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THERMAL EVALUATION OF SOLAR WATER DESALINATION SYSTEM WITH EVACUATED TUBES

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ABSTRACT

A solar still coupled with evacuated tube collector was designed and developed for distillation of water. As the wind velocity increased, the convective heat loss from glass cover to ambient increased, hence the glass cover temperature decreased which helped to increase the water glass cover temperature difference thereby the overall yield increased. Heat loss coefficient increases until it reaches maximum in solar noon due to high temperature difference between the inside still and the ambient temperature at this time, then it decreased at afternoon. The average internal heat transfer coefficient i.e. convective, radiative and evaporative was found to be 3.7, 8.33, 99.24 W/m^{2}K, respectively. The external heat transfer coefficient such as average overall top heat loss coefficient was found to be 9.92 W/m^{2}K as compared to bottom heat loss coefficient 0.31 W/m^{2}K. Therefore distillate yield was found to be maximum.

KEYWORDS: Evacuated Tubes, Heat Transfer Coefficients, Heat Transfer Rate, Solar Still

INTRODUCTION

As world population and social-economic growth, societies are challenged to provide fresh water to meet those needs for all of their people. Water is the basic necessity for human along with food and air. There is almost no water left on Earth that is safe to drink without purification. Only 1 per cent of Earth's water is in a fresh, liquid state, and nearly all of this is polluted by both diseases and toxic chemicals. For this reason, purification of water supplies is extremely important. Moreover, typical purification systems are easily damaged or compromised by disasters, natural or otherwise. This results in a very challenging situation for individuals trying to prepare for such situations, and keep themselves and their families safe from the myriad diseases and toxic chemicals present in untreated water. Everyone wants to find out the solution of above problem with the available sources of energy in order to achieve pure water. Fortunately there is a solution to these problems.

Desalination 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 (E. Mathioulakis, 2003). Aybar (2006) has carried out mathematical modeling for an inclined solar water distillation system. Tiwari and Tiwari (2007) have recommended an optimum inclination angle of glass cover equal to the latitude of the place.

MATERIAL AND METHODS

Details of Experimental Set Up

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 (Gnanadson *et al*, 2011).

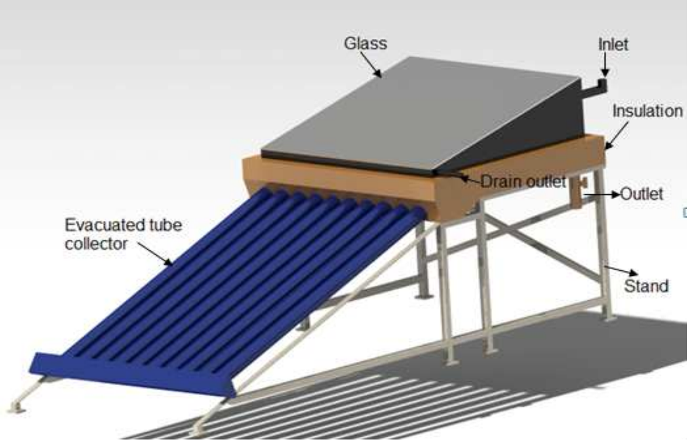

Figure 1: A Schematic View of Solar Still Coupled with Evacuated Tube Collector

Heat Transfer Mechanisms in a Solar Still

The heat transfer process in a solar still can be broadly classified into internal and external heat transfer processes based on energy flow in and out of the enclosed space. The internal heat transfer is responsible for the transportation of pure water in the vap our form leaving behind impurities in the basin itself, whereas the external heat transfer through the condensing cover is responsible for the condensation of pure vapour as distillate (Elango *et al*, 2014).

Internal Heat Transfer in a Solar Still

The heat exchange between water surface and glass cover inner surface of the solar still is known as internal heat transfer (Badran, 2011). There are three modes, namely convection, radiation and evaporation processes, by which the internal heat transfer process within the solar still is governed. These three modes of internal heat transfer process are described as follows:

- **Convection Heat Transfer**

Convection heat transfer process is complicated in nature by the fact that it involves fluid motion as well as heat conduction. The convection heat transfer strongly depends on fluid properties and geometry and roughness of solid surface involved. In a solar still, the convection heat transfer takes place between basin water and glass cover inner surface across humid air due to temperature difference between them.

