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DESIGN AND PERFORMANCE OF SOLAR STILL

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ABSTRACT

Solar still is widely used in solar desalination processes. But the productivity of the solar still is very low. To enhance the productivity of the single basin solar still many research works is being carried out up till now. In this work change the design of solar still used stepped solar still. Study the shape of the absorber surface over the distillate yield obtained the shape of the absorber surface provided in the basins of solar stills. The shape of use absorber surface plate area convex and concave increase basin water temperature cause the productivity and efficiency increase. In this work, to augment evaporation of the still basin water, fins were integrated at the basin of the still. Thus production rate accelerated. Also, for further increase in exposure area sponges were used. Production increases by fin and sponges stepped solar still. Experimental results were compared with conventional basin type still and still with wicks. That stepped solar stills can increase the distillate productivity about conventional solar stills, many reports studied the performance of stepped solar still. We are attempting to study the present status of different designs and performance of stepped solar stills enhances the productivity and efficiency of stepped solar still.

Keywords: Solar desalination, Stepped solar still, Convex and concave, Productivity.

I. INTRODUCTION

Water is the one of the resources that is potentially useful to all living beings. Often water sources are brackish containing harmful bacteria and therefore cannot be used for drinking. Distillation is the one of the processes that can be used for water purification. Desalination refers to the process of remove- ng salt and other minerals from water. Water is desalinated in order to convert salt water to fresh water which is suitable forhuman consumption or irrigation. Most of the research in desalination was focused on developing cost effective ways of providing fresh water for human use. Various research works are being carried out to improve the performance of the still. The basin area of the still, free surface area of water, inlet temperature of water, wind velocity, solar radiation, depth are some of the factors that affect the productivity of the solar still. Experimental investigations have been done by Moustafa et al. (1979) on stepped solar still and wick type evaporator still and the efficiency of the still improved by reducing the radiation losses from the basin. A simple expression was derived by Gandhidasan (1983) to calculate the amount of water evaporated from the tilted solar still. The energy balance equations in terms of various heat transfer coefficients of the solar were discussed by Tiwari (2002). Double glass cover was used and studied by Zurigat and Abu-Ara-bi (2004). Modeling of the system along with performance analysis was also compared. Aybar et al. (2005) tested the absorber plate with black cloth, wick materials and the experi- mental results showed an increase in the fresh water generation rate by two to three times more than the conventional system. Abdel-Rehim and Lasheen (2007) used the oil heat exchanger to preheat the saline water inside the solar still and got 18% increase in productivity. Suleiman (2007) studied the effect of water depth on productivity and their experimental results showed that a higher productivity of 6.7 L/day was obtained for a low water depth. Velmurugan and Srithar (2007) used sponge cubes in the still and acquired 57.8% more yield than the conventional still. Dimri et al. (2008) have done theoretical and experimental analyses of a solar still with a flat plate collector with various condensing materials. Velmurugan et al. (2009a) worked with an industrial effluent in a fin type single solar still and a stepped solar still separately. The max-imum output was found in the fin type solar still. Also Velmurugan et al. (2009b) used solar integrated along with solar still to enhance productivity. Many materials such as sponges, fins, wick and pebbles are added in the still and maximum 78% productivity was found for fin, sponge combinations. A new design of a stepped solar desalination system with a flashing chamber was experimentally investigated by El-Zaha-by et al. (2010). Effect of a spray system for sea water was investigated experimentally at different velocities. Kalidasa Murugavel et al. (2010) fabricated a still and tested it with different sensible heat storage materials like quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps. It was found that a inch quartzite rock is the effective sensible heat storage medium among the other materials. Dev et al. (2011) fabricated an inverted absorber solar still and the experimentation was carried out for different water depths and total dissolved solids. Results were compared with the conventional single slope solar still. Kalidasa Murugavel and Srithar (2011) used different wick materials like light cot-ton cloth, sponge, coir mate, waste cotton pieces in a double slope solar still. Higher yield was obtained by using light black cotton cloth. Omara et al. (2013) made a comparison study be-tween a modified stepped solar still with and without reflector and compared it with a conventional solar still. It was shown that about 20% of daily efficiency has been improved in the modified still. Lalit (2013) When the convex and concave type stepped solar stills were used, the average daily water distillate had been found to be 56.60% and 29.24% higher than that of flat type stepped solar still, respectively The current work focused on placing sponge cubes in the basin water in order to increase the wetted surface area in contact with the hot air inside the still. The small openings in the sponge cubes also reduces the surface tension between the water molecules, thus making it easier for the water molecules to evaporate. The presence of sponge cubes also suppresses heat transfer convection currents in the basin that reduce the amount of solar radiation reaching the basin. This reduces the heat transfer losses from the bottom of the still. The use of sponge cubes in the basin is a passive enhancement method and does not require frequent nor expensive maintenance once installed. The objective of this work is to improve the productivity by adding sponges and integrating fins at the basin in ordinary stepped type solar still. By increasing the area of the basin plate, productivity can be increased. This can be done by using sponges and integrating fins at the exposure surface of the basin plate. Simultaneously experiments are carried out with flat type stepped solar still, sponge type stepped solar still and fin type stepped solar still. Theoretical analysis is also made by solving energy balance equations and compared with experimental

