**IMPACT: International Journal of Research in Applied, Natural and Social Sciences (IMPACT: IJRANSS)**
**ISSN(P): 2347-4580; ISSN(E): 2321-8851**
**Vol. 4, Issue 12, Dec 2016, 99-106**


# DEVELOPMENT AND EVALUATION SOLAR STILL INTEGRATED WITH EVACUATED TUBES

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## ABSTRACT

This paper presents design and performance analysis of solar still integrated with evacuated tube collector in natural mode. Performance has been predicted theoretically in terms of water and inner glass cover temperatures, energy, exergy efficiencies and yield during typical summer days. The maximum daily energy and exergy efficiency was found to be 34.39 and 4.04 % during the sunshine hours for 3cm water depth, which decreases with increase in depth. However, the optimum performance has been found for basin water depth of 3 cm with distillate yield of about 8 liter. Hence integration of 10 evacuated tubes to the solar still with depth of 3 cm gives maximum daily yield.

**KEYWORDS:** Evacuated Tube Collector, Solar Still, Energy Efficiency, Exergy Efficiency

## INTRODUCTION

The demand for good quality drinking water is increasing steadily and could be a major problem in many developing countries. Distillation refers to the removal of salts and minerals in order to convert brackish/salt water to fresh water to make it suitable for human consumption. Conventional solar still continues to be a choice mainly for remote areas, due to the known advantages it has, such as use of free energy, eco-friendly, simple technological and constructional solutions that can be implemented locally (Mathioulakis and Belessiotis, 2003). Solar energy plays an important role for sustainable development in coming years as an alternative energy source. Solar stills are one of the most famous distillation technologies which use the solar energy in producing potable water. Many active designs of solar still (i.e. solar still integrated with parabolic concentrator, evacuated tube collector (ETC) and flat plate collectors (FPC), hybrid photovoltaic (PV-T) solar still) have been studied by various scientists to enhance the daily yield. The effects of shape and size by using plastic condensing cover for passive solar still have been proposed and used by various scientists (A. El-Nashar, 2009, Sharma and Diaz, 2011 and Tiwari, 2002). To enhance the distillated yield double basin solar still integrated with evacuated tubes was studied (Panchal, 2013). The present study carried out to evaluate performance of system and theoretical analysis was carried out to design single basin single slope solar still integrated with evacuated tubes.

## MATERIALS AND METHODS

### Experimental Setup

A solar still coupled with evacuated tube collector was developed and installed at Department of Unconventional Energy Sources and Electrical Engg. Dr. PDKV, Akola. It consisted of water basin, top cover, evacuated tube collector. A schematic view of solar still coupled with evacuated tube collector is shown in Figure 1.

As per design specifications of solar still coupled with evacuated tube collector having capacity of 60 lit/batch was designed and fabricated. The water basin was fabricated in square shape. Ten evacuated tube were fixed in the water basin. The basin was fabricated with mild still. The distillate channel was provided at the bottom of sloping side. The sloping side was covered with toughened glass of 4mm thickness. On the bottom side of the sloping side drain outlet was provided which was 0.75 inches. The evacuated tubes used in solar still were 2100 mm length and 58 mm outer diameter.

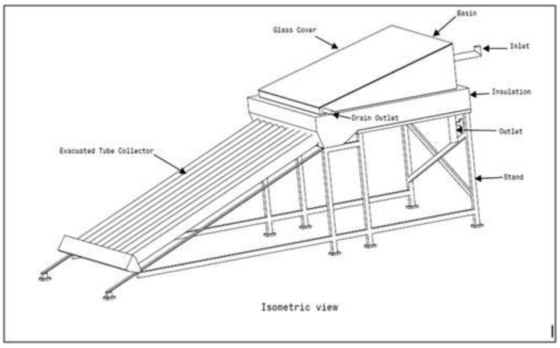


**Figure 1 Solar Still Coupled With Evacuated Tube Collector**

**Design Methodology**

To design the active solar still theoretical distillate yield calculated for which evaporative heat transfer coefficient calculated (Badran, 2011). Following table gives design parameters considered for design of solar still integrated with evacuated tube collector.

