for rural and remote locations which can be achieved by active mode operation of inclined solar stills. Omara et al., (2013) has reported that the yield from the inclined still can be enhanced by 114% by supplying the unit with preheated feed water from Evacuated Tube Collectors (ETCs). However, distillation units with low cost, simplicity and low maintenance are very important for rural based applications. Hence, in this work a hybrid solar distillation unit has been proposed which combines both inclined still and conventional still for better performance.

2. System description

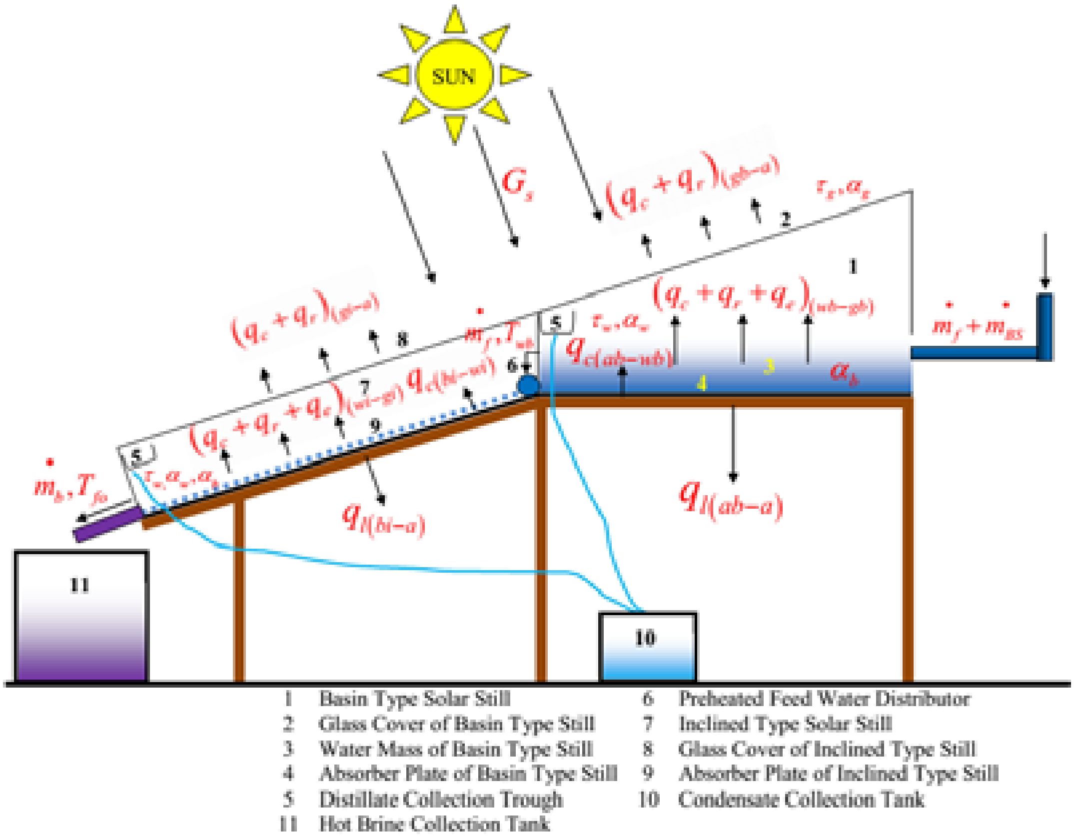

Fig. 1: Schematic represenation of the hybrid solar still along with the necessary energy transport processes

The schematic representation of the proposed hybrid solar still along with necessary energy transport processes is depicted in **Fig.1**. In the proposed system, active mode of operation of inclined still is achieved by coupling inclined still (1 m^2 area) with conventional basin type solar still (1 m^2 area). The inclination of glass cover of basin type still and inclined still is 13° facing south, corresponding to the local latitude considered in this study. The integrated conventional basin type solar still acts as feed water storage and preheating unit. Preheated feed water from conventional basin type still is allowed to flow as thin over the absorber plate of inclined solar still. The absorber plate of inclined still heat ups the preheated feed water to high temperature by receiving additional solar radiation hence enhanced evaporation begins and the condensate is collected using suitable provisions. The high temperature operation of distillation unit favors efficient removal of bacteria (Sodha et al., 1981) hence the rejected hot water from inclined still can be used for domestic purposes (Aybar, 2006). Additional distillate is also obtained from conventional basin type still. The effect of gap between condensing and evaporating surface of inclined still, thickness of fluid film, mass flow rate of feed, depth of water in the basin for summer and winter seasons on distillate yield has been simulated using the developed transient mathematical model.

