EXPERIMENTAL ANALYSIS OF PYRAMID SOLAR STILL WITH DIFFERENT ABSORBING MATERIALS

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Abstract: In the present work, an attempt has been made to determine the best absorbing material in the basin of pyramid wick-type solar still to produce high distillate yield. Three different absorbing materials viz., jute wick, sponge and charcoal have been selected and used in the basin of the still and the corresponding productivity has been measured. Among these absorbing materials, jute-wick in the basin has produced high distillate yield due to the low thermal capacity of the still. Jute wick is spread over the four tilted portions orienting towards north, south, east and west inside the still with saline water in the middle of the basin. The capillary action of the jute wick kept the wick surface wet throughout the working hours of the day with very low thermal capacity. It has been observed that, the total distillate yield over 24hr cycle of 3.25, 3.19 and 4.5 lit/day for charcoal, sponge and jute wick respectively.

Index Terms - Wick-type solar still, pyramid, distillate yield, absorbing materials.

I. INTRODUCTION

Solar distillation is one of the thermal applications of solar energy and viable technology for the distillation of saline/brackish water. Many researchers all over the world have designed and tested different designs of solar stills and documented. It has been observed that, absorbing materials in the basin can improve the productivity in a reasonable manner due the low thermal capacity and absorbance of the materials used in the basin. Minasian and Al-karaghouli (1995) have tested the improved solar still by connecting conventional basin-type solar still with a wick-type solar still. Provisions have been made to feed waste hot-water from the wick solar still to the basin solar still and also regenerative effect was incorporated in the basin solar still. It has been found that the improved solar still is more efficient than other types of solar still. A concave wick evaporating surface and pyramid shaped condensing surface has been designed by Kabeel (2009) and the results of the study revealed that the proposed still with increased evaporation surface has provided day time productivity of 4.1 L/m^2 with maximum instantaneous efficiency of 45% and average daily efficiency of 30%. Mahdi *et al.* (2011) have designed a tilted-wick type solar still with charcoal cloth as an absorbing material, evaporator and water transport medium. It has been concluded that the increase in saline water flow rate in charcoal cloth decreases the efficiency of the still. A basin type double slope solar still made of mild steel has been fabricated and tested with different wick materials and configuration of aluminium fins by Kalidasa Murugavel and Srithar (2011). Results of the test confirmed that light black cotton cloth spread over the rectangular aluminium fin in lengthwise direction has given high productivity of distillate yield. Matrawy *et al.* (2015) have tested a new corrugated wick-type solar still i.e., the porous material. It has been observed that the proposed mathematical model has given results in accordance with experimental results for productivity and efficiency. Also, the optimum inclination of reflector is found to be 30° with respect to the vertical direction. Samuel Hansen *et al.* (2015) have carried out experiment with an inclined solar still with different absorbing materials viz., wood pulp, paper wick, wicking waver coral fleece fabric and polystyrene sponge on flat, stepped and stepped absorber with wire mesh. Results have shown that still with water coral fleece fabric ove34 weir mesh-stepped absorber plate has provided productivity of 4.8 L/day. Comparison of the performance of conventional solar still and corrugated wick solar still with different nanoparticles for absorption of solar radiation has been done by Omar *et al.* (2015). It has been found that corrugated wick-type solar still with cuprous and aluminium oxide nanoparticles has enhance productivity of 285.10% and 254.88%. Ravi Gugulotyhy *et al.* (2015) have used phase change materials of potassium dichromate, magnesium sulphate hepta hydrate and sodium acetate for absorbing energy in the solar still to enhance the performance of the solar still and analyzed. Elango *et al.* (2015) have used different nanofluids in the single slope solar still and comparison for the performance of the still with and without nanofluids in the basin has been presented. It has been concluded that the productivity increased by 29.95%, 12.67% and 18.63% for Aluminium oxide, Zinc oxide and Tin oxide nanofluids. A thorough comprehensive review of various designs of solar still by incorporating different parameters viz., heat transfer analysis, energy analysis, exergy analysis, thermal efficiency and economic analysis has done by Saurabh Yadav and Sudhakar (2015) and results have been presented. Sholaby *et al.* (2016) have designed and tested a new V-corrugated abosorber solar still with built-in phase change materials. The productivity has increased by 11.7% for the PCM paraffin wax and 12.1% for corrugated wick over the absorber plate along with PCM. Kaushal *et al.* (2016) have designed, fabricated and tested a tilted double glass cover and single vertical distillation cell of two closely spaced vertical parallel plates. The vertical plates have been cooled by third vertical plate and found that the cumulative efficiency of the still has 10-15% magnitude higher than that of the conventional basin type solar still.