The convective heat transfer rate inside the solar still can be expressed in terms of water temperature (T_w) and glass cover inner surface temperature (T_{gi}) by the following relation:

$$q_{cwgi} = h_{cwgi}\left(T_w - T_{gi}\right)$$

In the above expression, h_{cwgi} is the convective heat transfer coefficient between water mass and glass cover inner surface and can be calculated as follows:

$$h_{cwgi} = 0.884 \times [\left(T_w - T_{gi}\right) + \left[\frac{\left(P_w - P_{gi}\right)\left(T_w + 273\right)}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}}$$

The saturation vapour pressures at water temperature and glass cover inner surface temperature are evaluated by the following expressions:

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

$$P_{gi} = \exp[25.317 - (\frac{5144}{T_{gi} + 273})]$$

Radiation Heat Transfer

The radiation heat transfer occurs through a mechanism that involves the emission of internal energy of the object. The energy transfer by radiation is the fastest and it suffers no attenuation in a vacuum. Also, the radiation heat transfer occurs in solids as well as in liquids and gases. Even it can occur between two bodies separated by a medium which is colder than both the bodies. The radiative heat transfer occurs at inside of the solar still between water mass and glass cover inner surface.

The view factor plays a major role in determining the rate of radiative heat transfer. In solar still, the view factor is assumed as unity since the inclination of glass cover with horizontal is small.

The radiative heat transfer rate between water and glass cover inner surface can be obtained by the following relation.

$$q_{rwgi} = h_{rwgi}\left(T_w - T_{gi}\right)$$

$$h_{rwgi} = \varepsilon_{eff} \times \sigma \times \left[\left(T_w + 273\right)^2 + \left(T_{gi} + 273\right)^2\right]\left(T_w + T_{gi} + 546\right)$$

The effective emittance between water mass and glass cover is given as

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)^{-1}$$

- **Evaporation Heat Transfer**

Evaporation occurs at the liquid vapour interface when the vapour pressures less than the saturation pressure of the liquid at a given temperature. The evaporation heat transfer occurs in the solar still between water and water vapour interface.

The rate of evaporative heat transfer between water mass and glass cover inner surface is given by

$$q_{ewgi} = h_{ewgi}\left(T_w - T_{gi}\right)$$

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

The total internal heat transfer rate is the summation of convective, radiative, and evaporative heat transfer rates between water mass and glass cover inner surface which is given as.

$$q_{twgi} = q_{cwgi} + q_{rwgi} + q_{ewgi}$$

The total internal heat transfer coefficient between water mass and glass cover inner surface (h_{twgi}) is obtained by the following expression:

$$h_{twgi} = h_{cwgi} + h_{rwgi} + h_{ewgi}$$

The rate of conductive heat transfer from glass cover inner surface to the glass cover outer surface is given by

$$q_{cdgio} = \frac{K_g}{L_g}\left(T_{gi} - T_{go}\right)$$

External Heat Transfer in Solar Still

The external heat transfer consisted of conduction, convection, and radiation processes which are independent of each other (Gupta *et al*, 2013). It is considered as the loss of heat energy from the solar still to the atmosphere. The heat lose in the solar still from glass cover outer surface to the atmosphere is called as top loss heat transfer process and from water mass to the atmosphere through insulation is called as bottom and side loss heat transfer process. The higher the former the higher will be the yield from the solar still and lower the latter better will be the yield.