3. Mathematical modeling of the proposed unit

The major assumptions that have been considered during modeling of hybrid still are given below:

a) The unit is air tight and free from vapor leakage
b) The heat capacity of glass cover, absorber plate and water mass are considered
c) There is no temperature gradient across the thickness of glass cover and water mass
d) The water level in the preheating unit (conventional still) is always maintained constant by supplying feed water
e) Heat transfer from the evaporating surface to the condensing surface is by convection, radiation and evaporation
f) Heat loss to the ambient is by convection and radiation from the glass cover and by conduction through the insulation

The energy transport process for different components of the proposed unit is given below:

Basin liner of Integrated Single Slope Still (ISSS),

$$(MC)_{ab}\frac{dT_{ab}}{dt} = G_s\tau_g\tau_w\alpha_p A_{ab} - q_{c(ab-wb)} - q_{l(ab-a)} \qquad (eq. 1)$$

Water mass of Integrated Single Slope Still (ISSS),

$$(MC)_{wb}\frac{dT_{wb}}{dt} = G_s\tau_g\alpha_w A_{wb} + q_{c(ab-wb)} + (\dot{m}_f + \dot{m}_{BS})C_{pw}T_{fi} - (q_c + q_r + q_e)_{(wb-gb)} - \dot{m}_f C_{pw}T_{wb} \qquad (eq. 2)$$

Glass cover of Integrated Single Slope Still (ISSS),

$$(MC)_{gb}\frac{dT_{gb}}{dt} = G_s\alpha_g A_{gb} + (q_c + q_r + q_e)_{(wb-gb)} - (q_c + q_r)_{(gb-a)} \qquad (eq. 3)$$

Basin liner of Active Inclined Still (AIS),

$$(MC)_{ai}\frac{dT_{ai}}{dt} = G_s\tau_g\tau_w\alpha_p A_{ai} - q_{c(ai-wi)} - q_{l(ai-a)} \qquad (eq. 4)$$

Water mass of Active Inclined Still (AIS),

$$(MC)_{wi}\frac{dT_{wi}}{dt} = G_s\tau_g\alpha_w A_{wi} + q_{c(ai-wi)} + \dot{m}_f C_{pw}T_{wb} - (q_c + q_r + q_e)_{(wi-gi)} - \dot{m}_b C_{pb}T_{fo} \qquad (eq. 5)$$

Glass cover of Active Inclined Still (AIS),

$$(MC)_{gi}\frac{dT_{gi}}{dt} = G_s\alpha_g A_{gi} + (q_c + q_r + q_e)_{(wi-gi)} - (q_c + q_r)_{(gi-a)} \qquad (eq. 6)$$

Convective heat transfer between the basin liner and water is given as,

For basin type still, (Zurigat and Abu-Arabi, 2004)

$$q_{c(ab-wb)} = 135.0A_{ab}(T_{ab} - T_{wb}) \qquad (eq. 7)$$

For inclined type still,

$$q_{c(ai-wi)} = h_{c(ai-wi)}A_{ai}(T_{ai} - T_{wi}) \qquad (eq. 8)$$

Convective heat transfer coefficient between the basin liner and flowing feed water film is given as, (El-Samadony and Kabeel, 2014)

$$h_{c(ai-wi)} = 0.664\frac{k_f}{L}Re_L^{\frac{1}{2}}Pr_f^{\frac{1}{3}}$$

If $Re_L \leq 500000$

$$h_{c(ai-wi)} = 0.037\frac{k_f}{L}\left(Re_L^{\frac{4}{5}} - 871\right)Pr_f^{\frac{1}{3}}$$

If $Re_L \geq 500000$

Convective heat transfer between evaporating and condensing surface of basin type still is given as,

$$q_{c(wb-gb)} = h_{c(wb-gb)}A_{wb}\left(T_{wb} - T_{gb}\right) \quad (eq.9)$$

Heat transfer coefficient is estimated as, (Hongfei et al., 2002)

$$h_{c(wb-gb)} = 0.2Ra'^{0.26}\frac{k_{av}}{w}$$

Evaporative heat transfer between evaporating and condensing surface of basin type still is given as,

$$q_{e(wb-gb)} = \dot{m}_{BS}h_{fg} \quad (eq.10)$$

Distillate yield is given as, (Hongfei et al., 2002)

$$\dot{m}_{BS} = \frac{h_{c(wb-gb)}}{\rho_{av}C_{pav}Le^{(1-0.26)}}\frac{M_v}{R}\left(\frac{P_{wb}}{T_{wb}} - \frac{P_{gb}}{T_{gb}}\right)A_{wb}$$

Radiative heat transfer between evaporating and condensing surface of basin type of still is given as,

$$q_{r(wb-gb)} = \frac{\sigma A_{wb}\left(T_{wb}^4 - T_{gb}^4\right)}{\left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)} \quad (eq.11)$$