Rajaseenivasan *et al.* (2016) have designed glass basing solar still with two sections of preheater (lower) and evaporator (upper) by a glass plate. The lower basin has provided with fins to hold the energy storing materials viz., charcoal, sand and metal scraps. It has been confirmed that the increase in depth of saline water in the lower basin decreases the productivity and still with charcoal has produced the productivity of 3.61 kg/day. The performance of corrugated-wick solar still has been found using double layer wick material and reflectors in the still. It has been revealed that the double layer wick material over the corrugated structure and reflector4 has given an efficiency of 59%.

Alaian *et al.* (2016) have tested the performance of solar still augmented with pin-finned wick evaporation surface and compared with the performance of conventional solar still. The productivity of the still with pin-finned wick surface is 23% higher than conventional solar still and the efficiency is found to be 55%. Arun Kumar *et al.* (2016) have compared the performance of conventional solar still and still with agitation effect and external condensation surface. The productivity of the solar still with agitation and external condenser provided the distillate yield of 39.49% higher than the conventional solar still. Hitesh N. Panchal (2016) has presented a detail review of use of thermal energy storage materials for the enhancement of distillate yield. In the review, the impact of thermal energy storage materials on the performance of various designs of solar stills has been documented. Further Dsilva Winfred Rufun *et al.* (2016) have undergone a review based on design, performance and materials for solar stills and revealed that the advance materials of phase change materials and nanocomposites has significant impact for the enhancement of productivity of solar still.

In the present work, energy absorbing materials of charcoal, sponge and jute-wick has been used in the pyramid wick-type solar still. The absorbing materials of charcoal and sponge has been introduced in the basin of the still directly and jute-wick has been spread over the structure made of four titled-portion along with storage tank for saline water. Jute-wick has been made black by spraying mat black paint over the wick to increase the absorption of solar energy.

II. 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. Glass wool is filled in the gap to minimize the heat loss by thermal conduction. Glass wool 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 thickness 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 one of the corner of the still at a height of 0.05m from the base to introduce the saline water into the storage tank.

A blackened jute-wick 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 as 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.

Charcoal and sponge materials are directly introduced in the basin saline water and the performance of the proposed system is tested. 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 arrangement made inside the still for the jute wick material to be spread over the tilted portion. Figure. 2 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. Similarly, the absorbing materials of charcoal and sponge can also be placed in the basin holding the saline water instead of four tilted portion with storage water tank.

Fig. 1 Photograph of the arrangement of the tilted portion for the jute wick to be spread

Fig. 2 Photograph of the experimental pyramid tilted-wick type solar still

III. Experimental method

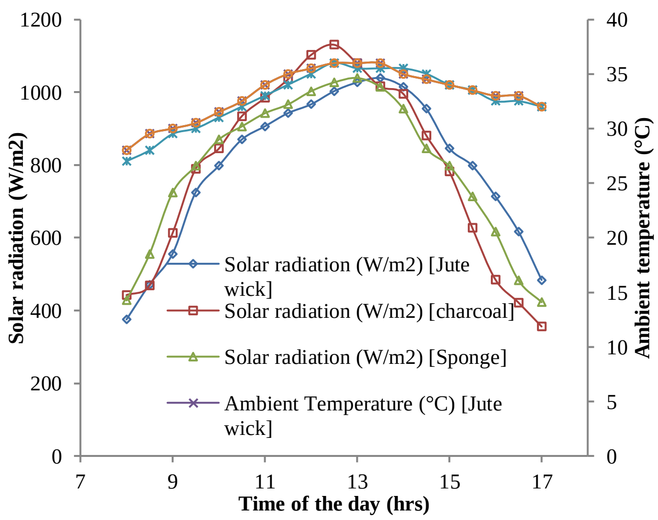
Experiments have been conducted with the proposed still with jute-wick, charcoal and sponge material in the basin in the month of April and May 2016 and temperature elements of the still has been measured at regular intervals (30 minutes) separately. Calibrated Copper-Constantan thermocouples have been 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 out 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 same and 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.

