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Thermal performance of single slope passive solar still with separate V finned condenser

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Abstract

A passive single-slope solar distillation unit was designed with separate condenser to enhance the condensation rate and improve the system's overall productivity. To further boost the condenser's efficiency, V shaped external fins were added. The mathematical model of the proposed design has been developed and validated experimentally. Finned condenser helps to enhance the rate of heat rejected from condenser to ambient which helps to increase the overall production from solar still. For the climate of Raipur, Chhattisgarh, India (21.2514° N, 81.6296° E) numerical computation has been performed to determine the thermal performance of the proposed solar still with finned condenser. For a typical day in summer the proposed design gives 6.30L of distillate output. The daily distillate output given by proposed finned condenser SS is 16.7% more than the daily distillate output given by SS having separate condenser without fins.

Keywords:

Passive solar still, separate condenser, V fins, daily distillate output

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1. Introduction

Water, often viewed as a divine gift, is essential for shaping economies and ensuring the well-being of societies. However, many regions around the world face ongoing challenges related to water availability, quality, and access. Despite the Earth's supply of freshwater remaining constant, the growing global population and rapid industrialization have led to an increasing demand for water. A critical issue is the lack of clean drinking water, which affects both developed and developing countries. Inadequate access to safe water contributes to widespread health problems.

In recent years, certain areas have experienced insufficient rainfall, resulting in water scarcity. This scarcity often leads to higher salinity levels in water, making it unsuitable for both drinking and agriculture. Increased salinity not only harms soil quality but also reduces crop yields and disrupts ecosystems. Additionally, industrialization, urbanization, and population growth have intensified water pollution. Waste from factories, sewage, and agricultural runoff contaminates water sources, particularly in urban areas where pollution from human activities is concentrated. The lack of clean water has a direct impact on public health, with waterborne diseases remaining a major threat. Millions of people die each year due to unsafe drinking water, particularly in rural and underdeveloped areas where basic medical facilities are often lacking.

While scientific advancements have led to the development of numerous high- and medium-tech water purification methods that rely on conventional energy, "solar distillation" offers a simpler, cost-effective, and eco-friendly alternative. This method uses renewable energy instead of traditional energy sources to produce clean drinking water. Solar stills are small devices that use the sun's energy to evaporate and condense water, turning contaminated or salty water into drinkable water. The low production output has motivated more and more researchers to explore different designs of SS to increase its overall productivity. The most common design designs include basin type stills of single slope solar still (SSSS). This design is simple to construct but the production output of SSSS is very low. Researchers suggested number of design modification in the previous design of SSSS to enhance its productivity [1-8]. A comprehensive review on different techniques used to enhance the stills productivity was summarized by [9-11]. These modifications suggested to improve the rate of evaporation, condensation and reduction of various losses from SS.

In almost all the existing designs of SS the glass cover is used to transmit the solar radiation to incident on basin water. This helps to increase the temperature of water stored in the basin water. The water gets evaporated and condenses in the inner surface of the glass cover the latent heat of condensation is rejected into the atmosphere. Because of the low conductivity of glass, it sometimes fails to transfer all the latent heat of condensation to atmosphere that results in increasing the temperature of glass cover which results in lowering the rate of condensation over glass cover. To address this problem researchers in past proposed a new design of SS having separate external condenser (EC) [12-15]. This external condenser can be incorporated in three main ways: as a built-in condenser, an internal condenser, or an external condenser (EC). Most research has focused on how the EC impacts the still's performance, particularly under diffusion and purging modes. However, its operation under natural convection (NC) mode hasn't been fully explored.

In hot weather, the temperature of the still's glass cover rises due to high solar radiation and ambient heat, which reduces its ability to condense all the vapor produced inside the still. In such conditions, the EC plays a crucial role by drawing away the excess water vapor and transferring the accumulated heat from the still to the surrounding environment, thanks to its excellent thermal conductivity. Essentially, the EC acts as an additional heat sink, supporting the glass cover by boosting heat and mass transfer. Thermally, the condenser helps maintain low pressure and temperature within the still by increasing heat loss and absorbing excess vapor, improving overall efficiency.

In this work authors suggested a SSSS having separate condenser unit. The condenser plate designed as corrugated V shaped which behaves as fins. The presence of fins will help to reject more amount of heat from condensing plate into the atmosphere which would help to increase the overall production of SS. In this work authors developed a mathematical model of the proposed design of SS having separate V finned condenser. The mathematical model has been validated by conducting experiment on a typical day (21/3/2023) in the climate of Raipur, Chhattisgarh, India (21.2514° N, 81.6296° E). Numerical computations have been performed to determine the daily performance of the proposed design of SS. The performance of the proposed model of SS having separate V finned condenser has been compared with the performance of SS having separate condenser without fins.