NOMENCLATURE

T_a – ambient temperature, K

T_b - absorber plate temperature at the basin, K

T_w - saline water temperature in the basin, K

T_{wi} - initial saline water temperature at starting of experiment, K

T_{gi} – glass cover temperature at the inner surface, K

T_{go} – glass cover temperature at the outer surface, K

T_v - average of saline water and inner glass cover temperatures, K

ΔT - effective temperature difference, K

Y – distillate yield, ml

I_b – beam radiation intensity on a horizontal surface, W/m^2

I_g – global radiation intensity on a horizontal surface, W/m^2

V – wind velocity, m/s

A_b – area of still basin, m^2

A_w – area of free water surface, m^2

A_g – area of glass cover, m^2

C_{pw} – specific heat of water, J/kgK

L_c – cover spacing, m

Gr – Grashoff number

Pr - Prandtl number

Ra - Rayleigh number, (Gr.Pr)

$h_{cw\text{-}g}$ – convective heat transfer coefficient from water surface to the glass cover, W/m^2K

$h_{ew\text{-}g}$ – evaporative heat transfer coefficient from water surface to the glass cover, W/m^2K

$h_{rw\text{-}g}$ – radiative heat transfer coefficient from water surface to the glass cover, W/m^2K

K_a – thermal conductivity of the humid air, W/mK

h_{fg} – latent heat of vaporization, J/kg

m_{ew} – distillate output, kg

P_{gi} – partial vapour pressure at glass cover temperature, Pa

P_w – partial vapour pressure at water temperature, Pa

$q_{cw\text{-}g}$ – convective heat transfer rate from water surface to glass cover, W/m^2

$q_{ew\text{-}g}$ – evaporative heat transfer rate from water surface to glass cover, W/m^2

ρ - density of humid air, kg/m^3

μ - dynamic viscosity of humid air, Ns/m^2

β - coefficient of volumetric thermal expansion, K^{-1}

σ - Stefan Boltzman's constant, W/m^2K^4

II. OBJECTIVES OF THE PRESENT STUDY

The present study aims to improve the solar still performance and to increase its distillate yield. So it is necessary to evaluate some important parameters affecting the system productivity. The effect of depth of water, glass cover thickness, shape of the absorber area and various enhancements provided on the distillate yield are to be evaluated. In the same time, the effects of the design and operational parameters on the solar desalination process were investigated. The study aims to introduce the applicability of a stepped type solar still to determine the following:

1. Critical review of the literature on stepped type solar still.
2. To distinguish various parameters that influence the performance of stepped type solar still.
3. Based on above parameters, fabrication of different configurations of stepped type solar still.
4. To change the convex shape of absorber of stepped type solar still.
5. To change the concave shape of absorber of stepped type solar still.
6. To provide different enhancements in the basin of stepped type solar still.

7. To develop a mathematical model to determine the convective heat transfer coefficient for various configurations of solar stills.

III. 8. Presentation of the optimized results obtained after detailed analysis of the data generated for various configurations of solar stills.

Depending on the different readings obtained for various configurations of stepped type solar still; performance optimization will be done on the basis of following parameters:

1. Variation of convective, radiative and evaporative heat transfer coefficients for various configurations of the solar stills.
2. Variation of distillate yield with time of the day for various configurations of the solar stills.
3. Variation of still efficiency for various configurations of the solar stills.
4. Variation of distillate yield with wind velocity for various configurations of the solar stills.

The various factors affecting the performance of the solar still are solar intensity, wind velocity, ambient temperature, water surface and inner glass cover temperature difference, free surface area of water, absorber plate area, temperatures of inlet water, glass cover inclination, still orientation and depth of water. The solar intensity, wind velocity, ambient temperature cannot be controlled as they are meteorological parameters whereas the remaining parameters can be varied to enhance the productivity of the solar stills. By considering the various factors affecting the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still.

IV. EXPERIMENTAL SET UP

The experimental setup consisting of different types of solar stills mounted on an iron stand with a saline water storage tank is as shown in Fig 3.1 The relationship between the size of a solar still and its capacity depends upon its design and efficiency. On cloudy or rainy days, production stops so it is necessary to build a solar device to anticipate this handicap. Therefore, it is best to provide for a good storage facility to hold the distilled water produced. Because this still is quite small, it is designed so that water collected can be drained into bottles.