Heat loss from the absorber plate to the ambient through insulation is given as,

$$q_{l(ab-a)} = k_d A_{ab}\frac{(T_{ab} - T_a)}{x_d} \quad (eq.12)$$

Convective heat transfer between the glass cover of basin type still and ambient is given as, (Zurigat and Abu-Arabi, 2004)

$$q_{c(gb-a)} = \left(2.8 + (3V)\right)A_{gb}\left(T_{gb} - T_a\right) \quad (eq.13)$$

Radiative heat transfer between the glass cover of basin type still and ambient is given as,

$$q_{r(gb-a)} = \sigma\varepsilon_g A_{gb}\left(T_{gb}^4 - T_a^4\right) \quad (eq.14)$$

The convective, evaporative and radiative heat transfer occurring in the inclined still is found by replacing $(wb - gb)$ by $(wi - gi)$ in eq. 9 to eq. 11 and $(gb - a)$ by $(gi - a)$ in eq.12 to eq. 14.

The distillation efficiency is given as,

$$\eta_{di} = \frac{(\dot{m}_{BS} + \dot{m}_{is}) \times h_{fg} \times \Delta t}{\left(G_s \times \Delta t \times \left(A_{gb} + A_{gi}\right)\right)} \times 100 \quad (eq.15)$$

The overall efficiency is given as,

$$\eta_o = \frac{\left[\left(\dot{m}_b C_{pb}\left(T_{fo} - T_a\right)\right) + \left((\dot{m}_{BS} + \dot{m}_{is}) \times h_{fg}\right)\right] \times \Delta t}{\left[G_s \times \Delta t \times \left(A_{gb} + A_{gi}\right)\right]} \times 100 \quad (eq.16)$$

The above mentioned differential equations eq. 1 to eq. 6 were first discretized using finite difference method and were converted into algebraic equations. The obtained algebraic equations were solved using iteration method using the program written in FORTRAN language. The necessary input files were fed as separate file for solving the equations. The time step size and convergence criteria were kept as 10 s and 0.001, respectively. The solar radiation profile for Chennai location was simulated using the method given by (Katiyar and Pandey, 2011). The monthly average wind velocity and hourly ambient temperature for the months of April and December were used for simulation.

4. Results and discussion

Effect of different parameters on the performance of the hybrid still was simulated for summer and winter months and is presented in this section. The solar radiation profile simulated for the month of April and December along with the ambient temperature is shown in **Fig. 2**. The maximum solar radiation was around 896.27 W/m^2 and 661.54 W/m^2 for summer and winter months, respectively.

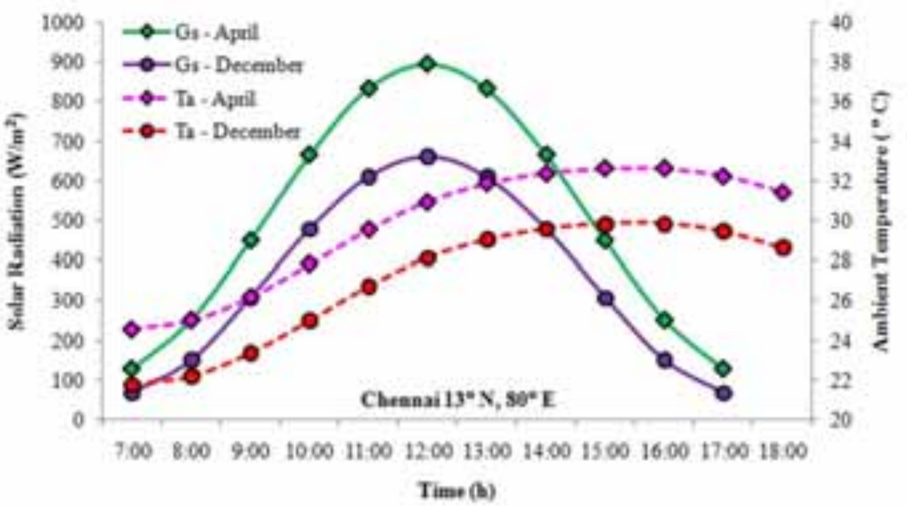

Fig. 2: Solar radiation and ambient temperature profile of Chennai during April and December

4.1. Gap between evaporating and condensing surface

The simulation was carried out for the month of April and December for 0.05 m feed water depth in basin, 0.005 kg/s feed water mass flow rate and 0.002 m fluid film thickness in inclined still. The impact of gap between the evaporating and condensing surface on the distillate yield of active inclined still during summer and winter is shown in **Fig. 3**. The yield is found to decrease from 3.11 kg/m^2-d to 2.44 kg/m^2-d with the increase in gap from 0.05 m to 0.50 m during summer. Increase in gap denotes increased air volume within the system which acts as resistance to the transfer of vapors from the evaporating surface to the condensing surface. The yield is found to decrease by 21.79 % and 25.58 %, during summer and winter with the increase in gap from 0.05 m to 0.50 m. The distillate yield during summer and winter for a gap of 0.05 m is only 6.87 % and 8.86 % higher than the yield for a gap of 0.10 m. The optimum gap can be kept as 0.10 m by considering operation and maintenance point of view.

