EXPERIMENTAL ANALYSIS OF PYRAMID WICK-TYPE SOLAR STILL

A.Prakash[1], R.Jayaprakash[2] and Sanjay Kumar[3]

[1] Research and Devlopment Centre, Bharathiar University, Coimbatore – 641 046, Tamilnadu, India.

[2] Solar Energy Laboratory, Department of Physics, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore – 641 020, Tamilnadu, India.

[3] Centre for Renewable Energy and Environmental Research, Muzaffarpur- 842 001, Bihar, India

E.mail: prakashrvscet@gmail.com

Abstract- An attempt has been made to design, fabricate and analyze a new pyramid wick-type solar still. In the basin of the still, saline water storage tank with four tilted portions has been made and selectively coated jute wick painted black has been spread on the tilted portions. The efficiency of the still has been found by conducting experiments and measuring various temperature elements of the still, solar radiation intensity and ambient temperature. The productivity of the proposed still is compared with that of the pyramid basin type solar still and it has been found that, an increase of 17.68% distillate yield. The average efficiency of the still is found to be 50.25% and it can produce 4.820 l/m2day in the local climatic conditions of Coimbatore, Tamilnadu, India.

Keywords: Ambient temperature, Distillate yield, Efficiency, Jute wick, Productivity, Pyramid solar still, Solar radiation

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1 Introduction

Life in earth is sustained by two most essential resources viz., water and energy. Conservation and preservation of water and energy is indispensable for the sustainable development of the globe. Water plays a vital role in human activities and seems to be precious resource. Scarcity of fresh water for drinking and domestic purposes has made the researchers all over the world to determine an alternate way of converting saline/brackish water into fresh water which is simple and viable. Solar distillation is one of the simplest techniques which uses solar energy for the production of distilled water from saline/brackish water. Researchers all over the world have made sincere efforts to find the parametric influence on the performance of different designs of solar still and attempted to optimize the parameters.

Tiwari*et al*. [1] have discussed the present status of solar distillation and inferred that passive distillation is economical in production of fresh drinking water using solar radiation. Bechki*et al*. [2] have made an attempt to predict the distillate yield of the coupled basin type solar stills in series.It has been inferred that the distillate yield is increased by 33.7% and 12% in second and third in the series. Velmurugan*et al*. [3] have confirmed that the basin type solar still is the simplest and proven one for effective distillation. The solar still with 60mm insulation thickness has significant effect on productivity than 30 and100 mm have been confirmed by Abdul Jabbar N. Khalifa*et al*. [4].

The solar still with concave wick surface has produced a higher distillate yield due to increased evaporation area [5]. Shakthivel*et al*. [6] have experimentally studied a regenerative solar still with jute cloth as energy storage medium and confirmed that jute cloth serves as a water transporting medium in the still. Increase in length and inclination of the reflector, increased the daily distillate productivity of the tilted wick type solar still have been concluded by Hiroshi Tanaka and YashuhitoNakatake [7]. KalidasaMurugavel and Srithar [8] have examined a tilted-wick type still with various wick materials and predicted that the light black cotton cloth with increased evaporation area produced a higher output. Arjunan*et al*. [9]

have studied different designs of solar stills and predicted that, the multiple wick-type solar still and roof type concrete solar distillation plant are found to be best and economical choice.

KalidasaMurugavel*et al*. [10] have studied a single basin solar still with various absorbing materials and predicted that ¾ inches sized quartzite rock is the most effective absorbing material in production. Increase in water flow rate of saline water in the basin have resulted in higher distillate yield but decrease in internal heat and mass transfer have been inferred by FarshadFarshchiTabrizi*et al*. [11]. A flexible packed media of coiled copper wires are considered as a good media for absorbing and transferring heat and a thermal storage system have been inferred by Khaled M.S. Eldalil [12].

Abdul JabbarN.Khalifa [13] has inferred that the condensing cover tilt angle of 20º angle produced large amount of distillate yield. Velmurugan*et al*. [3] have concluded that the yield is maximum when the tilt angle is equal to the latitude of the place. Further, Abdul JabbarN.Khalifa*et al*. [14] have reported that the tilt angles of the condensing glass cover from 10º -21º seems to be optimum and 30º- 60º are accepted tilt angles for better result. Raghuldev*et al*. [15] have shown that the water depth of 0.03m of an inverted absorber solar still has produced thrice the amount of output yield. The transmittance of the glazing has been included for the prediction of the thermal performance and inferred that the theoretical results correlated better with that of the experimental results [17]. Reilizadeh [18] have inferred that the back and side walls and the radiation received by each components of the still should be included to predict the thermal performance of the system.