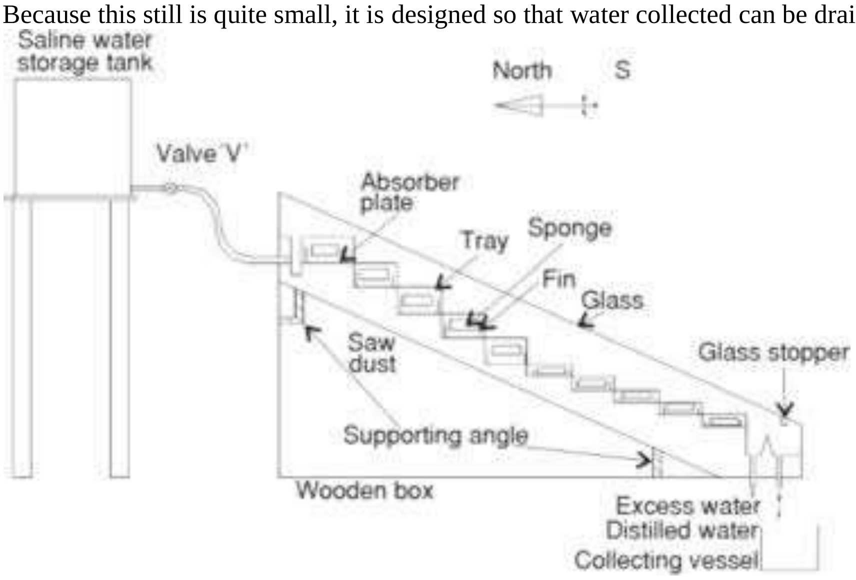


Fig 3.1 ; Stepped type Solar Still with sponges and fins

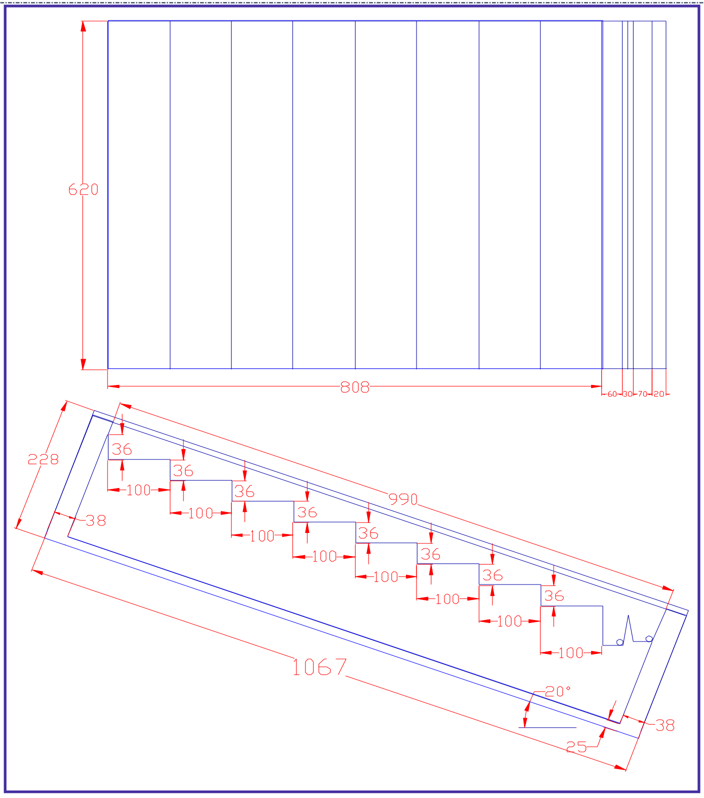
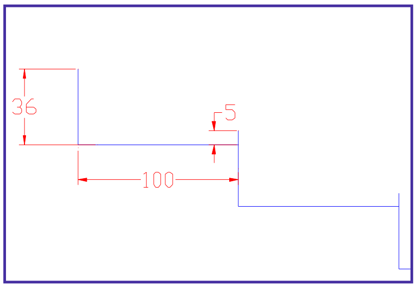
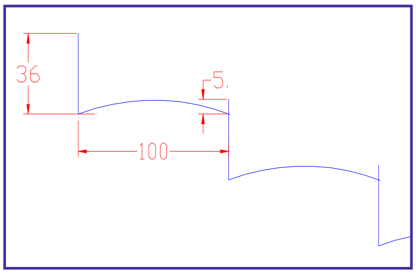


Fig 3.2 : Plan and elevation of the stepped type absorber plate

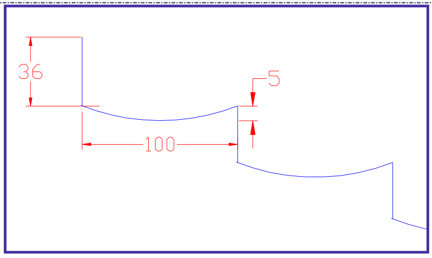
The side view of the absorber plate of solar still A flat surface, solar still B with convex surface and solar still C with concave surface are as given in Fig 3.3



a) Absorber surface of flat type solar still A



b) Absorber surface of convex type solar still B



c) Absorber surface of concave type solar still C
Fig. 3.3 : Absorber plate provided with different shapes

A separate hole is drilled in the sidewall of the still to fix thermocouples to sense the temperatures of water in the basin, absorber plate temperature and inner glass cover temperature. The entire unit is placed on an angle iron stand inclined at an angle of 20.50 equal to the latitude of Buldana to the horizontal. The still requires unobstructed sunshine from early morning to late afternoon. The solar still is oriented due south as the location lies in the northern hemisphere to receive maximum solar radiation throughout the year. This stepped type solar still system has been fabricated in the workshop of Rajarshi Shahu College of Engineering, Buldana. The experimental work was carried out on the roof of the non conventional energy systems laboratory, Mechanical Engineering Department of the institute. The experiments were performed during the months of January 2018 to April 2018 when the sky was clear i.e. on sunny days. The average sunshine at the selected location of Buldana was 4.88 kWh/m2/day in January, 5.52 kWh/m2/day in February, 6.3 kWh/m2/day in March and 6.63 in April.