4.2. Thickness of feed water film and mass flow rate

The simulation was carried out for the month of April and December for 0.05 m feed water depth in basin, 0.10 m gap between condensing and evaporating surface and mass flow rate of 0.005 kg/s. The impact of thickness of fluid film on the distillate yield of active inclined still during summer and winter is shown in **Fig. 4**. The yield is found to decrease from 2.94 to 2.80 kg/m^2-d while increasing the thickness of fluid film from 0.001 m to 0.01 m during summer and from 1.60 to 1.53 kg/m^2-d during winter for a mass flow of 0.005 kg/s. As the thickness increases, heat capacity of fluid film increases leading to reduced heat transfer from the absorber plate to the fluid film. Hence, it is necessary to maintain reduced fluid film thickness for the inclined still for better yield. The thin fluid film can be achieved by spreading thin metal wire mesh or porous cloth of required thickness over the absorber plate and allowing feed water to drip over these surfaces (Aybar, 2006).

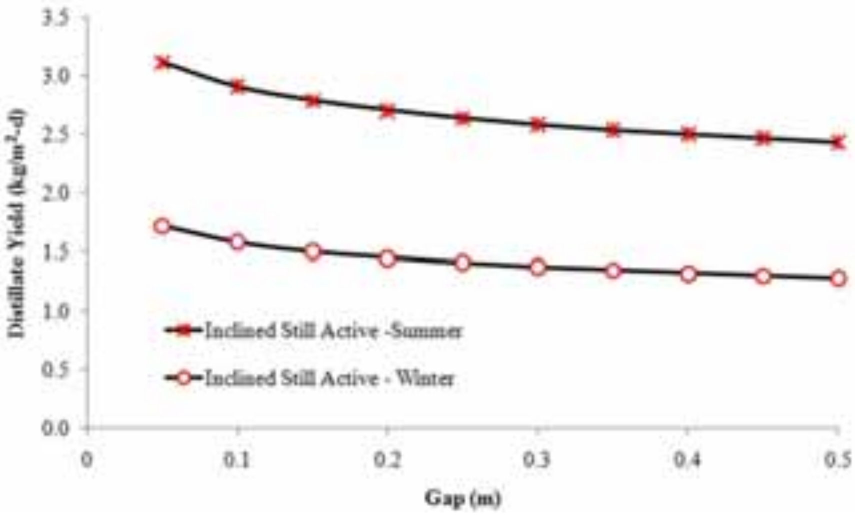

Fig. 3: Impact of gap between evaporating and condensing surface on distillate yield of active inclined still

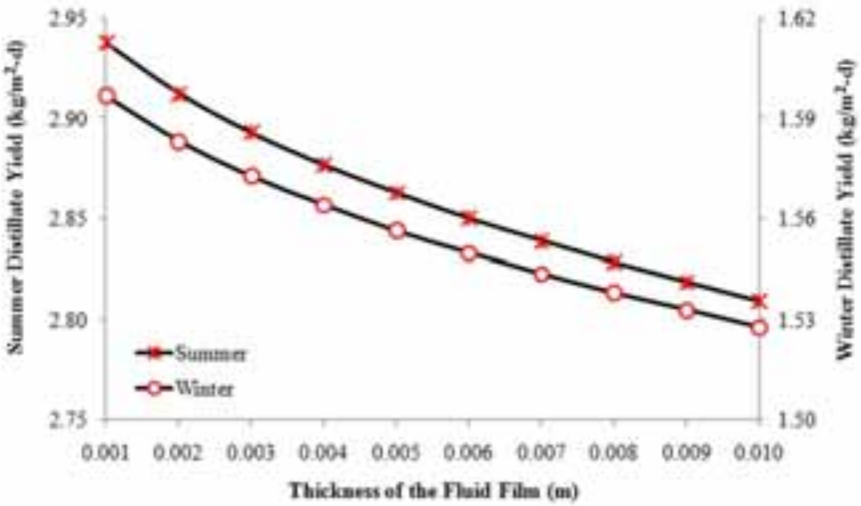

Fig. 4: Impact of thickness of fluid layer on distillate yield of active inclined still

The simulation was carried out for the month of April and December for 0.05 m feed water depth in basin, 0.10 m gap between condensing and evaporating surface and 0.001 m fluid film thickness in inclined still. The impact of mass flow rate of feed water on the distillate yield of the active inclined still is shown in **Fig. 5**. The yield is found to decrease from 9.10 kg/m^2-d to 1.24 kg/m^2-d with the increase in mass flow rate from 0.001 kg/s to 0.01 kg/s, during summer. At lower mass flow rates, the operating temperature will be higher leading to increased evaporative heat transfer and yield. At higher mass flow rates, the residence time of the feed water inside the distillation unit decreases leading to lower heat transfer from the absorber plate to water film causing reduced yield (Tabrizi et al., 2010a). The mass flow rate must be selected properly such that the feed water wets the entire absdorber plate and prevents the formation of dry patches on the surface. For a mass flow rate of 0.003 kg/s, the yield is found to be around 4.82 and 2.59 kg/m^2-d during summer and winter, respectively.