2. Mathematical analysis

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Dunkle's relations were used to calculate the heat and mass transfer in the humid air inside both the evaporator and the condenser. The air-vapor mixture moves from the evaporator to the condenser through a horizontal slot driven by the pressure difference. This difference arises because the small volume of the air-vapor mixture in the evaporator, due to continuous evaporation leading to higher pressure, contrasts with the larger volume in the condenser, where lower pressure prevails. This density variation between the evaporator and condenser is caused by the temperature gradient within the fluid.

The energy balance equations for various components of the proposed still are as follows

1. Glass cover

$$M_g c_g \frac{dT_g}{dt} = \tau_1 I A_g + h_i A_w (T_w - T_g) - h_o A_g (T_g - T_a) \quad (1)$$

Neglecting thermal capacity of glass cover and considering $A_g = A_w$, Eq.1 can be written as,

$$\tau_1 I A_g + h_i A_w (T_w - T_g) = h_o A_g (T_g - T_a) \quad (2)$$

Here h_i is the total internal heat transfer coefficient between water and glass cover which is given by,

$$h_i = h_{cwg} + h_{rwg} + h_{ewg} \quad (3)$$

In above equation h_{cwg}, h_{rwg} and h_{ewg} are convective, radiative and evaporative heat transfer coefficients between basin water and glass cover

$$h_{cwg} = h_c (1 - \frac{V_c}{V}) \quad (4)$$

$$h_{ewg} = h_e (1 - \frac{V_c}{V}) \quad (5)$$

In Eqs. 4 & 5 V_c is the volume of condenser (air+vapors) and V is the total volume of condenser and evaporator ($V = V_c + V_e$)

$$h_{cw} = 0.884[(T_w - T_{g/c}) + \frac{(P_w - P_{g/c})(T_w + 273)}{(268.9 \times 10^3 - P_w)}]^{1/3} \quad (6)$$

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$$h_{ew} = 16.273 \times 10^3 h_{cw} \frac{(P_w - P_{g/c})}{(T_w - T_{g/c})} \tag{7}$$

$$P_w = \exp\left[25.317 - \left(\frac{5144}{273 + T_w}\right)\right] \tag{8}$$

$$P_g = \exp\left[25.317 - \left(\frac{5144}{273 + T_{g/c}}\right)\right] \tag{9}$$

$$h_{rwg} = h_r = \varepsilon_{eff} \sigma[(T_w + 273)^2 + (T_g + 273)^2](T_w + T_g + 546) \tag{10}$$

In Eq. 2 h_o is the total outer heat transfer coefficient between glass and air which is given by,

$$h_o = 5.7 + 3.8 v_a \tag{11}$$

From Eq.2 the temperature of glass cover will be given by,

$$T_g = \frac{\tau_1 I + h_i T_w + h_o T_a}{h_i + h_o} \tag{12}$$

2. Basin water

$$M_w c_w \frac{dT_w}{dt} = \tau_2 I A_w + h_b A_b (T_b - T_w) - h_i A_w (T_w - T_g) - h_c A_w (T_w - T_c) \tag{13}$$

In eq. 13 h_c is the total heat transfer coefficient (evaporation and convection) between water and condenser

$$h_c = h_{ewc} + h_{cwc} \tag{14}$$

$$h_{ewc} = h_e (\frac{V_C}{V}) \tag{15}$$

$$h_{cwc} = h_c (\frac{V_C}{V}) \tag{16}$$

3. Basin liner

$$M_b c_b \frac{dT_b}{dt} = \tau_3 I A_b - h_b A_b (T_b - T_w) - U_b A_b (T_b - T_a) \tag{17}$$

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Neglecting heat capacity of basin liner Eq.17 can be written as,

$$\tau_3 I A_b = h_b A_b (T_b - T_w) + U_b A_b (T_b - T_a) \tag{18}$$

In Eq.18 h_b and U_b are the heat transfer coefficients between basin and water and overall heat transfer coefficient between basin and ambient air. From Eq. 18 the temperature of basin liner T_b will be given by,

$$T_b = \frac{\tau_3 I + h_b T_w + U_b T_a}{h_b + U_b} \tag{19}$$

4. Condensing cover

$$M_c c_c \frac{dT_c}{dt} = h_c A_w (T_w - T_c) - h'_o A_c (T_c - T_a) \tag{20}$$