Table 3.1: Experimental Setup

Sr. No.	Component	Description
1	Saline water storage tank	Volume - 1000 liters
2	Stepped type absorber plate	GI sheet - 22 gauge
3	Coating of absorber plate	Heat absorbent black dye
4	Design parameters to be varied	shape of absorber surface, use sponges and fins
5	Shapes to be provided to the absorber surface	Convex and concave
6	Metal box	Overall dimensions : 1067mm(L) x 686mm(W) x 228mm(H)
7	To compensate loss of water	Every half an hour

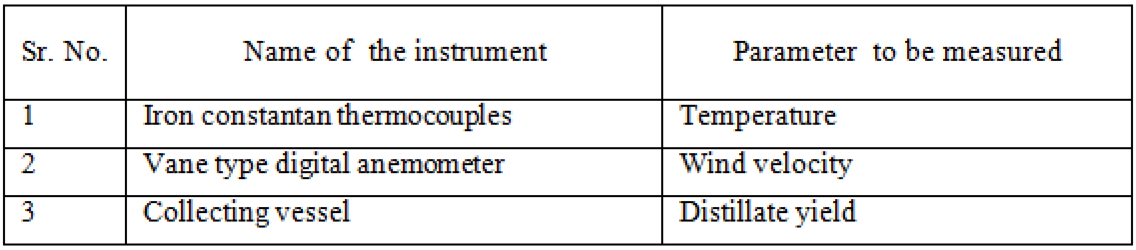
3.1 Working of the Still

The stepped type solar still used in the present work has been provided with eight number of steps of size 620 mm (L) x 100 mm (W). The steps are filled with saline water one after another starting from the top and the excess water comes out from the excess water channel provided at the bottom. The excess water, if any is collected for reuse in the solar still. The average spacing between the saline water surface and the condensing glass cover is kept as 0.01m. When solar radiations fall on the glass cover, it gets absorbed by the black absorber plate. Due to this, the water contained in the steps begins to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. When the water absorbs maximum solar radiations equal to the specific heat capacity of its mass, it is saturated and evaporation of water takes place. The basin also radiates energy in the infrared region, which was reflected back into the solar still by the glass cover, trapping the solar energy inside the solar still. The water vapors formed due to the evaporation of water are condensed at the inside of glass cover, as its temperature is less. The condensed water trickles down to the distillate collection trough provided at the bottom and is collected into a glass beaker by using a hosepipe, which is mounted at the side of the solar still. As evaporation of water in the steps takes place, the saline water level in the solar still decreases. The distillate yield was measured every one hour during daylight from 10 am to 5 pm. The distillate yield during non-sunshine hours was collected daily in the morning at 9 am before the commencement of the experiment. To compensate the loss of water, for every half an hour, the makeup water was added to the solar still from the storage tank.

3.2 Data Recording System

The list of the instruments used for measuring different parameters of the stepped type solar still is given in Table 3.2.

Table 3.2: Measuring Instruments



Sr. No.	Name of the instrument	Parameter to be measured
1	Iron constantan thermocouples	Temperature
2	Vane type digital anemometer	Wind velocity
3	Collecting vessel	Distillate yield

The alloy combination, polarity and measurement range for the thermocouples is as given in the Table 3.3

Table 3.3 : Thermocouples

Item	Specification
Type of thermocouple	J - Type Iron constantan thermocouple
Alloy of positive wire	Iron (100% Fe)
Alloy of positive wire	Constantan (55% Cu - 45% Ni)
Temperature range	0 - 750^{0}C

V. OBSERVATIONS

1. Stepped type solar stills with varying shape of absorber surface

- Variation between the temperatures at different locations of solar stills

- Variation of productivity in convex and concave type solar still

2. Stepped type solar stills with sponges and fins
   - Stepped type solar stills with sponges at the basin
   - Stepped type solar still with fins at the basin
   - Variation between the temperatures at different locations of solar stills
   - Variation of productivity in sponge type solar still
   - Variation of productivity in fin type solar still

4.1 Stepped Type Solar Stills with Varying Shape of Absorber Surface

The configuration and design parameters of solar stills A, B and C are as given in the Table 4.1

Table 4.1: Design parameters of solar stills A, B and C

Sr. No.	Type of solar still	Glass cover thickness in mm	Depth of water in mm	Shape of absorber surface
1	A	4	5	Flat
2	B	4	5	Convex
3	C	4	5	Concave

4.2 Stepped type solar stills with sponges and fins

The configuration and design parameters of solar stills A, D and E are as given in the Table 4.2

Table 4.2: Design parameters of solar stills

Sr. No.	Type of solar still	Glass cover thickness in mm	Depth of water in mm	Shape of absorber surface	Type of enhancement
1	A	4	5	Flat	No enhancement
2	D	4	5	Flat	Sponges placed over the basin
3	E	4	5	Flat	Fins soldered over the basin

VI. DEVELOPMENT OF MATHEMATICAL MODEL

5.1 Energy Analysis in Stepped Type Solar Still

The experiments done on the five different configurations of a stepped type solar still were carried out on successive days during the period from January 2018 to April 2018. Each experiment started from 9:00 am in the morning to 6:00 pm in the evening. The electrical and electronic parts were tested and calibrated before being used on the various designs of the solar stills. The experimental work was fully carried out in the solar energy park of Rajarshi Shahu College of Engineering, Buldana.

Five different thermocouples were installed on the solar still system at different locations. These locations were: (a) a basin base to measure the temperature of the plate, (b) inner surface of the glass, (c) outer surface of the glass, (d) water temperature in the basin and (e) water vapor. The various energy transfers occurring in stepped type solar still.

The general equation to describe various heat transfers in a solar still is an energy balance equation, which says that the sum of the total heat in must be equal to the sum of the total heat out. This is based on the law of the conservation of energy which says that heat can neither be created nor destroyed: it can only be changed from one form to another. This energy balance can be written for the entire still or on a smaller scale for the heat transfer of the absorber plate, saline water and glass cover of the still as given below.

$$\sum q_{in} = \sum q_{out}$$

Where the q's can represent heat transfer by the combination of any of the three modes of heat transfer i.e. conduction, convection or radiation.

The energy balance equation for the absorber plate, saline water and glass of solar still can are written as shown below.