- **Top Loss Heat Transfer**

The heat energy from the glass cover outer surface is lost to the atmosphere by convection and radiation heat transfer processes. The convection heat loss from glass cover outer surface of the solar still to the atmosphere is given by

$$q_{cgoa} = h_{cgoa}\left(T_{go} - T_a\right)$$

The convective heat transfer coefficient (h_{cgoa}) is expressed in terms of wind velocity (v) as follows:

$$h_{cgoa} = 2.8 + (3 \times V)$$

The radiation heat loss from glass cover outer surface of the solar still to the surroundings is given by.

$$q_{rgoa} = h_{rgoa}(T_{go} - T_a)$$

The radiative heat transfer coefficient between glass cover outer surface and the surrounding is given as

$$h_{rgoa} = \varepsilon_g \times \sigma \times \left[\frac{(T_{go} + 273)^4 - (T_{sky} + 273)^4}{T_{go} - T_a}\right]$$

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

The total top heat loss is the summation of convective and radiative heat losses which is given as

$$q_{tgoa} = q_{cgoa} + q_{rgoa}$$

The total top heat loss coefficient between glass cover outer surface and atmosphere can be obtained by the following relation:

$$h_{tgoa} = h_{cgoa} + h_{rgoa}$$

The overall heat loss coefficient from glass cover inner surface to the ambient is given as

$$U_{tgia} = \frac{\frac{K_g}{L_g} \times h_{tgoa}}{\frac{K_g}{L_g} + h_{tgoa}}$$

The overall top heat loss coefficient from water mass to the atmosphere (U_{twa}) through the glass cover is expressed as

$$U_{twa} = \frac{h_{twgi} \times U_{tgia}}{h_{twgi} + U_{tgia}}$$

- **Bottom and Side Loss Heat Transfer**

The heat energy is lost from water to the atmosphere through basin liner and insulation by conduction, convection and radiation processes.

The rate of convective heat transfer between basin liner and the water mass (q_w) is given by

$$q_w = h_w(T_b - T_w)$$

Convective heat transfer coefficient from basin liner to water (h_w) is expressed by follow

$$h_w = \frac{K_w}{X_w} C(G_r \times P_r)^n$$

The rate of conduction heat transfer between basin liner and the atmosphere (q_b) is given by

$$q_b = h_b(T_b - T_a)$$

The heat transfer coefficient between basin liner and the atmosphere (h_b) through the insulation is

$$h_b = \left[\frac{L_{ins}}{K_{ins}} + \frac{1}{h_{tba}}\right]^{-1}$$

$$h_{tba} = 5.7 + (3.8 \times V)$$

The overall bottom heat loss coefficient between water mass and atmosphere is given by.

$$U_b = \frac{h_w \times h_b}{h_w + h_b}$$

The overall side heat loss coefficient between water mass and atmosphere is expressed as

$$U_{ss} = \left(\frac{A_{ss}}{A_b}\right) U_b$$

For lower water depth, the overall side heat loss coefficient (U_{ss}) can be neglected since the area of side walls losing heat (A_{ss}) is very small compared with area of basin (A_b) of the solar still.

The total bottom and side heat loss coefficient (U_{bs}) from water mass to atmosphere can be given by

$$U_{bs} = U_b + U_{ss}$$

For lower water depth, the overall side heat loss coefficient (U_{ss}) can be neglected since the area of side walls losing heat (A_{ss}) is very small compared with area of basin(A_b) of the solar still.

The overall external heat loss coefficient from water mass to the atmosphere through top, bottom and sides (U_{LS}) of the solar still is expressed as.

$$U_{Ls} = U_{twa} + U_{bs}$$

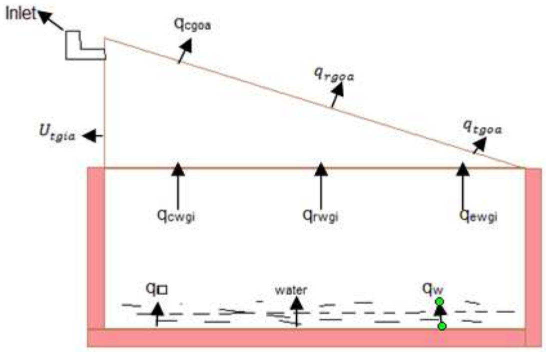

Figure 2: Schematic of Energy flow in a Single Basin Solar Still

Theoretical Distillate Yield

The hourly distillate yield (kg/m^{2}h) obtained from solar still canbe evaluated from known values of T_w and T_{gi} obtained as

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

Heat Transfer in Evacuated Tube

In a steady state, an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal losses, and optical losses describes the performance of an evacuated tube (Arora *et al*, 2011).