Neglecting thermal capacity of condenser Eq. 20 can be written as,

$$h_c A_w (T_w - T_c) = h'_o A_c (T_c - T_a) \tag{21}$$

In Eq. 21 h'_o is the total heat transfer coefficient between V corrugated condenser plate and ambient

From Eq. 21 the temperature of condensing plate T_c will be given by,

$$T_c = \frac{h_c A_w T_w + h'_o A_c T_a}{h_c A_w + h'_o A_c} \tag{22}$$

Putting the values of T_g , T_b and T_c in Eq. 13 we have

$$M_w c_w \frac{dT_w}{dt} + K_1 T_w = K_2 \tag{23}$$

In above equation the value of constants are given below

$$K_1 = \frac{H_1 U_b + H_2 h_o + H_3 h_o A_c}{M_w c_w} \tag{24}$$

$$K_2 = \frac{I(\tau_1 H_2 + \tau_2 A_w + \tau_3 H_1) + T_a (H_1 U_b + H_2 h_o + H_3 h_o A_c)}{M_w c_w} \tag{25}$$

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$$H_1 = \frac{h_b A_b}{h_b + A_b} \tag{26}$$

$$H_2 = \frac{h_i A_w}{h_i + A_w} \tag{27}$$

$$H_3 = \frac{h_c A_w}{h_o A_c + h_c A_w} \tag{28}$$

Eq. 23 could be solved to give us

$$T_w = \frac{K_2}{K_1}(1 - e^{-K_1 t}) + T_{w0} e^{-K_1 t} \tag{29}$$

T_{w0} is the initial water temperature at time t=0

The hourly distillate output produced would be the sum of distillate output produced by glass as well as condenser

$$\dot{m}_w = \frac{h_{ewg} A_w (T_w - T_g) + h_{cwg} A_c (T_w - T_c)}{L} \times 3600 \tag{30}$$

Eq. 30 will be used to determine the hourly distillate output produced by the proposed solar still having separate finned condenser

3.3.1 Expressions for determine τ_1, τ_2 and τ_3

$$\tau_1 = (1 - R_g)\alpha_g \tag{23}$$

$$\tau_2 = (1 - R_g)(1 - \alpha_g)(1 - R_w)\alpha_w \tag{24}$$

$$\tau_3 = (1 - R_g)(1 - \alpha_g)(1 - \alpha_w)(1 - R_w)\alpha_b \tag{25}$$

3. Description of the proposed design

The whole setup consists of two different parts separated by an insulated partition. The part at left hand side is evaporator unit and at right hand side called as condenser unit. Air and Vapour mixture produced due to solar radiation absorbed by water in evaporative chamber is purged from evaporator to condenser section. There it gets condensed beneath the finned condenser plate. Although a major part of this mixture condensed beneath condenser plate the remaining

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part goes and condensed beneath glass cover. The schematic of the proposed design is shown in fig.1.