IV. Results and discussion

Experimental observations with the still incorporated by charcoal, sponge and jute-wick materials have been made in the month of April and May 2016. It is observed that the solar radiation intensity reached the maximum on these days due to cloudless nature during summer days. Observations have been considered for the comparison of the performance of the still with different absorbing materials for one of the typical days with charcoal, sponge and jute-wick materials. Fig. 3 shows the variation of intensity of solar radiation and ambient temperature for one of the typical days for the three absorbing materials in the basin of pyramid wick-type solar still.

Fig. 3 Variation of solar radiation and ambient temperature for jute wick, charcoal and sponge absorbing materials



From the figure, it is observed that the variation of solar radiation and ambient temperature for the working days for charcoal, sponge and jute wick materials in the pyramid wick-type solar still has conjoint trend. Since the variation seems to be same for the working days with different absorbing materials, those days are given equal weightage while studying the performance of the system with different absorbing materials. Condensing glass cover and evaporating water temperature have been measured with time interval of 30 minutes for the still with jute wick, charcoal and sponge materials. Fig. 4 shows the variation of condensing glass cover and evaporating water temperature for the three absorbing materials used in the pyramid solar still. From the figure, it is observed that the difference in temperature between the condensing glass cover and evaporating water temperature is higher for jute wick material than the other two absorbing materials i.e., sponge and charcoal. This is due to lower thermal capacity of the evaporating water in the jute wick material i.e., the saline water flow towards the four tilted portion due to capillary action. The water flowing towards the tilted-wick portion keeps the wick material wet throughout the working hours of the still and also thin layer of water in the wick material maintains lower thermal capacity. Sponge and charcoal materials in the basin of the still have higher thermal capacity and large amount of energy and time is required to raise the temperature of the water to be evaporated.

Fig. 4 Variation of condensing glass cover and evaporating water temperature for jute wick, charcoal and sponge absorbing materials

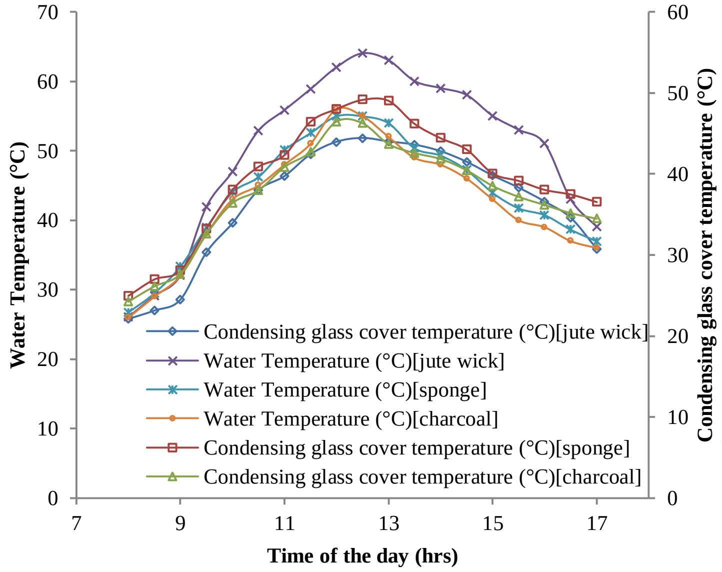


Fig. 5 Variation of evaporative heat transfer coefficient for jutewick, sponge and charcoal absorbing materials in the proposed still