Anil kumarTiwari and Tiwari [19] have analyzed the solar still by using the concept of solar fraction for six different water depths and inferred that the theoretical values are in accordance with experimental observations. Rajesh Tripathi and G.N. Tiwari [20-21] have studied the performance evaluation and predicted that solar fraction plays a vital role at lower values of solar altitude angles. Further RavishankarSathyamurthy*et al*. [22] have made an attempt to find the factors affecting the performance of triangular pyramid solar still and inferred that the increase in wind speed from 1.5m/s to 3 m/s and 4.5 m/s has shown in the increase of productivity by 8 and 15%. The productivity of triangular pyramid solar still with and without latent heat storage medium has been experimentally found by RavishankarSathyamurthy*et al*. [23] in Chennai, India. It has been found that the productivity of the still with and without latent heat storage medium was found to be 5.5 l/m^{2}day and 3.5 l/m^{2}day. Kabeel [24] has found the capability of glass pyramid shape with a multi-shelf solar system to produce water from humid air. The utilization of pyramid shape with four glass surfaces and multi-shelves increased the water productivity by 90-95%.

In the present work, a new pyramid tilted-wick solar still has been fabricated to overcome the inconveniences in the existing pyramid basin solar still. Experiments have been conducted in the department of Physics, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore, Tamilnadu, India.

Design of the pyramid tilted-wick solar still

A pyramid tilted-wick type solar still has been designed with an effective evaporation area of 1m^2 using mild steel to withstand throughout the year. The still is enclosed in a double walled plywood box with a gap of 0.05m. Glasswool is filled in the gap to minimize the heat loss by thermal conduction. Glasswool has thermal conductivity of 0.0038 W/mK and served as a good thermal insulator for the still. The still has been covered by a pyramid made of glass with a thickess of 0.004m. The structure of the pyramid has been made using four pieces of glass cover in the form of a triangle with base and height of 1m and 0.056m. Inside the still, a saline water storage tank of 0.30m X 0.30m X 0.12m has been designed exactly in the center. Four tilted portions have been made and fixed at the four edges of the storage rank with rivets. The region inside the still has been painted black using mat black paint to absorb the incoming solar radiation effectively. An inlet pipe has been fixed at corner of the still at a height of 0.05m from the base to introduce the saline water into the storage tank.

A blackened blanket with required length and breadth has spread on the four tilted portions of the still and the remaining portion of the wicks has been prepared in a corrugated shape using a thermocole of thickness 0.002m and allowed to float in water in the storage tank. The saline water in the tank has been maintained in such a way that it cannot overflow on the tilted-wick portion. Hence the water level in the tank is maintained at 0.05m below the top surface of the tank. The water rises through the wick due to capillary action and flow towards the tilted-wick portion on the four sides. The corrugated floating wick surface has also been served as an evaporation area since the wick in the water tank floats on the surface of saline water. Collection channels have been fixed along the lower side of the inner glass cover surface in the four sides and joined. Distillate yield from the still drained to the measuring jar and has been measured with an interval of 30 minutes. Figure. 1 shows the photograph of the experimental pyramid tilted-wick type solar still. Thermocouples have been fixed at regular intervals in the tilted (four sides) and floating wick portion of the still to measure the temperature of the water flowing towards the wick surfaces. Thermocouples have also been fixed on the glass cover to measure the temperature at regular intervals of time.

Fig. 1 Photograph of the experimental pyramid tilted-wick type solar still

2 Experimental method

Experiments have been conducted with the proposed still with wick material in the basin as evaporating surface and without wick material in the basin in the month of April and May 2015 and temperature elements of the still has been measured at regular intervals (30 minutes) viz., glass cover, tilted-wick and floating wick temperatures. Calibrated Copper-Constantan thermocouples have been used to measure the temperature elements of the still. Solar radiation intensity and ambient temperature has been measured with pyranometer and digital thermometer during the working hours of the still. Experiments have been carried in the Department of Physics, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore, Tamilnadu, India. In pyramid tilted wick-type solar still the, the temperature of the four tilted wick-portion at any instant seems to be similar and thus the average of all the temperatures of the four tilted-wicks has been taken as tilted-wick temperature. Similarly the average of all the glass cover temperatures has been taken as glass cover temperature for the calculation of efficiency and amount of distillate yield produced.