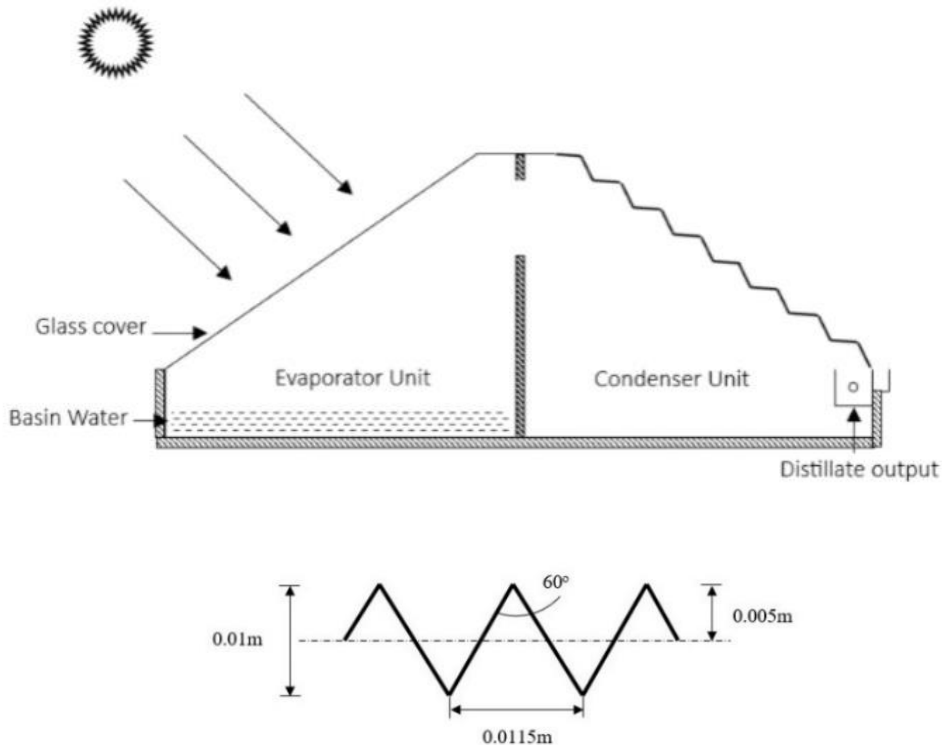

Fig.1 Schematic of the proposed design (number of fins n=10)

The condenser plate is made of V corrugated aluminium sheet (Fig.1). The area condenser (condenser unit) and area of glass cover (evaporator unit) considered are 1m^2.

4. Experimental Validation of mathematical model

To validate the proposed model an experiment was performed considering a solar still having separate V finned condenser. The photograph of the experimental setup is shown in Fig. 2. The theoretical water temperature, temperature of glass cover, and the temperature of condenser plate have been determined at a time interval of one hours. The theoretical readings have been compared by corresponding experimental readings. Experiment was performed at Raipur (21°14′40"N and 81°37′50″E) in a typical day 21/3/23. Hourly ambient temperature and solar radiation during experiment is shown in Fig. 3. Initial water temperature in basin, glass cover temperature and initial temperature of condenser was recorded as 21.5^o C, 18.6^o C and 21.2^o C, respectively details of various instruments used during experiment was given in Table 1.

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Fig.2 Photograph of experimental setup

Table 1 Details of various instrument used during experiment

Instrument	Range	Accuracy	Uncertainty
Temperature sensor K type- constantan	0°C to 150°C	±0.2°C	2% to 0.4% (10°C to 50°C)
RTD- Platinum temperature sensor	-50°C to 199.9°C	±0.1°C	1% to 0.2% (10°C to 50°C)
Digital anemometer	0.0m/s to 45.0m/s	±0.1m/s	5% (2m/s)
Pyranometer (Kipps and Zenon)	0W/m^2 to 1500W/m^2	73µV/W/m^2 (Sensitivity)	10%
Stop watch	-	±0.01s	-

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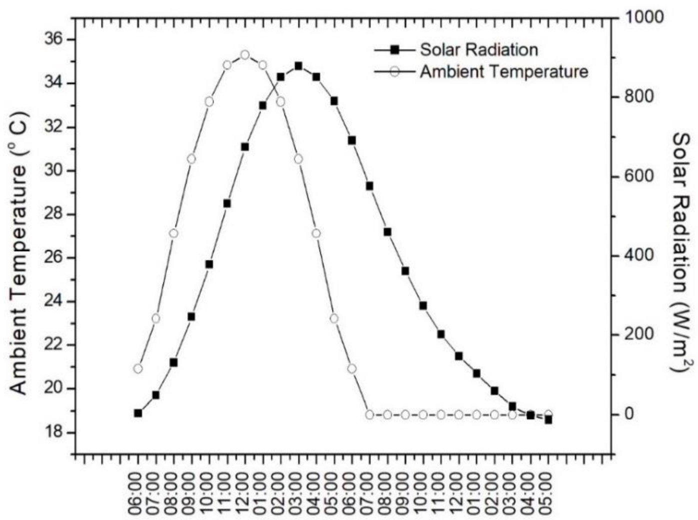