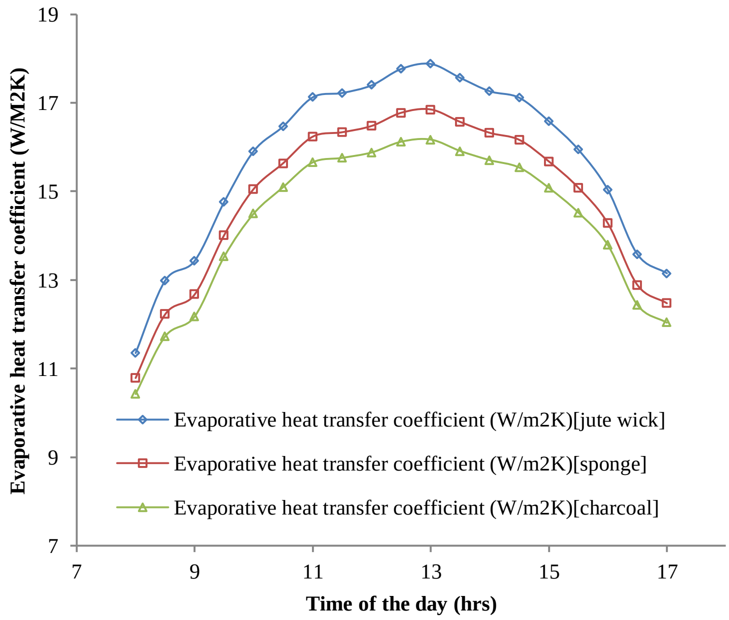


Fig. 6 Variation of convective heat transfer coefficient for jutewick, sponge and charcoal absorbing materials in the proposed still

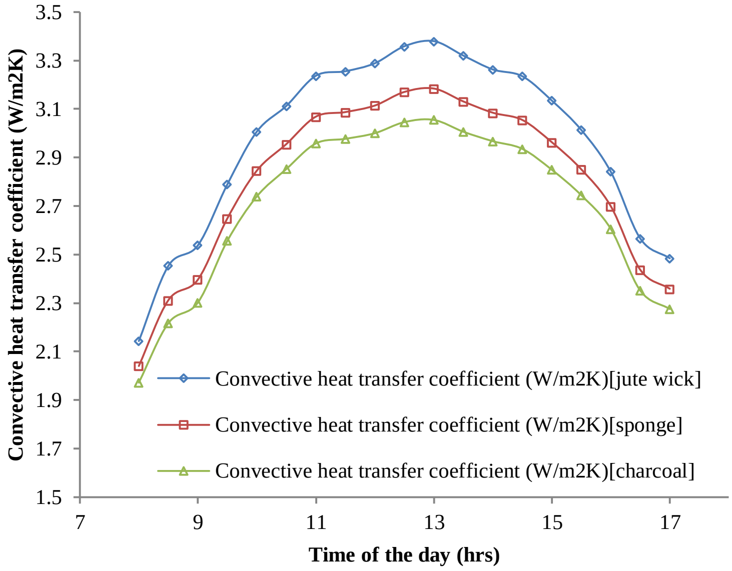


Fig. 5 and 6 shows the variation of evaporative and convective heat transfer coefficients for the three absorbing materials in the proposed still. It has been observed that both the evaporative and convective heat transfer coefficients for the jute wick material in the basin is more pronounced than the other two sponges and charcoal absorbing materials. Since the thermal capacity plays a vital role to influence the evaporation and convection, from the figure, it is clear that for the jute wick material in the still, evaporation of saline water and convection of thermal energy inside the still is high compared to sponge and charcoal absorbing materials. Charcoal and sponge materials have large number of pores and saline water diffuses through the pores to increase the thermal capacity of the still. Though the convection inside the still for the three absorbing materials has same trend, the convection for jute-wick materials in the tilted portion is higher and led to the trapping of higher thermal energy inside the still. The night time collection of the still with jute wick material in the basin is higher due to flow of thin layer of water in the jute wick during daytime.