Energy received by basin plate [I(t) A_b α_b]
= Energy gained by basin plate [m_b C_{pb} dT_b/dt] +
Energy lost by convective heat transfer beam basin & water [Q_c, b-w] +
Side and bottom losses [Q loss]

$$I(t)A_b\alpha_b = m_b c_{pb}\frac{dT_b}{dt} + Q_{c\,b-w} + Q_{loss} \qquad (1)$$

The absorptivity of the still α_b is taken as 0.95.
I(t), the total solar flux on a inclined surface is obtained from

$$I(t) = (Ig - Id)\frac{\cos\theta i}{\cos\theta h} + Id\ \frac{1+\cos\beta}{2} \qquad (2)$$

The convective heat transfer between basin and water is taken as

$$Q_{c\,b-w} = h_{c\,b-w}A_b(T_b - T_w) \qquad (3)$$

The convective heat transfer between basin and water is 135 W/m^{2}K. The heat loss from basin to ambient is taken as:

$$Q_{loss} = U_b A_b(T_b - T_a) \qquad (4)$$

Where U_b is taken [17] as 14 W/m^{2}K

Energy received by saline water in the still [I(t) A_w α_w + Q_c, b-w]
(From the sun & basin)
= Energy lost by convective heat transfer between water & glass [Q_c, w-g] +
Radiative heat transfer between water & glass [Q_r, w-g] +
Evaporative heat transfer between water & glass [Q_e, w-g] +
Energy gained by the saline water [m_w Cp_w dT_w/dt]

$$I(t)\alpha_w A_w + Q_{c\,b-w} = Q_{c\,w-g} + Q_{r\,w-g} + Q_{e\,w-g} + m_w c_{pw}\frac{dT_w}{dt} \qquad (5)$$

The mass of water in the still is taken as 3.75 kg and the absorptivity of the water α_w is taken as 0.05.

The convective heat transfer between water and glass is given by

$$Q_{c\,w-g} = h_{c\,w-g}A_w(T_w - T_g) \qquad (6)$$

The convective heat transfer co-efficient between water and glass is given by:

$$h_{c\,w-g} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273.15)}{268.9\times10^3 - P_w}\right]^{1/3} \qquad (7)$$

The radiative heat transfer between water and glass is given by:

$$Q_{r\,w-g} = h_{r\,w-g}A_w\left(T_w - T_g\right) \qquad (8)$$

Radiative heat transfer co-efficient between water and glass is given by:

$$h_{r\,w-g} = \varepsilon_{eff}\sigma\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right](T_w + T_g + 546) \qquad (9)$$

Where,

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{gi}} - 1} \qquad (10)$$

The areas of glass *(*A_g*)* and basin *(*A_b*)* are taken as 1 by 0.5 m which is the size of the basin. The area of saline water (A_w) is the total area of the trays, taken as 0.49 m^2.

Energy received by glass cover [I(t) A_g α_g + Q_c, w-g + Q_r, w-g + Q_e, w-g]
(From sun & convective, radiative, evaporative heat transfer from water to glass)
= Energy lost by radiative heat transfer between glass & sky [Q_r, g- sky] +
Energy gained by glass [m_g Cp_g dT_g/dt]

$$I(t)\alpha_g A_g + Q_{c\,w-g} + Q_{r\,w-g} + Q_{e\,w-g} = Q_{r\,g-sky} + m_g c_{pg}\frac{dT_g}{dt} \qquad (11)$$

The evaporative heat transfer between water and glass is given by:

$$Q_{e\,w-g} = h_{e\,w-g} A_w (T_w - T_g) \qquad (12)$$

The evaporative heat transfer co-efficient between water and glass is given by:

$$h_{e\,w-g} = (16.237 \times 10^{-3})\, h_{c\,w-g}\frac{P_w - P_g}{T_w - T_g} \qquad (13)$$

The radiative heat transfer between glass and sky is given by:

$$Q_{r\,g-sky} = h_{r\,g-sky} A_g (T_g - T_{sky}) \qquad (14)$$

Under clear and cloudy skies, the difference between ambient temperature and effective sky temperature is taken as [17, 22, 23] 6 °C. So, the effective sky temperature is taken as:

$$T_{sky} = T_a - 6 \qquad (15)$$

The radiative heat transfer co-efficient between glass and sky is given by [10]:

$$h_{r\,g-sky} = \varepsilon_{eff}\sigma\left[(T_g + 273)^2 + (T_{sky} + 273)^2\right](T_g + T_{sky} + 546) \qquad (16)$$

Where,

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_{gi}} + \frac{1}{\varepsilon_{go}} - 1} \qquad (17)$$

In eq. (17) terms ε_{gi} and ε_{go} indicates the emissivities of the inner and outer surfaces of the glass, respectively. The time interval is assumed as 5s and for first iteration, the water temperature, glass temperature, and plate temperature are taken as ambient temperature. The change in basin temperature (dT_b), glass temperature (dT_w), and increase in saline water temperature (dT_g) are computed for every 5 s by solving eqs. (1), (5), and (11), respectively. For evaluating, the above said temperatures in the simulation, the experimentally measured values of solar radiation and ambient temperature of the corresponding day and hour were used.

The total condensation rate is given by [17]:

$$\frac{dm_c}{dt} = h_{c\,w-g}\frac{T_w - T_g}{h_{fg}} \qquad (18)$$

For the next step, the parameter is redefined as:

$$T_w = T_w + dT_w \qquad (19)$$
$$T_g = T_g + dT_g \qquad (20)$$
$$T_b = T_b + dT_b \qquad (21)$$

The iteration is performed for 8 hours duration from 9 am to 5 pm with a time interval of 5 s. The metrological parameters, namely air temperature and solar intensity are taken from the actual measured values in hourly intervals.