Fig. 3 Solar radiation and ambient temperature during experiment

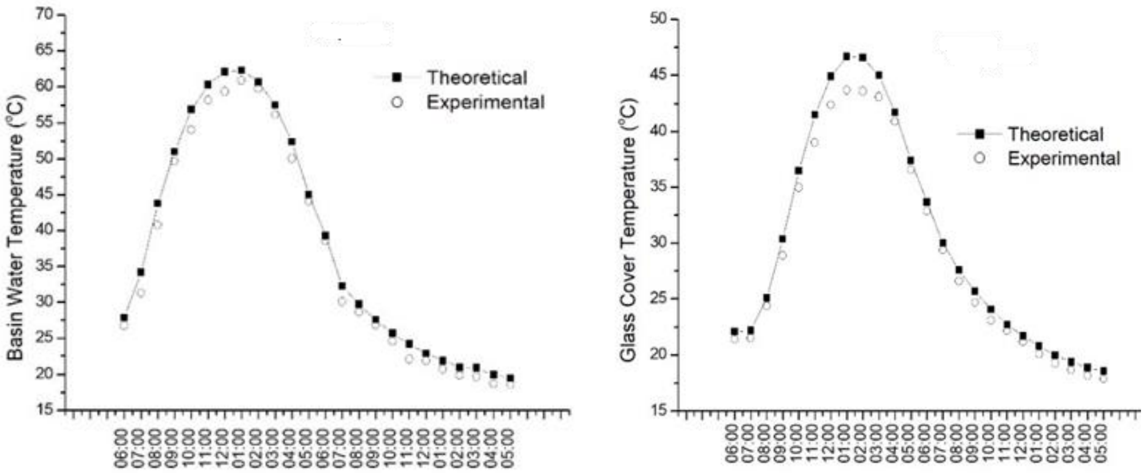

Fig.4 Theoretical and experimental readings of basin water temperature & glass cover temperature

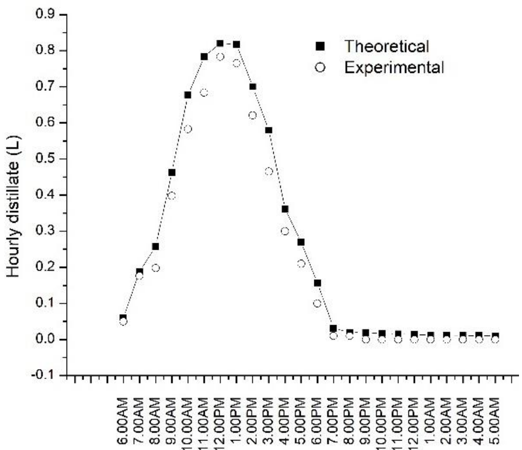

Fig.5Theoretical and experimental distillate output

The corresponding theoretical values of basin water temperature glass cover temperature and condensing cover temperature was theoretically computed by mathematical model. It is seen from Figs. 4 and 5 that the experimental values are reasonably close to theoretical values.

4. Numerical computations

Numerical computations have been performed to determine the thermal performance of the design of proposed SS. Various parameters used in numerical computations are given in Table 2.

Table 2 Different parameters used for computations

$A_w = A_g = 1m^2$	$A_c = 1.34m^2$	$c_w = 4190 J / kg\,^oC$
$M_w = 10kg$ n=10	$v = 2m/s$	$U_b = 2W / m^2K$
$h_b = 135W / m^2K$	$\sigma = 5.67x10^{-8}$	$\tau_1 = 0.0475, \tau_2 = 0$
$\tau_3 = 0.68$	$L = 2022\times10^3 J / kg$	$V_e = V_c = 1m^2$

Daily distillate output of the proposed SS having V finned separate condenser has been determined for a day in summer for Raipur, Chhattisgarh. The climatic parameters considered for computations are same as given in Fig. 3. Other relevant parameters used for computing yield are given in Table 2. To compare the performance of the proposed SS having fins with SS having separate condenser without fins the hourly distillate output has been computed and shown in Fig. 6.

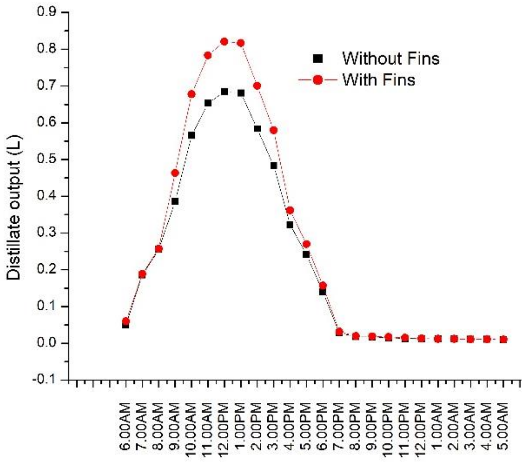

Fig. 6 Comparison of the proposed SSSC with finned condenser and SSSC without Fins