Fig. 7 Variation of instantaneous distillate yield for jute wick, sponge and charcoal absorbing materials

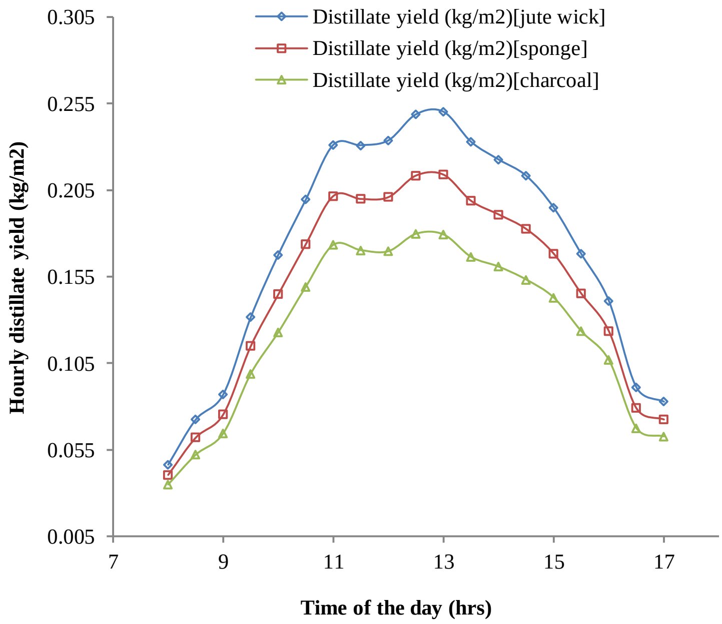
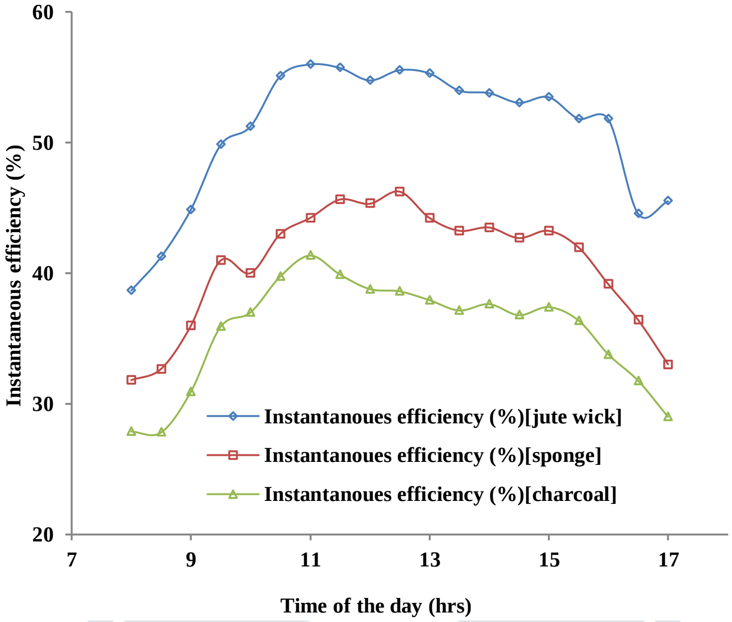


Fig. 7 shows the variation of distillate yield for the three absorbing materials in the still. It is observed that the instantaneous distillate yield for jute wick is higher compared to sponge and charcoal absorbing materials in the still. The total daytime collection of distillate yield for jute wick is found to be 3.247 kg/m^2 while it is 2.804 and 2.380 kg/m^2 for sponge and charcoal materials respectively. It is found that, the instantaneous distillate yield for the jute wick is higher throughout the working hours of the still than the sponge and charcoal materials in the basin. The night time collection of the still with jute wick, sponge and charcoal are found to be 1.240, 0.850 and 0.750 kg/m^2 respectively reflecting the pronounced distillate yield for jute wick. Over 24hr cycle, total distillate yield for jute wick, sponge and charcoal are 4.487, 3.654 and 3.13 kg/m^{2}day.