5.2 Thermal Model

A thermal model has been developed to determine the convective heat transfer for different Grashoff numbers in the solar distillation process. The model is based on simple regression analysis. Based on the experimental data obtained from the rigorous outdoor observations on various configurations of stepped type solar stills for summer climatic conditions, the values of C and n have been calculated. From these values, convective heat transfer coefficient is calculated based on the distillate yield obtained from the experimental observations. The percentage deviation between experimental and theoretical distillate yield is also obtained.

5.3 Thermo physical Properties of Water

The thermo physical properties of water [11] have been evaluated by using the following expressions wherein T_v represents an average [12] of the temperatures of evaporation and condensing surfaces and can be expressed as follows:

$$T_v = \frac{(T_w + T_{gi})}{2}$$

$$\rho = \frac{353.44}{(T_v + 273.15)}$$

$$\beta = \frac{1}{(T_v + 273.15)}$$

$$C_{pw} = 999.2 + 0.1434 \times T_v + 1.101 \times T_v^{-2} - 6.75 \times 10^{-8} \times T_v^3$$

$$K_a = 0.0244 + 0.7673 \times 10^{-4} \times T_v$$

$$\mu = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times T_v$$

$$h_{fg} = 2324.6(1.0727 \times 10^3 - 1.0167 \times T_v + 1.4087 \times 10^{-4} \times T_v^2 - 5.1462 \times 10^{-6} \times T_v^3)$$

$$P_w = e^{(25.317 - 5144/T_w)}$$

$$P_{gi} = e^{(25.327 - 5144/T_{gi})}$$

5.4 Internal Heat Transfer Coefficients

Numerous empirical co-relations for heat and mass transfer coefficients to predict the hourly and daily distillate yield for different designs solar distillation units have been developed by various researchers. Most of these developed relations are based on simulation studies.

Dunkle formulated a semi-empirical relation for internal heat and mass transfer in solar distillation units for the first time in 1961. He proposed the values of C = 0.075 and n = 1/3 on the basis of simulation studies for Gr > 3.2 x 105. However, this relation has the following

limitations:

1. It is valid only for a mean operating temperature range of 500C and equivalent temperature difference of approximately 10C.
2. It is independent of cavity volume i.e. the average distance between the condensing and evaporating surfaces.
3. It holds good for heat flow upwards in horizontally enclosed air space.

The convective heat transfer rate from water surface to condensing glass cover is given by:

$$q_{c\,w-g} = h_{c\,w-g}(T_w - T_{gi}) \qquad (1)$$

Where,

h_{cw-g} is convective heat transfer coefficient from water surface to condensing glass cover. The convective heat transfer coefficient h_{cw-g} is calculated by using the non-dimensional Nusselt number as shown below:

$$Nu = h_{cw-g}\frac{L_c}{K_a} = C\,(Gr.Pr)^n \qquad (2)$$

In equation (2), non- dimensional numbers Gr and Pr are called Grashoff number and Prandtl numbers respectively. These numbers are expressed as:

$$Gr = \frac{\beta g L_c^3 \rho^2 \Delta T}{\mu^2} \qquad (3)$$

$$Pr = \frac{\mu C_{pw}}{K_a} \qquad (4)$$

Where

$$\Delta T = (T_w - T_{gi}) + \left[\frac{(P_w - P_{gi})(T_w + 273.15)}{268.9 \times 10^3 - P_w}\right]$$

Variables on right hand side of expressions are the temperature dependent physical properties and are determined as discussed in the previous section.

Equation (2) can be rewritten as,

$$h_{cw-g} = \frac{K_a}{L_c}.C(Gr.Pr)^n$$

$$h_{cw-g} = \frac{K_a}{L_c}.C(Ra)^n \tag{5}$$

Where Ra = Gr.Pr is the Rayleigh number.

Malik *et. al*.,1982 [2] have assumed that water vapour obeys the perfect gas equation and have given the expression for evaporative heat transfer rate as:

$$q_{ew-g} = h_{ew-g}(T_w - T_{gi}) \tag{6}$$

Where, h_{ew-g} is the evaporative heat transfer coefficient between water surface and condensing glass cover and expressed as

$$h_{ew-g} = 0.01623\,.\,h_{cw-g}.\frac{(P_w-P_{gi})}{(T_w-T_{gi})} \tag{7}$$

Where

$P_w = e^{(25.317-5144/T_w)}$

$P_{gi} = e^{(25.327-5144/T_{gi})}$

It is worth mentioning here that only evaporative heat transfer causes and contributes to water distillation

Substituting the value of h_{ew-g} in equation (6) above, we get

$$q_{ew-g} = 0.01623\,.\,h_{cw-g}.\left(P_w - P_{gi}\right) \tag{8}$$

Substituting the value of h_{cw-g} in the above equation, we get

$$q_{ew-g} = 0.01623\,.\frac{K_a}{L_c}\,.\left(P_w - P_{gi}\right).C.(Ra)^n \tag{9}$$

By knowing the evaporative heat transfer rate; mass of the water distilled can be derived by the following equation:

$$\dot{m}_{ew} = \frac{q_{ew-g}.A_w.t}{h_{fg}} \tag{10}$$

Substituting the value of q_{ew-g} in the above equation, we get

$$\dot{m}_{ew} = 0.01623\left(P_w - P_{gi}\right)\left(\frac{K_a}{L_c}\right)\frac{1}{h_{fg}}\ C\ (Ra)^n \tag{11}$$

$$\dot{m}_{ew} = R.C.(Ra)^n \tag{12}$$

$$\frac{\dot{m}_{ew}}{R} = C\ (Ra)^n \tag{13}$$

Where,

$R = 0.01623\left(P_w - P_{gi}\right)\frac{K_a}{L_c}.\frac{1}{h_{fg}}$

In equation (13), there are two unknown parameters C and n. They are determined by regression analysis using experimental values of distillation yield (m_{ew}), saline water temperature in the basin (T_w), glass cover temperature at the inner surface (T_{gi}).