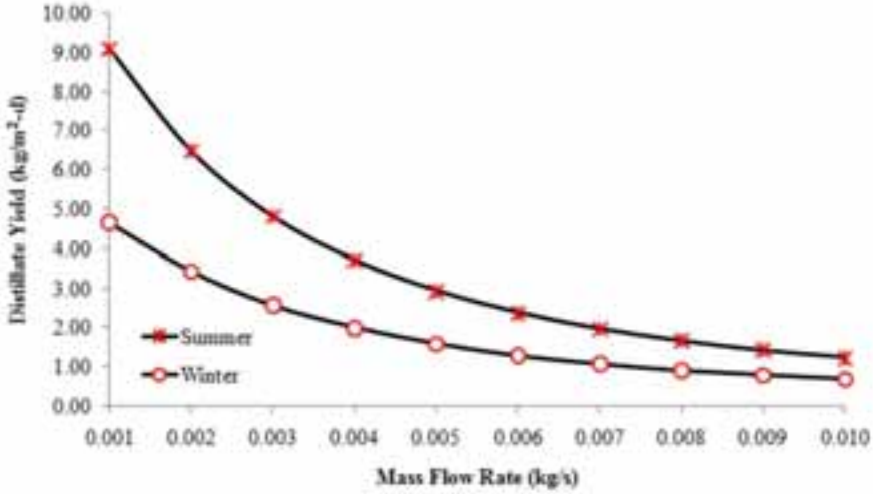

Fig. 5: Impact of mass flow rate of feed water on distillate yield of active inclined still

4.3. Depth of feed water in basin

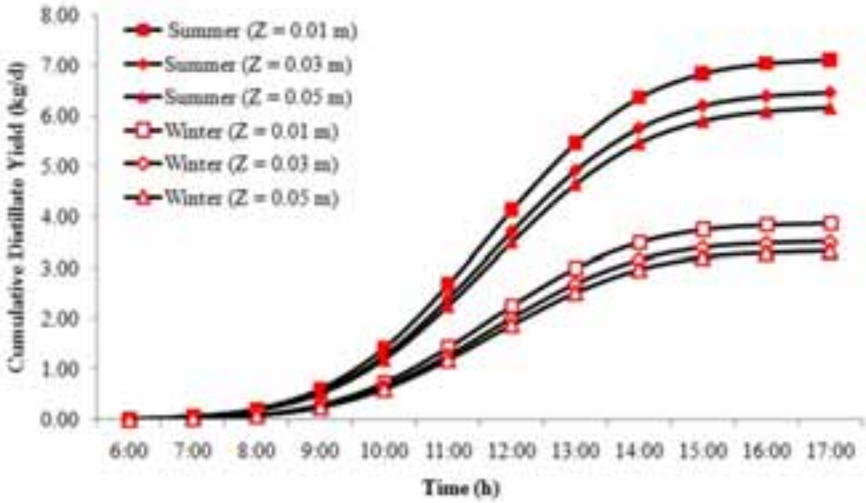

Fig. 6: Impact of depth of feed water in basin on cumulative distillate yield of the hybrid still

Feed water preheated in the basin type still is fed as input to the inclined still hence it is necessary to achieve maximum temperature using the basin type still for improved yield and hot water from inclined still. Depth of feed water in the basin type still is a major parameter which influences the yield from the hybrid still. The simulation was carried out for the month of April and December for 0.10 m gap between condensing and evaporating surface, mass flow rate of 0.003 kg/s, fluid film thickness of 0.001 m in inclined still and feed water depth of 0.01 m, 0.03 m and 0.05 m in basin. The impact of depth of feed water in basin on the distillate yield of hybrid still during summer and winter is shown in **Fig. 6**. The distillate yield is found to increase with the reduction in depth of feed water in the basin from 0.05 m to 0.01 m. Reduced yield at high depth is due to the increased mass of water in the basin which increases the heat capacity and reduces the transmissivity of the water leading to reduced radiation reaching the absorber plate of the basin type still (El-Sebaii, 2000). For a depth of 0.01 m the hybrid still produces a distillate yield of 7.12 and 3.86 kg/d during summer and winter, respectively. The yield is nearly 15.39 % and 15.91 % higher than the yield during summer and winter, respectively for a depth of 0.05 m.