Based on the distillate yield, instantaneous efficiency of the still with the three absorbing materials viz., jute wick, sponge and charcoal has been measured and also evaluated using Dunkle's expression. Fig. 8 shows the variation of instantaneous efficiency of the still with jute wick, sponge and charcoal in the proposed still. It is observed that, the instantaneous efficiency for the three materials in the basin of the still gradually increases during the forenoon session and reached a maximum at 1.30 pm. In the evening hours, efficiency gradually decreases from maximum. Among the three absorbing materials, jute wick has given higher distillate yield throughout the working hours of the day while the other two absorbing materials have produced moderate distillate yield due to acceptable limit of effective evaporation. The daily average efficiency of 50.86%, 40.69% and 35.57% has been obtained for jute wick, sponge and charcoal respectively.

Fig. 8 Variation of instantaneous efficiency for jute wick, sponge and charcoal materials in the pyramid wick-type solar still



V. CONCLUSION

The following conclusions have been drawn from these experimental study and are

(i) Jute wick in the pyramid solar has produced a total distillate yield of 4.487 kg/m^{2}day with daily average efficiency of 50.86%.

(ii) The capillarity of the jute wick has significantly reduced the stagnancy of saline water in the material and leading to lower thermal capacity of water with least water depth throughout the working hours of the still

(iii) The performance of the still with jute wick material is good due to the increased evaporation area by the introduction of tilted portion arrangement inside the still

(iv) The salt scale formation in the basin has been significantly reduced for the jute wick material in the basin as the saline water is flowing due to the capillarity of the wick.

(v) The instantaneous distillate yield and efficiency of the proposed still with jute wick absorbing material is pronounced during the daytime and also the night time production increased a lot due to less thermal capacity of the system.

(vi) The proposed still with pyramid shaped condensing surface has distributed the vapor to be condensed in a uniform manner and led to the decrease in temperature of condensing glass cover.

(vii) The difference in between the evaporating water and condensing glass cover temperature is higher for the jute wick absorbing material.

Optimization of design and climatic parameters of the still with jute wick materials will lead to the large scale installations for future use.

VI. APPENDIX

6.1. Internal heat transfer modes

Convective heat transfer coefficient can be found by

$$h_{cw} = 0.884 \times \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3} \quad (6.1)$$

The rate of convective heat transfer is given by

$$q_{cw} = h_{cw}(T_w - T_g) \quad (6.2)$$

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

$$h_{rw} = \varepsilon_{ff}\sigma\left[((T_w + 273)^2 + (T_g + 273)^2 (T_w + T_g + 546)\right] \quad (6.3)$$

$$\varepsilon_{ff} = \left[\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right] \quad (6.4)$$

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

$$q_{rw} = h_{rw}(T_w - T_g) \quad (6.5)$$

The coefficient of evaporative heat transfer is given by

$$h_{ew} = 0.0163 \times h_{cw} \quad (6.6)$$

The rate of evaporative heat transfer is given by

$$q_{ew} = h_{ew}(T_w - T_g) \quad (6.7)$$

6.2 External heat transfer mode

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

$$q_a = q_{rg} + q_{cg} \quad (6.8)$$

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

$$q_{rg} = h_{rg}(T_g - T_a) \qquad (6.9)$$

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

$$T_{sky} = T_a - 6 \quad (6.10)$$

and

$$q_{cg} = h_{cg}(T_g - T_a) \quad (6.11)$$

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.

6.3 Instantaneous distillate yield

The distillate water output is the amount of energy utilized in vaporizing 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

$$m_w = \frac{q_{ew} \times 60 \times 60 \times A_s}{L} \text{ kg/ } A_s \text{ hr.} \qquad (6.12)$$

6.4 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

$$\eta = \frac{m_w \times L}{A_s \times I(t)} \quad (6.13)$$

where m_w is the hourly distillate output from the still.

6.5 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

6.6 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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