**Table 1: Initial Design Consideration for Design Solar Still**

| S. N. | Design parameters | Values |
|---|---|---|
| 1 | Location | Dr. PDKV, Akola |
| 2 | Latitude of Akola | $20^\circ.7''$ North |
| 3 | longitude of Akola | $77^\circ.07''$ East |
| 4 | Specific heat of water ($C_w$), kJ $kg^{-1}$ $C^{-1}$ | 4.17 |
| 5 | Average sunshine hours, h | 08 |
| 6 | Latent heat of vaporization of water (λ), $kJkg^{-1}$ | 2446.80 |
| 7 | Global radiation at Akola, W $m^{-2}$ | 750 |
| 8 | Density of water, $kg/m^3$ | 996.62 |
| 9. | Emissivity of glass | 0.92 |
| 10. | Emissivity of water | 0.98 |
| 11. | Thermal conductivity of glass, W/m K | 0.8 |
| 12. | Thermal conductivity of insulation, W/m K | 0.016 |
| 13. | Kinematic viscosity(v),$m^2/s$ | $8.84 \times 10^{-7}$ |
| 14. | Dynamic viscosity(μ),N $s/m^2$ | $2.86 \times 10^{-4}$ |

Design calculations were made using following equations

**Evaporation heat transfer coefficient from water to glass cover inner surface**, $W/m^2$ K

$$h_{ewgi} = 16.273 \times 10^{-3} \times h_{cwgi} \left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right]$$

Where, $h_{cwgi}$ = convective heat transfer coefficient from water to glass surface ($W/m^2K$).

$P_{gi}$ = partial vapour pressure at inner glass surface

$P_w$= Partial vapour pressure at water surface

$T_W$ = temperature of water

$T_{gi}$ = temperature of inner glass surface

Theoretical distillate yield

The hourly distillate yield obtained from solar still can be evaluated using following equation

$$M_{ew} = \frac{h_{ewgi}(T_W - T_{gi}) \times 3600}{L}$$

Where, $T_w$ = temperature of water in basin,°C

$T_{gi}$ = temperature of inner glass surface, °

L = Latent heat of vaporization of water (J/kg)

Base area

The calculation of the base area of the solar still is the most essential part as it is vital to know the area needed for desired amount of solar radiations to be incident in order to produce the required output. With a desired output of 10 litres of water, the amount of solar energy required can be calculated as follows:

$$M_{ew} = \frac{Q_{req}}{L}$$

$$Q_{req} = M_{ew} \times L$$

Now, In order to calculate the amount of incident solar energy ($Q_{inc}$) it is needed to analyze the data of the average amount of solar energy incident in Akola. The peak value of solar energy received in Akola throughout the year is 1000 $W/m^2$. Therefore,

Commercial glass transmits a minimum of 80% of light rays incident on it and Assuming a period of 8 hours per day of incident solar energy,

$$Q_{inc} = \frac{I \times sunshinehour \times incident}{1000}$$

Area of base required $A_b = \frac{Q_{req}}{Q_{inc}}$

The useful energy output of an evacuated tubes, (Hlaing and Soe, 2015)

$$Q_u = Q_{absorber} - Q_{thermallosses}$$

$$Q_{absorber} = A_a \times \eta_{opt} \times I$$

Where,

$Q_u$ =The useful energy output of an evacuated tube, W

$Q_{absorber}$ =The solar radiation absorbed by the tube, W

$A_a$ = Aperture area of the absorber, $m^2$

I = Solar radiation on horizontal surface, $W/m^2$

$\eta_{opt}$: Optical efficiency, %

$$Q_{thermallosses} = Q_{rad} \times Q_{con}$$

Where,

$Q_{rad}$ = The radiation heat transfer from outer glass tube, W

$Q_{con}$ = The convection heat transfer from outer glass tube, W

Collector efficiency, η

The thermal performance of evacuated tube solar collector can be estimated by the solar collector efficiency, η, which is defined as the ratio between the net heat gain and the solar radiation energy (Arora*et al*, 2011).

$$\eta = \frac{Q_u}{A_c \times I_c}$$

Where,

$Q_u$ =The useful energy output of an evacuated tube, W

$I_c$ :=The solar radiation on collector, $W/m^2$

$A_c$= Area of collector, $m^2$

Area of evacuated tubes

$$A_{et} = \pi \times r \times l$$

Where,

$A_{et}$ = Area of Evacuated tube, $m^2$

r = Radius of evacuated tube, m

l : Length of evacuated tube,

Number of tube

$$N_t = \frac{Collectorarea}{Areaoftube}$$

$N_t$ is the number of tube used in the collector

**Performance Analysis of System**

In the testing of solar still coupled with evacuated tube collector was fill up the water basin by water up to the fixed depth 3 cm. The experiment was conducted in the month of April 2016. The all temperature, relative humidity, solar radiation and wind velocity for solar still was measured. Experiment was conducted between 7:00am to 6:00 h day with evacuated tube. Outside glass surface temperature and inside glass temperature, relative humidity and wind speed were recorded at one hour interval during the test run. From the observations energy and exergy efficiency are calculated as follows.