4.4 Performance of the optimized hybrid distillation unit - hourly distillate and hot water productivity

The cumulative distillate yield of hybrid still is compared with passive inclined still and is shown in **Fig. 7.** Cumulative yield from passive inclined still and active inclined still is 2.54 kg/d and 5.31 kg/d, respectively. Cumulative yield of integrated single slope still (ISSS) which acts as the preheating unit for the active inclined is 1.81 kg/d. Hence, the total yield form the hybrid still (AIS +ISSS) is 7.11 kg/d. The distillate yield is found to be minimum during 6:00 to 9:00 due to reduced solar intensity and the yield increases steadily from 9:00 to 14:00, beyond 14:00 cumulative increase in yield remains nearly constant for the distillate units considered for study

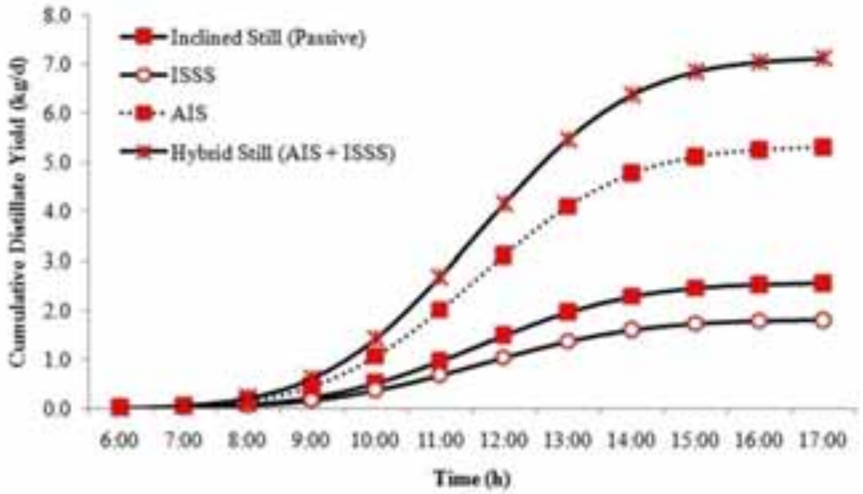

Fig. 7: Comparison of cumulative distillate yield of different distillation units

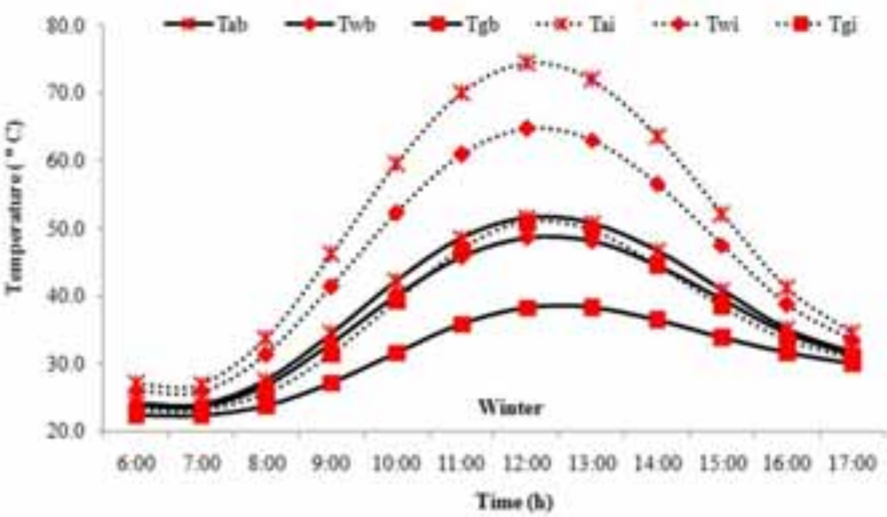

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Fig. 8: Hourly variation of temperature for different components of the hybrid still

The hourly temperature profile of different components of hybrid still for the month of December is shown in **Fig. 8**. The temperature profile is found to follow the solar radiation profile for the considered day. The temperature is found to increase with the increase in solar radiation up to 12:00 and then starts decreasing beyond 12:00. The maximum temperature of the absorber plate of integrated solar still and active inclined still is 51.48 ˚C and 74.35 ˚C, respectively. Maximum temperature of the feed water while leaving basin type still is 48.59 ˚C and it reaches 64.65 ˚C while leaving the absorber plate of the inclined still. Maximum glass temperature of the basin type still and inclined still is 38.33 ˚C and 50.86 ˚C, respectively.