Equation (13) can be rewritten in the following form:

$$Y = aX^b \tag{14}$$

Where, $Y = \frac{\dot{m}_{ew}}{R};\quad X = Ra;\quad a = C;\quad b = n$

Equation (14) can be reduced to a linear equation by taking log on both the sides:

$$ln\ (Y) = ln(a) + bln(X) \tag{15}$$

OR $$Y' = a' + b'X' \tag{16}$$

Where

$$Y' = \ln(Y)\,;\quad a' = 1n(a);\quad b' = b;\quad X' = \ln(X) \tag{17}$$

From equation (17), the values of coefficients a' and b' are calculated using regression analysis. The expressions for a' and b' are given by:

$$b' = \frac{N(\Sigma X'Y')-(\Sigma X')(\Sigma Y')}{N(\Sigma X'^2)-(\Sigma X')^2} \tag{17a}$$

$$a' = \frac{\Sigma Y'}{N} - b' \frac{\Sigma X'}{N} \qquad (17b)$$

where N is the number of experimental observations.

Knowing a' and b' from equation (15), the value of C and n can be obtained by the following expressions:

$$C = e^{a'} \text{ and } n = b'$$

Once the values of C and n are known, the experimental data are used to obtain the internal heat and mass transfer coefficients for the solar stills. Equation (3) can be used to obtain the convective heat transfer coefficient, h_{cw-g}. Dunkle [1], by using the values of C = 0.075 and n = 1/3, gave following expression forh_{cw-g}, valid for a mean operating temperature range of approximately 50^{0}C.

$$h_{c\,w-g} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})\,(T_w + 273.15)}{268.9\times 10^3 - P_w}\right]^{1/3} \qquad (18)$$

The internal heat transfer coefficient; heat transfer from water to glass cover inside the solar still is done by three possible ways called evaporation, convection and radiation, Hence total internal heat transfer coefficient of solar still is sum of all three possible ways heat transfer coefficients,

$$h_1 = h_{cw-g} + h_{ew-g} + h_{rw-g} \qquad (19)$$

In equation (19), h_1 is total heat transfer coefficient and h_{cw-g}, h_{ew-g} and h_{rw-g} are called convective, evaporative and radiative heat transfer coefficients.

The radiative heat transfer coefficient between the water surface and condensing glass cover is given by is given by following equation:

$$h_{rw-g} = \varepsilon_{eff}\sigma\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right]\left(T_w + T_g + 546\right) \qquad (20)$$

Where, $\sigma = 5.669 \times 10^{-8}\, W/m^2K^4$

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \qquad (21)$$

Where, ε_g and ε_w are emissivities of basin water and glass cover and are given by

$$\varepsilon_w = \varepsilon_g = 0.9$$

5.5 Efficiency of Solar Still

Efficiency of solar still is simply defined as the ratio between thermal energy utilized to get distillate water in a period and energy supplied to solar still during the same period. The efficiency can be calculated by using the following equation,

$$\eta = \frac{\sum m_{ew}.h_{fg}}{\sum I(t).A_b + m_w.C_{pw}.(T_{wi} - T_a)} \times 100 \qquad (22)$$

Where $\sum m_{ew}$ is the distillate yield obtained in kg/m^2/day and
$\sum I(t)$ is the average solar radiation intensity in kWh/m^2/day

The energy required to evaporate water is the latent heat of vaporisation of water. This has a value of 2260 kJ/kg. This means that to produce 1 litre (i.e. 1 kg since the density of water is 1 kg/litre) of pure water by distilling brackish water requires a heat input of 2260 kJ.

5.6 Experimental Uncertainty

Data of a particular measurement for a number of days have been taken and an estimate of individual uncertainties of the sample values has been calculated. An estimate of internal uncertainty (U_i) has then been found by

$$U_i = \sqrt{\frac{\sum \sigma_i^2}{N^2}}$$

where σ_i is the standard deviation of the ith sample and N is the total number of samples.

VII. RESULTS AND DISCUSSIONS

Results of the experiments and numerical calculations carried out for studying the performance of various configurations of stepped type solar stills a represented in this section. The distillate yield is the major factor in determining the performance of a solar still. The efforts of all the researchers working in this area are directed towards obtaining the maximum distillate yield for the given set of conditions.

The experiments were conducted during the period of January 2018 to April 2018. All the solar stills were operated in the same climatic conditions to analyze the influence of the various configuration parameters on the distillate yield. Different variables are measured hourly such as Basin temperature (Tb), saline water temperature (Tw), inner glass cover temperature (Tgi), outer glass cover temperature (Tgo),ambient temperature (Ta), wind speed (V) and distillate yield (Yact).