The operation of a solar still is governed by two basic heat transfer modes namely internal and external heat transfer modes. The internal heat transfer occurs within the still and the external heat transfer occurs between the still and the atmosphere. The main difference between the internal and the external heat transfer is that, within the still convective heat transfer occurs simultaneously with evaporative mass transfer while in external heat transfer no such mass transfer occurs. Radiative heat transfer occurs in both the regions along with the other modes. In internal heat transfer mode, the solar radiation falling on the glass cover, after transmission, is absorbed by the tilted-wick and floating-wick surfaces. A part of the energy is utilized to heat the water flowing through the wicks due to capillary action. There is a transfer of energy from the tilted-wick and floating-wick surfaces to the glass cover by evaporation, convection and radiation, among which, the evaporative heat transfer has the major contribution. Externally, from the glass cover due to radiation and convection, heat energy transferred to the surroundings and termed as external heat transfer mode in the proposed still. The equations for the internal and external heat transfer coefficients have been given in the appendix.

3 Results and Discussion

Fig. 1 represents the variation of intensity of solar radiation and ambient temperature for one of the two typical experimental days for pyramid wick-type and pyramid basin type solar still. From the figure it is observed that the intensity of solar radiation gradually increases during forenoon and reaches the maximum of 1035 W/m² and 954 W/m² for pyramid wick and basin solar still at 1pm. During the afternoon hours, the intensity of solar radiation decreases gradually. For both the experimental days, the intensity of solar radiation has same trend and thus both the days are given the same weightage for the calculation of instantaneous efficiency and distillate yield. Similarly, the variation of ambient temperature shows same trend for both the experimental days. The maximum intensity of solar radiation for all the experimental days lies during the time between 12.30pm to 1pm. The variation of tilted-wick, floating-wick, water temperature and glass temperatures of the pyramid wick and pyramid basin solar still has been plotted against the working hours of the day is depicted in the Fig. 2. It is observed that the glass temperature for both pyramid wick and basin solar still seems to be varying with same trend throughout the working hours of the day. In pyramid wick type solar still, the temperature difference between evaporating surfaces (floating wick and tilted wick) and the condensing surfaces is large as the thermal capacity of the water content in the wick due to capillary action is small. In the case of pyramid basin solar still, large thermal capacity of basin water led to the decrease in temperature difference between evaporating and condensing surface.

Fig. 3 represents the convective, evaporative and Radiative heat transfer coefficients from the evaporating surface (wick and basin) to the condensing surface (glass) for pyramid wick and basin solar still for one of the typical days in the working hours of the still. It has been found that the convective, evaporative and Radiative heat transfer coefficients for the pyramid wick solar still is higher than that for the pyramid basin solar still throughout the working hours of the day. This is because of the low thermal capacity of water in the tilted and floating wick as the saline water flows through the tilted wick portion slowly due to capillary action. But in the case of pyramid basin solar still, saline water in the basin has large thermal capacity leading to take much time for the water to get heated for evaporation. Due to this factor, evaporation and radiation rate are always smaller than that of the pyramid wick type solar still. In both pyramid wick and basin solar still, the convective heat transfer coefficient is smaller than the Radiative and evaporative heat transfer coefficients. This is due to the fact that, pyramid shape condensing surface has an advantage of suppressing convection of air inside the still.

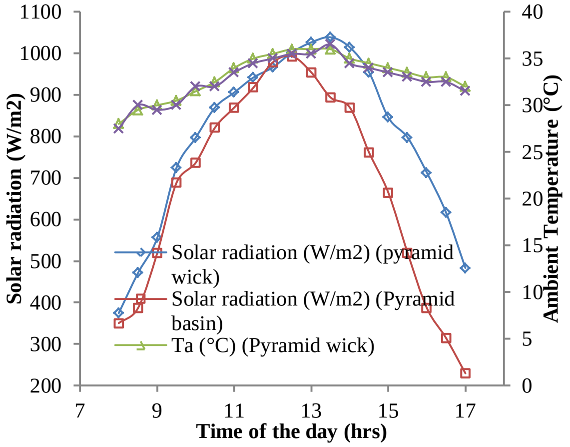

Fig. 1 Variation of solar radiation and ambient temperature

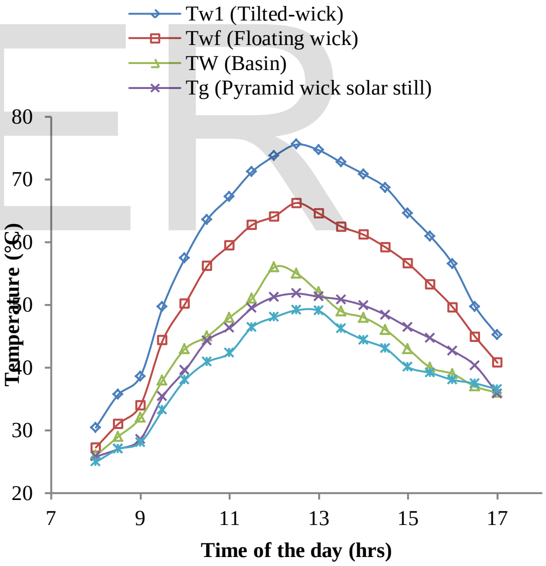

Fig. 2 Variation of tilted-wick, floating-wick, water and glass temperature for pyramid wick and pyramid basin solar still