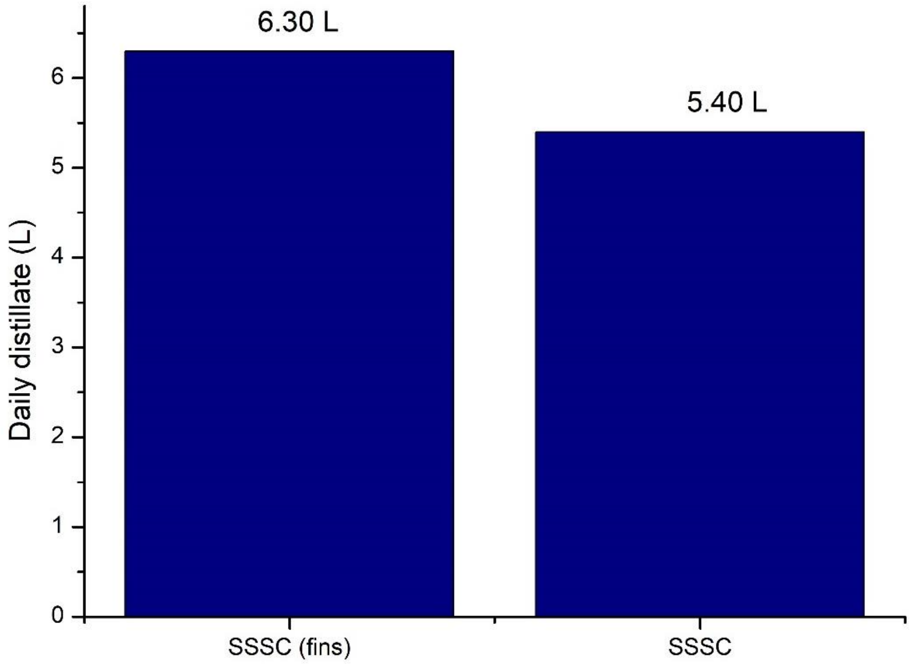

Fig. 6 Total daily distillate from SSSC with finned condenser and SSSC without Fins

It is seen that the SS with separate finned condenser performs better than the SS with separate condenser without fins. The total daily distillate output for a day by SS with fins is 6.30L for the same climatic condition for the SS without fins the total distillate output is 5.40 (Fig.6). The separate condensing chamber helps to extract the air vapor mixture away from the evaporator chamber. With fins the total condensing area increases and the fins helps to enhance the rate of heat transfer from condensing plate to ambient. This helps to condense the more amount of water vapor beneath the condensing plate. There is about 16.7% increase in total daily distillate output with separate v finned condenser.

5. Conclusions

In this study, the authors proposed a single-slope solar still (SSSS) with a separate condenser unit. The condenser plate was designed in a corrugated V-shape, functioning as fins. These fins help dissipate more heat from the condensing plate into the atmosphere, which in turn boosts the overall production of the solar still. Additionally, the authors developed a mathematical model for the proposed design, incorporating the separate V-finned condenser. Proposed design performs well the distillate output produced for a summer day in Raipur is 6.30L which is 16.7% more as compared to SSSS having separate condenser without fins.

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Nomenclature

A_g	Area of the glass cover	m^2
A_w	Area of the water in asun	m^2
b	Breadth of glass cover	m
c_w	Specific heat capacity of water	W/kg^oC
d	Length of glass cover	m
h_{cwg}	Convective heat transfer coefficient between water and glass	$W/m^{2o}C$
h_{rwg}	Radiative heat transfer coefficient between water and glass	$W/m^{2o}C$
h_{ewg}	Evaporative heat transfer coefficient between film and air	$W/m^{2o}C$
h_{ewc}	Evaporative heat transfer coefficient between water and condenser plate	$W/m^{2o}C$
h_{cwc}	Convective heat transfer coefficient between water and condenser plate	$W/m^{2o}C$
U_b	Overall heat transfer coefficient between basin and air	$W/m^{2o}C$
L	Latent heat of vaporisation	J/kg
M_w	Mass of water in basin	kg
m_w	Hourly distillate output	$kg(L)$
P_f	Saturated vapor pressure of air at film temperature	N/m^2
P_a	Saturated vapor pressure of air at air temperature	N/m^2
S	Solar radiation	W/m^2
T_a	Ambient air temperature	^oC
T_w	Temperature of water	^oC
T_g	Temperature of glass cover	^oC
T_b	Temperature of basin liner	^oC
T_c	Temperature of condensing plate	^oC

Greek Letters

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ε_w	Emissivity of water
ε_g	Emissivity of glass
ε_{eff}	Effective emissivity
σ	Stefan's Boltzmann Constant
α_g	Absorptivity of glass
τ_g	Transmissivity of glass
α_w	Absorptivity of wick

Abbreviation

MFR	Mass flow rate
SSSS	Single slope solar still