**Energy and Exergy Efficiency**

The energy output from the solar still can be obtained using following equation (Kumar, 2014)

$$q_{out} = h_{ew} \times (T_s - T_{gi})$$

Instantaneous energy efficiency of the integrated system can be obtained as;

$$\eta_{is} = \frac{h_{ew}\times(T_w - T_{gi})}{I_s \times A_b + I_c \times A_a}$$

The exergy output of a the solar still can be obtained as follows

$$Ex_{evap} = h_{ew} \times A_b \times (T_w - T_{gi})\left(1 - \frac{T_a}{T_w}\right)$$

The maximum exergy of the solar radiation at temperature is expressed as follows,

$$Ex_{evap} = 0.933 \ \times I_{sun}$$

The exergy efficiency (ε) of the solar still is defined as the ratio of exergy output associated with distillate yield to the exergy input (radiation exergy), and can be expressed as

$$\varepsilon = \frac{Ex_{evap}}{Ex_{sun}}$$

Where,

ε : The exergy efficiency, %

$Ex_{evap}$:Exergy output of the solar still, W

$Ex_{sun}$: Exergy input of the solar still, W

$I_s$ : Solar radiation, W/m$^2$

$q_{out}$ : Energy output of solar still, W

## RESULTS AND DISCUSSIONS

**Design of Proposed System**

In order to design the solar still theoretical distillate yield was calculated from evaporative heat transfer coefficient. Then base area of solar still was calculated and it was found to be 1 m$^2$. The useful energy output from evacuated tubes was calculated from which collector area was determined and then number of tubes were calculated. The number of tubes was found to be 10 for theoretical distillate yield of about 10 liter for maximum water depth of about 3 cm. Table 2 gives design specification solar still coupled with evacuated tube collector.

**Table 2: Design Specification of Solar Still Integrated with Evacuated Tube Collector**

| Sr. No. | Particular | Specification |
|---|---|---|
| 1 | Collector area, $m^2$ | 2.10 |
| 2 | Area of basin, $m^2$ | 1.00 |
| 3 | Area of glass cover, $m^2$ | 1.04 |
| 4 | Angle of inclination of glass,˚ | 21.00 |
| 5 | Width of basin, m | 1.00 |
| 6 | Number of tube | 10.00 |
| 7 | Length of tube, m | 2.10 |
| 8 | Outer diameter of tube, m | 0.058 |
| 9 | Inner diameter of tube, m | 0.048 |
| 10 | Area of tube, $m^2$ | 0.19 |
| 11 | stand height, m | 1.25 |

**Performance Assessment of System**

Performance of system was evaluated in terms of energy and exergy efficiency. The solar still coupled with evacuated tube collector was evaluated at full load conditions. Temperature of water in the basin, glass cover inner surface, glass cover outer surface and water temperature in evacuated tube were recorded with the help of calibrated thermocouple in combination with digital temperature indicator (Zargistalukder*et al*, 2013). The results obtained from experiments are summarized as follows

Figure 2 shows the variation of temperature and solar radiation with respect to time. It has been observed that as intensity of solar radiation increased the temperature also increased and it was found to be maximum of about 43˚c at 14.00 h.

Average temperature of evacuated tube was found to be 68.08˚C with corresponding average ambient temperature of about 39.25˚C and solar radiation of about 541.72 W/$m^2$. As temperature in evacuated tube were measured to determine the useful energy from the collector, similarly the temperature of inner glass surface and outer glass surface was found to be in the range of 36.1 to 87.5 ˚C and 35.1 to 81.9ºC, respectively. The temperature of water in the basin was found to be in the range of 38.8 to 91.70˚C as it is the temperature which is responsible for evaporation of water in the basin (Hunashikatti, 2014).