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

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

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

The heat lost by the tube is given by:

$$Q_{lt} = U_L A_{ig}(T_{ig} - T_a)$$

The heat loss coefficient U_L is calculated from thermal resistance between the absorber tube and the outer glass tube and between the outer glass tube and the surrounding air such that:

$$U_L = \left[\left\{\frac{1}{h_{rog} + h_{wp}}\right\} + \frac{1}{h_{rig}}\right]^{-1}$$

- **Radiation from the Outer Glass Tube**

The radiation loss from the outer glass tube surface accounts for radiation exchange with the sky at temperature, T_s. For simplicity, it is referenced to the ambient air temperature, T_a so that the radiation heat transfer coefficient from the outer glass tube surface can be written in following equation (Hlaing and Soe, 2015).

$$h_{rog} = \varepsilon_{og} \times \sigma \times \frac{({T_{og}}^4 - {T_s}^4)}{(T_{og} - T_a)}$$

$$T_s = 0.0552 \times {T_a}^{1.5}$$

Sky temperature to the local air temperature in the simple relationship shown below

- **Outer Glass Tube Convection**

The wind loss coefficient or adjusted convection heat transfer coefficient h_{wp} of the outer glass tube surface is approximated by heat transfer coefficient around the outer glass tube.

Wind loss coefficient (h_{wp})

$$h_{wp} = \frac{A_{og}}{A_{ig}} \times 0.6 \times h_w$$

$$h_w = 5.7 + (3.8 \times V)$$

- **Radiation between Absorber Glass Tube to the Outer Glass Tube**

The coefficient of radiation heat transfer between the absorber tube and outer glass tube can be written as:

$$h_{rig} = \varepsilon_{igog} \times \sigma \frac{\left(T_{ig}{}^{4} - T_{og}{}^{4}\right)}{\left(T_{ig} - T_{og}\right)}$$

Where ϵ_{ig} is the effective emissivity between the absorber glass tube (inner tube) and the outer glass tube

$$\varepsilon_{igog} = \left\{\frac{1}{\varepsilon_{ig}} + \frac{A_{og}}{A_{ig}}\left(\frac{1}{A_{og}} - 1\right)\right\}^{-1}$$

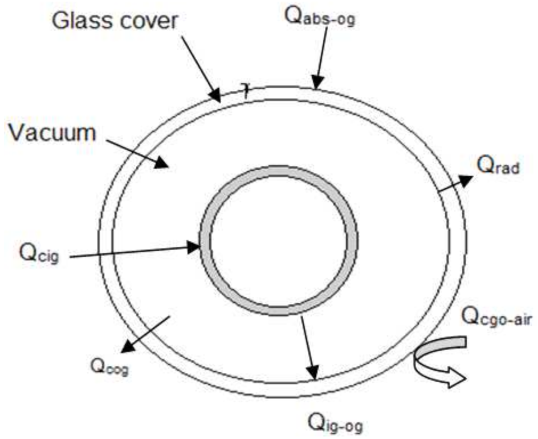

Figure 3: Energy Components in an Evacuated Tube

RESULTS AND DISCUSSIONS

Performance of Solar Still

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. The results obtained from experiments are summarized as follows:

Figure 4 and Table 1 depicted the values of convective heat transfer coefficient between basin water to the inner glass surface (h_{cwgi}), radiative heat transfer coefficient (h_{rwgi}) and evaporative heat transfer coefficient (h_{ewgi}) were found to be 3.70, 8.24 and 99.23 W/m^{2}K, respectively throughout the day at water depth of 0.03 m in the basin coupled with 10 number of evacuated tubes (Panchal, 2013). The evaporative heat transfer was found more than convective and radiative heat losses which may be due to basin water temperature increased due to integration of 10 number of evacuated tubes. Total heat transfer coefficient from water to glass cover (h_{twgi}) was found to be 111.27 W/m^{2}K (Patel and Meena, 2011).