Therefore, the total internal heat transfer rate of pyramid wick solar still is higher than the pyramid basin solar still leading to the increased rate of distillate yield and efficiency. Moreover, the tilted wick portion in pyramid wick solar still is almost parallel to the condensing surface led to the evaporation rate between parallel plane surfaces and exist in large temperature difference between evaporating and condensing surface.

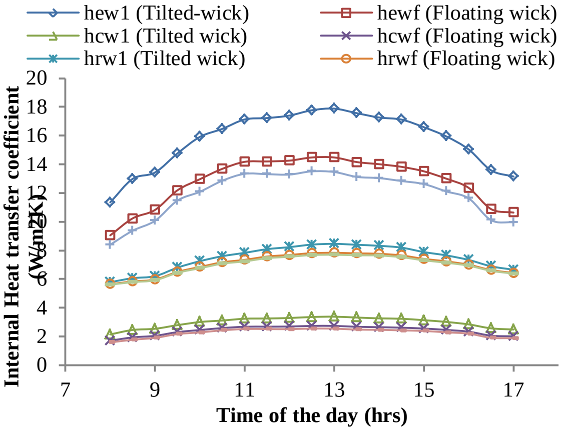

Fig. 3 Variation of internal heat transfer coefficient for pyramid wick and basin solar still

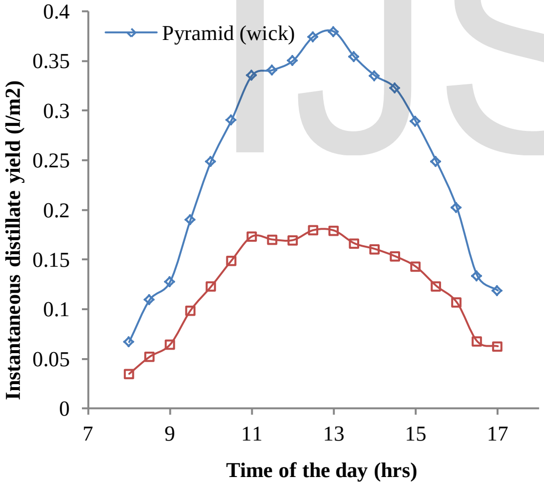

Fig. 4 Instantaneous distillate yield for pyramid wick and basin solar still

Fir. 4 represents the instantaneous distillate yield for pyramid wick and basin solar still with respect to the working hours of the still. It has been observed that the hourly distillate yield for both the still increases gradually with respect to the intensity of solar radiation and reached a maximum distillate at 1pm. For pyramid wick type solar still, the distillate yield of 0.380 litre has obtained at 1pm and 0.180 litre for pyramid basin solar still at 1pm. In wick type solar still, saline water due to capillary action, drops of water flow through the tilted wick portion making thermal capacity of evaporating water small enough as much as possible. In the basin type solar still, the thermal capacity of water is large and evaporation rate decreases though the intensity of radiation is high.

The instantaneous efficiency of both the stills has been depicted in Fig. 5 and it has been observed that, the efficiency of the wick solar still is higher than the basin solar still throughout the working hours of the stills. The average efficiency of the wick and basin type solar still are found to be 50.25 and 35.20% respectively. Moreover, the instantaneous efficiency of both the stills has dependence on the intensity of solar radiation. It has same trend as that of the solar radiation.