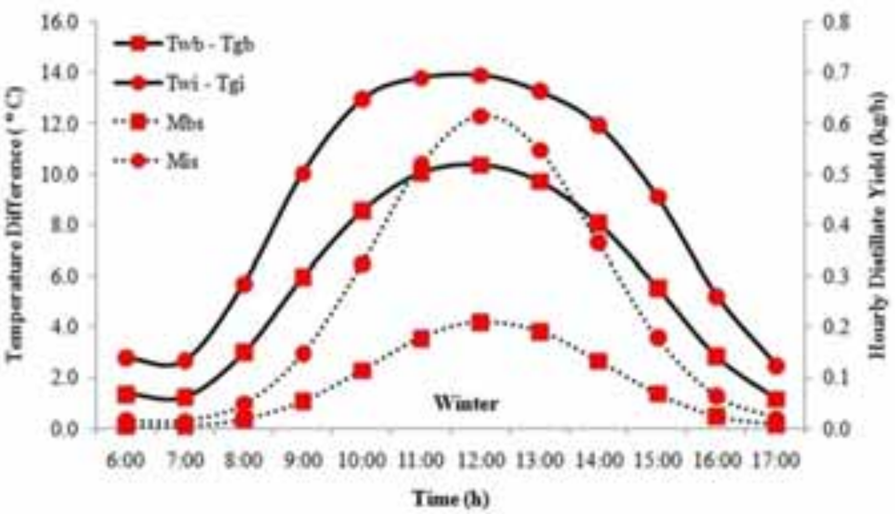

Fig. 9: Hourly distillate yield and temperature difference between evaporating and condensing surface of the hybrid still

The temperature difference between the evaporating and condensing surface of hybrid still along with its hourly distillate productivity for the month of December is shown in **Fig. 9**. The maximum temperature difference between the evaporating and condensing surface of the integrated single slope still and active inclined still is 10.35 ˚C and 13.90 ˚C, respectively. The maximum hourly productivity of the integrated single slope still and active inclined still is 0.21 kg/h and 0.61 kg/h, respectively making the total hourly productivity of the hybrid still to be around 0.82 kg/h.

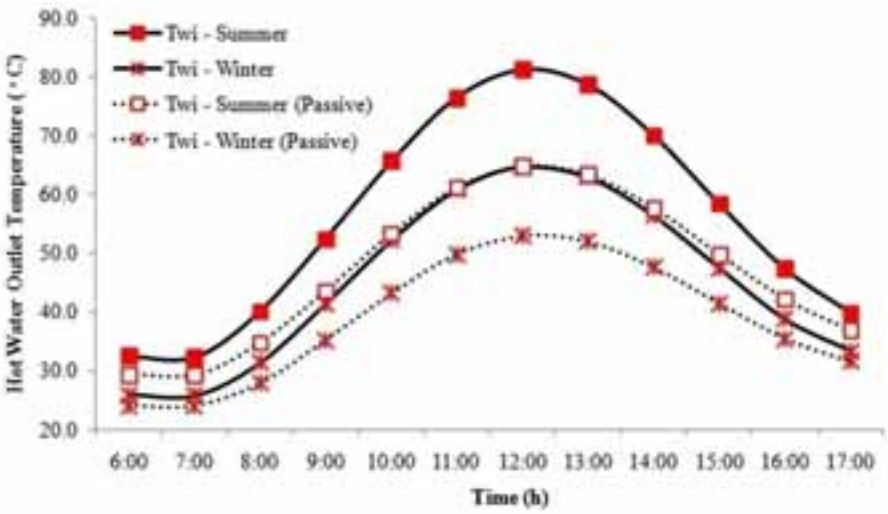

Fig. 10: Hourly temperature variation of hot water generated by the active and passive inclined still

The hourly temperature profile of the hot water generated by hybrid still during summer and winter in comparison with passive inclined still is shown in **Fig. 10.** The maximum temperature of hot water produced by passive inclined still is 64.84 ˚C and 52.91 ˚C, respectively during summer and winter. The maximum temperature of hot water produced by hybrid still is 81.29 ˚C and 64.65 ˚C during summer and winter which is higher than passive inclined still by 16.45 ˚C and 11.74 ˚C, respectively. The increase in hot water temperature of active inclined still is mainly due to preheating of feed water in the integrated single slope still of hybrid still. The average temperature of hot water generated by hybrid still is around 56.28 ˚C and 45.09 ˚C during summer and winter, respectively and the amount of hot water generated is more than 100 kg/d for both the seasons. The produced hot water can be used for domestic purposes like washing, flushing and it depends on the salinity of the feed water too (Aybar, 2006).