From Table 2 it was observed that the convective heat transfer coefficient from glass cover outer surface to ambient (h_{cgoa}) and radiative heat transfer coefficient between glass cover outer surface and ambient (h_{rgoa}) were found to be 9.40 and 11.20 W/m^{2}K.The total top heat loss (h_{tgoa}) thus observed to be 20.60 W/m^{2}K. The overall heat loss coefficient from glass cover inner surface to the ambient and overall heat loss coefficient from water mass to the atmosphere was found to be 9.92 W/m^{2}K and 8.66 W/m^{2}K, respectively (Ziabari *et al*, 2013).

Table 1: Internal Heat Transfer Coefficient for Solar Still

Time ,(h)	$h_{cwgi,}$ (W/m^{2}K)	$h_{rwgi,}$ (W/m^{2}K)	$h_{ewgi,}$ (W/m^{2}K)	$h_{twgi,}$ (W/m^{2}K)
7.00	1.92	6.13	10.66	18.72
8.00	3.06	6.57	23.74	33.38
9.00	4.06	7.14	47.42	58.61
10.00	4.36	7.73	71.25	83.34
11.00	4.49	8.37	103.74	116.60
12.00	4.58	8.84	133.92	147.34
13.00	4.40	9.42	167.20	181.02
14.00	4.77	9.51	189.13	203.40
15.00	4.67	9.52	186.07	200.26
16.00	3.73	9.36	137.05	150.14
17.00	2.67	8.90	80.24	91.80
18.00	1.72	8.44	40.42	50.58
Average	**3.70**	**8.24**	**99.23**	**111.27**

In bottom and side of solar still the convective heat transfer coefficient from basin liner to water (h_w), conduction heat transfer coefficient between basin liner and atmosphere (h_b) were found to be 56.89 and0.31 W/m^{2}K**.** The overall bottom loss coefficient between water mass and atmosphere (U_b) and overall heat loss coefficient from water mass to the atmosphere were determined as 0.31 and 8.81W/m^{2}K**,** respectively.

Table 2: External Heat Transfer Coefficient for Solar Still

Time,h	$h_{cgoa,}$ W/m^{2}K)	$h_{rgoa,}$ W/m^{2}K	$h_{tgoa,}$ W/m^{2}K	$h_{b,}$ W/m^{2}K	$h_{w,}$ W/m^{2}K	$U_{b,}$ W/m^{2}K	$U_{LS,}$ W/m^{2}K	U_{tgia} W/m^{2}K	U_{twa} W/m^{2}K
7.00	7.83	29.74	37.56	0.31	56.89	0.31	7.82	12.76	7.39
8.00	9.48	12.23	21.71	0.31	56.89	0.31	8.19	10.35	7.87
9.00	12.40	10.94	23.34	0.31	56.89	0.31	9.29	10.70	9.37
10.00	9.85	9.54	19.39	0.31	56.89	0.31	9.09	9.82	9.07
11.00	9.18	8.97	18.14	0.31	56.89	0.31	9.03	9.43	9.21
12.00	7.98	8.80	16.78	0.31	56.89	0.31	8.88	9.10	8.91
13.00	8.73	8.83	17.55	0.31	56.89	0.31	9.13	9.27	8.71
14.00	11.73	8.94	20.67	0.31	56.89	0.31	9.89	10.05	9.44
15.00	10.08	9.00	19.08	0.31	56.89	0.31	9.56	9.69	8.92
16.00	8.20	8.89	17.10	0.31	56.89	0.31	8.94	9.16	9.07
17.00	9.33	9.24	18.56	0.31	56.89	0.31	8.86	9.48	8.29
18.00	8.05	9.34	17.39	0.31	56.89	0.31	8.05	9.22	7.66
Avg.	**9.40**	**11.20**	**20.60**	**0.31**	**56.89**	**0.31**	**8.89**	**9.92**	**8.66**

As the wind velocity increased, the convective heat loss from glass cover to ambient also increased hence the outer glass cover temperature decreased which increased difference between water glass cover temperature thus overall distillate yield increased. Heat loss coefficient increased until it reaches maximum in solar noon due to high temperature difference between the inside still and the ambient temperature then it reduced in the afternoon hours.