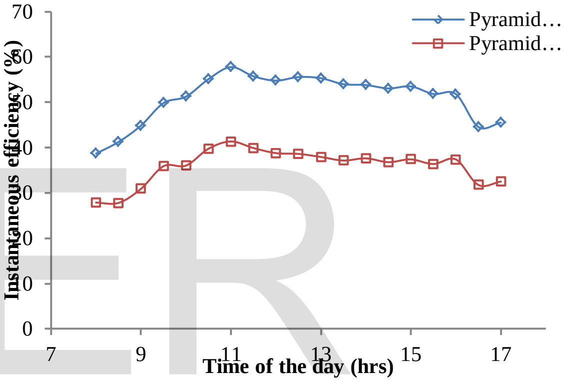

Fig. 5 Instantaneous efficiency of pyramid wick and basin solar still

4 Conclusion

The following conclusions have been drawn from the following studies carried out

i. The pyramid shape condensing surface for the still led to the evaporation process taking place between two parallel plane surfaces

ii. The total internal heat transfer from evaporating to condensing surface for pyramid wick solar still is higher than that of the pyramid basin solar still confirming the suitability of the wick solar still in the local climatic conditions of Coimbatore

iii. The instantaneous distillate yield and efficiency of the wick solar still again confirming the higher productivity of wick solar sill than conventional basin solar still

iv. Thermal capacity of saline water can be reduced using the wick to increase the evaporation rate leading to more mass transfer rate inside the still

v. The average efficiency of the pyramid wick solar still is found to be 50.25% with a total distillate yield in 24hrs cycle of 5.25 l/m^2day.

vi. It has been confirmed that pyramid wick solar still has better efficiency than the pyramid basin solar still.

Appendix

Convective heat transfer coefficient can be found by

$$h_{cw} = 0.884 \times \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3}$$

The rate of convective heat transfer is given by

$$q_{cw} = h_{cw}(T_w - T_g)$$

The coefficient of heat transfer from water surface to the glass cover and is given by

$$h_{rw} = \varepsilon_{ff}\,\sigma\left[((T_w + 273)^2 + (T_g + 273)^2 (T_w + T_g + 546)\right]$$

$$\varepsilon_{ff} = \left[\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1 \right]$$

The rate of radiative heat transfer (q_{rw}) from water surface to the glass cover is given by

$$q_{rw} = h_{rw}(T_w - T_g)$$

$$T_{sky} = T_a - 6$$

and

$$q_{cg} = h_{cg}(T_g - T_a)$$

where (a) $h_{cg} = 2.8 + 3.0V$ (Watmuff*et al.*,1977)

(b) $h_{cg} = 5.7 + 3.8V$ (Duffie and Beckman, 1980)

V is the wind velocity.

Instantaneous distillate yield

The distillate water output is the amount of energy utilized in vaporizing the water in the still over the latent heat of vaporization of water. Then the mass of hourly distillate output from the still of evaporation area is given by

Internal heat transfer modes

The coefficient of evaporative heat transfer is given by

$$h_{ew} = 0.0163 \times h_{cw}$$

The rate of evaporative heat transfer is given by

$$q_{ew} = h_{ew}(T_w - T_g)$$

External heat transfer mode

The external radiation and convection losses from the glass cover to ambient can be expressed as

$$q_a = q_{rg} + q_{cg}$$

where $q_{rg} = \varepsilon_g \sigma\left[(T_g + 273)^4 - (T_{sky} + 273)^4\right]$

$$q_{rg} = h_{rg}(T_g - T_a)$$

where $h_{rg} = \dfrac{\varepsilon_g \sigma\left[(T_g + 273)^4 - (T_{sky} + 273)^4\right]}{(T_g - T_a)}$

$$m_w = \frac{q_{ew} \times 60 \times 60 \times A_s}{L} \text{ kg/ } A_s \text{ hr.}$$

Instantaneous efficiency

At thermal equilibrium, the evaporation process inside the distiller to be isobaric, all the absorbed solar radiation is utilized for evaporation and thermal losses.

Hence the instantaneous efficiency is defined as

$$\eta = \frac{m_w \times L}{A_s \times I(t)}$$

where m_w is the hourly distillate output from the still.

NOMENCLATURE

h_{cb} -Convective heat transfer coefficient from the bottom of insulation to ambient, W/m^2°C
h_{rb} -Radiative heat transfer coefficient from the bottom of insulation to ambient, W/m^2°C
h_w -Convective heat transfer coefficient from the basin liner to water or vice versa, W/m^2°C
m_w -Distillate output, kg/m^2/s
q -Rate of heat transferred, W/m^2
T -Temperature, °C
T_a -Ambient air temperature, °C
T_g -Glass cover temperature, °C
T_{sky} -Sky temperature, °C
T_w -Water temperature, °C
U_L -Overall heat transfer of a still, W/m^2°C
V -Wind velocity, m/s

GREEK SYMBOLS

ε_g -Emmisivity of glass cover
ε_w -Emmisivity of water surface
η -Thermal efficiency of the system (percentage)
σ -Stefan –Boltzman constant (5.66 * 10^{-8} W/m^{2}K^4)

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