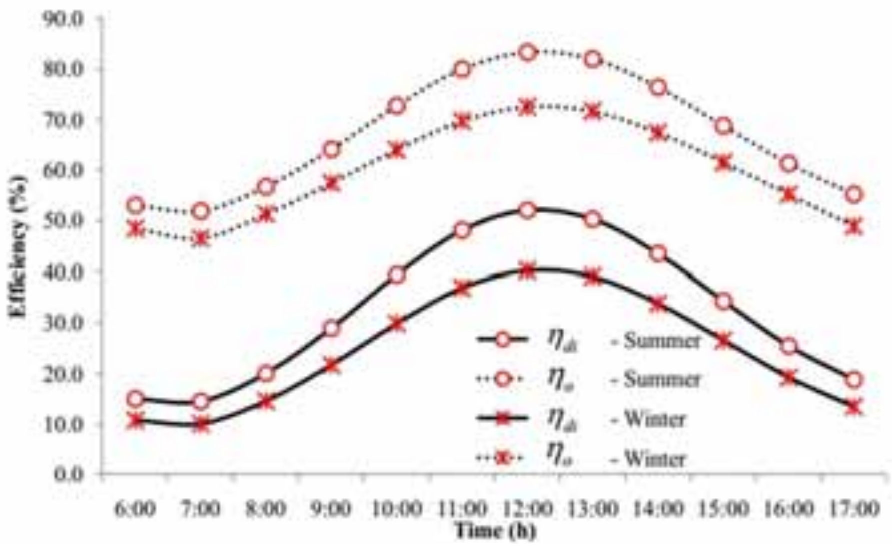

Fig. 11: Hourly variation of distillation and overall efficiency of hybrid still

The hourly variation of distillation efficiency and overall efficiency of hybrid still for summer and winter months is shown in **Fig. 11**. Distillation efficiency represents the ratio between energy content of the fresh water generated to the solar radiation input to the system. Overall efficiency represents the ratio between the energy content of the fresh water generated and useful energy of the hot water generated to the solar radiation input to the system. The efficiency varies with time due to variation in solar intensity and it reaches maximum during noon. The maximum distillation efficiency during summer and winter day is 52.14 % and 40.30 %, respectively. The maximum overall efficiency during summer and winter day is 83.40 % and 72.57 %, respectively. The average distillation efficiency and overall efficiency of the system is 32.59 % and 67.18 %, 24.73 % and 59.61 % for summer and winter, respectively.

5. Conclusion

Solar stills can carry out both desalination and detoxification in a single unit and are highly suitable for remote applications. In this study, transient simulation of hybrid solar still which has the ability to generate both potable water and hot water was carried out successfully. The distillate yield from hybrid still is found to increase with the decrease in depth of feed water in the basin type still, feed water mass flow rate and thickness of fluid film. Distillate yield from hybrid solar still is around 7.12 kg/d and 3.86 kg/d during summer and winter, respectively. Average temperature of hot water generated by the unit is around 56.28 °C and 45.09 °C during summer and winter, respectively. Overall efficiency of the hybrid unit is around 67.18 % and 59.61 % during summer and winter, respectively. The amount of hot water generated is more than 100 kg/d which is fairly sufficient for domestic activities like washing and flushing. The proposed unit will be of great benefit to rural and remote communities.

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7. Acknowledgement

The financial support provided by the Department of Science and Technology (DST, Government of India), New Delhi through the research project (Grant No: DST/TM/SERI/2k12/16(G)) is duly acknowledged.

8. Nomenclature

Nomenclature	
A	Area (m^2)
C_p	Specific heat capacity (J/kgK)
G	Solar radiation (W/m^2)
h_c	Convective heat transfer coefficient (W/m^2-K)
h_{fg}	Latent heat of evaporation (J/kg)
k	Thermal conductivity of insulation (W/m-K)
L	Length of active inclined still (m)
Le	Lewis number
M	Molecular weight (kg/kmol)
MC	Heat capacity (J/K)
$\dot{m}_{BS}$	Distillate yield from basin still (kg/s)
$\dot{m}_f$	Mass flow rate of feed water (kg/s)
$\dot{m}_{is}$	Distillate yield from inclined still (kg/s)
Pr	Prandtl number of fluid
q_c	Convective heat transfer (W)
q_e	Evaporative heat transfer (W)
q_l	Conductive heat loss (W)
q_r	Radiative heat transfer (W)
R	Universal gas constant (J/kmol-K)
Ra'	Rayleigh number
Re_L	Reynolds number
T	Temperature ($\circ$ C)
V	Wind velocity (m/s)
x	Thickness of insulation (m)
α	absorbtivity
ε	emissivity
ρ	Density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2 -K^4)
τ	Transmissivity
η	Efficiency (%)
Δt	Time step size (s)
Subscripts	
a	Ambient
ab	Basin liner of integrated single slope still
ai	Basin liner of active inclined still
av	Humid air
b	Brine
d	Insulation
di	Distillation
f	Fluid film
fi	Inlet feed water
fo	Outlet brine water
g	Glass
gb	Glass cover of integrated single slope still
gi	Glass cover of active inclined still
o	Overall
p	Plate
s	Global
w	Water
wb	Water mass of integrated single slope still
wi	Water mass of active inclined still