6.1 Variation of Distillate Yield for Solar Stills A, B and C

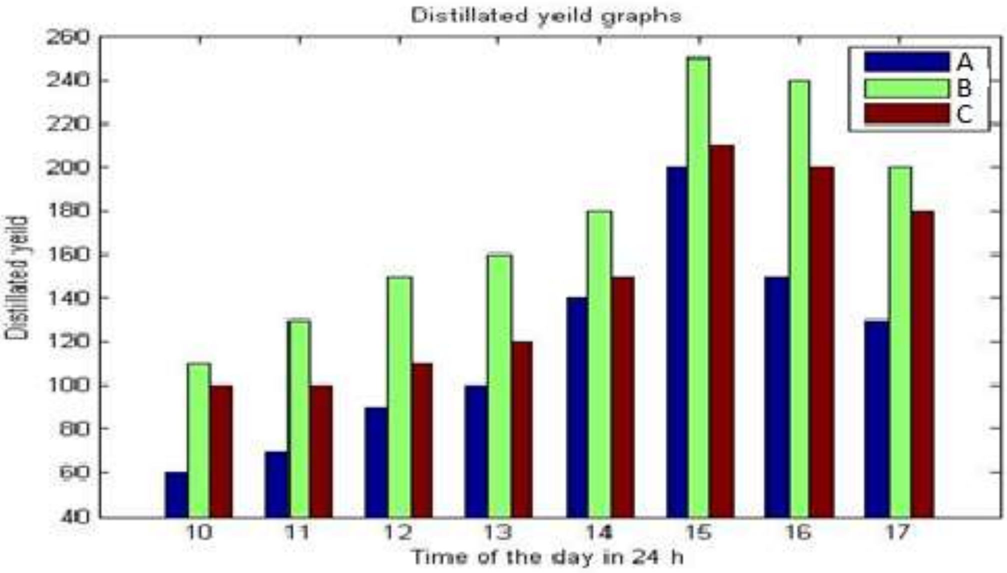


Fig 6.1 : Distillate yield with time of the day for solar stills A, B and C

6.2 Variation of Distillate Yield for Solar Stills A, D and E

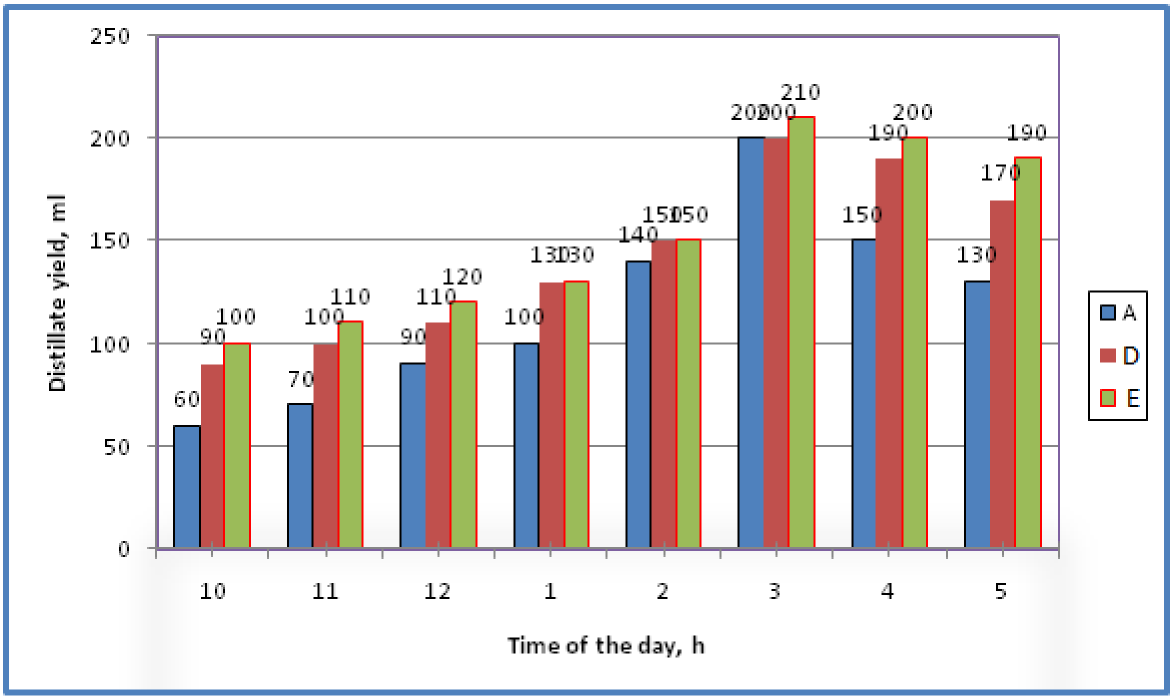


Fig.6.2 : Distillate yield with time of the day for solar stills A, D and E

VIII. CONCLUSION

Solar still A is provided flat surface area of the basin, Solar still B is provided convex type surface area of the basin and solar still C is provided concave type surface area of the basin . Solar still B was shown to have the highest distillate yield of 1680 ml and the highest thermal efficiency of about 33.80%. It has been observed that the distillate yield of convex type solar still B is 57.55% higher than that of A and distillate yield of concave type solar still C is 29.90% higher than that of A.

Solar still A is provided flat surface area of the basin, solar still D is provided with sponge cubes in the basin and solar still E is provided with circular fins at the basin. Solar still E was shown to have the highest distillate yield of 1430 ml and the highest thermal efficiency of about 28.54% . The yield of sponge type solar still D is 26.16% higher than that of A and distillate yield of fin type solar still E is 33.64% higher than that of A.

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