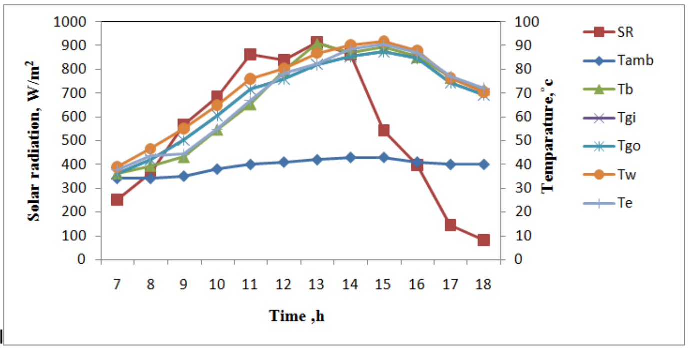


**Figure 2: A Hourly Variation of Temperature and Solar Radiation With Respect to Time for Water Sample**

Figure 3 shows the variation of distillate yield and solar radiation with respect to time. Performance of still mainly depends on the intensity of solar radiation absorbed by absorber plate and hence increased in distillate yield due to increased difference between temperature of water and glass cover temperature. It was observed that performance of still directly affected by solar radiation particularly at 14 h when maximum production was observed i.e 950 ml with corresponding maximum solar radiation of 862.4 W/m$^2$. Increased in solar radiation resulted in increase of water mass temperature, hence it would cause evaporation at faster rate. Therefore, the decreased solar radiation intensity would lower the system distillate yield. The solar radiation curve followed the same path as that of the distillate yield.

It was also observed that solar radiation was found to be low during late hours with corresponding distillate yield of about 800ml. It was observed that due to the increase in solar radiation the temperature of water in the basin increases until the intensity of radiation decreases. Therefore the distillate yield was maximum during late hours as compared to earlier. These results were found to be in agreement of (Yadav and Sudhakar, 2015). The solar radiation was found to be in the range of 80.6 to 913.7 W/m$^2$ with corresponding distillate yield of about 8.30 liter.

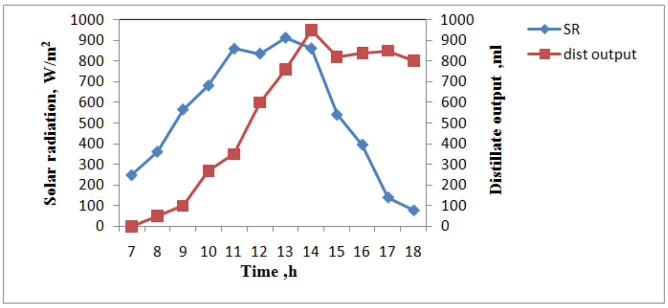


**Figure 3: A Variation of Distillate Yield and Solar Radiation with Respect to Time for Water Sample**

Figure 4 gives the variation of energy and exergy efficiency with respect to solar radiation. It has been observed that the energy efficiency was found to be minimum of about 7.70 to 26.53 % during early hours and similar trend were observed for exergy efficiency as it was directly related to solar radiation. The variation of energy efficiency of system was found to be in the range of 7.70 to 72.05 % during 9.00 and 15 h. The energy efficiency was found to be less during early hours due to is increase in heat flow rate to the saline water. The average energy efficiency was found to be 34.39 %.

Similar trend were observed for exergy efficiency as shown in figure 4. It was found to be less than energy efficiency because of incoming solar energy was destroyed due to irreversibility of different components. Exergy efficiency of the system was found to be in the range of 0.13 – 10.32 % between 9.00 and 15.00 h. The average exergy efficiency was found to be 4.04 %. The trend of curve was similar to that reported by (Shivkumar, 2013)**.**

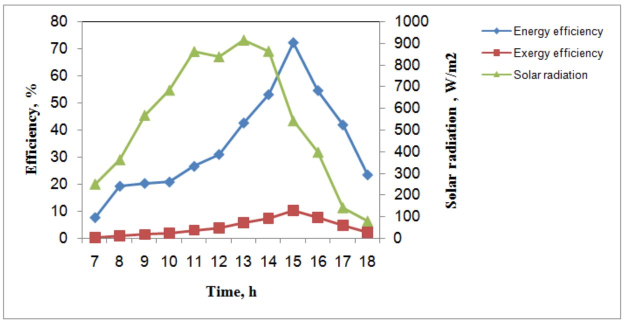


**Figure 4: A Variation of Energy, Exergy Efficiency and Solar Radiation with Respect to Time for Water Sample**

## CONCLUSIONS

A solar insolation is an important parameter in determination of yield from solar still and thus the output from still depends on the distribution of radiation throughout the day. The yield was maximum when the daily insolation and mean ambient temperature were consistently high. The distillate yield was found to be 8 liter with corresponding water depth of about 3cm. The maximum daily energy efficiency was found to be 34.39 % and exergy efficiency was 4.04 % due to thermal losses in system.

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