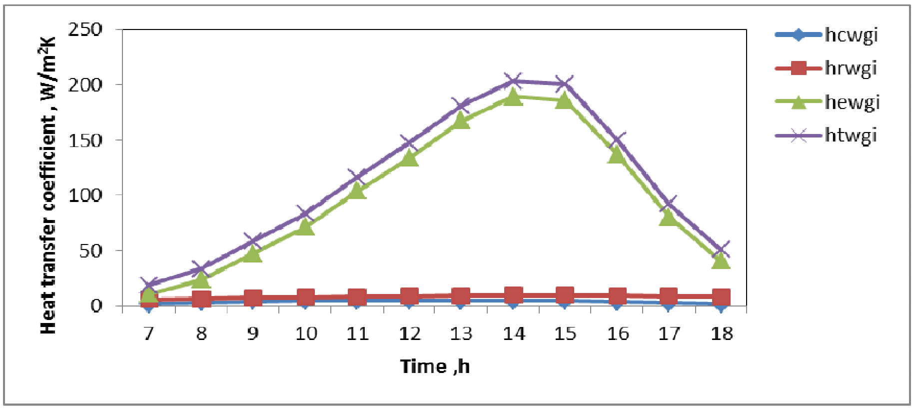

Figure 4: A Hourly Variations in Convective, Radiative and Evaporative Heat Transfer Coefficient

CONCLUSIONS

Internal heat transfer coefficient i. e. the evaporative heat transfer coefficient was found to be in the range of 10. 66 to 89.13 W/m^{2}K. The radiative and convective heat transfer coefficient were found to be in the range of 6.13 to 9.52, 1.72 to 4.17, respectively for solar still As radiative and convective heat transfer coefficient were found to be less as compared to evaporative heat transfer coefficient hence rate of evaporation increased therefore the distillate yield was found to be increased. The external heat transfer coefficient such as average overall top heat loss coefficient was found to be 9.92 W/m^{2}K as compared to bottom heat loss coefficient 0.31 W/m^{2}K.

NOMENCLETURE

A_a: Aperture area of the absorber, m^2

A_b: Area of basin liner, m^2

A_c: Area of collector, m^2

A_{ig}: Area of the inner glass tube, m^2

A_{ss}: Area of side wall of solar still in contact with water mass, m^2

G_r: Grashof number

H: height of basin

h_b: Heat transfer coefficient between basin liner and ambient (W/m^2 K)

h_{cgoa}: Convective heat transfer coefficient from glass cover outer surface of solar still to atmosphere, W/m^{2}K

h_{cwgi} is the convective heat transfer coefficient between water mass and glass cover inner surface

h_{cwgi}: Convective heat transfer coefficient from water to glass inner surface, W/m^{2}K

h_{ewgi}: Evaporation heat transfer coefficient from water to glass cover inner surface, W/m^2 K

h_{rig}: The adjusted convection heat transfer coefficient of the outer glass tube, W/m^{2}K

h_{rog}: The radiation heat transfer coefficient of the outer glass tube, W/m^{2}K

h_{rwgi}: Radiative heat transfer coefficient from water to glass cover surface, W/m^{2}K

h_{tba}: Total heat transfer coefficient between basin liner and atmosphere (W/m^2K)

h_w: Convective heat transfer coefficient between basin liner and water mass W/m^2K

h_w: Convection heat transfer coefficient around the outer glass tube,

h_w: Convective heat transfer coefficient from basin liner to water, W/m^2

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

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

K_g: Thermal conductivity of glass, W/mK

K_{ins}: Thermal conductivity of insulation, W/mK

K_w: Thermal conductivity of water, W/mK

L: Length of basin

L_g: Thickness of glass, m

L_{ins}: Thickness of insulation, m

P_{gi}: Partial vapour pressure at glass inner surface temperature, N/m^2

P_r: Prandlt number

P_w: Partial vapour pressure at water surface temperature, N/m^2

Q: Sloping side of basin

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

q_{cdgio}: Conductive heat transfer from glass cover inner surface to glass cover outer surface, W/m^2

q_{cgoa}: Convective heat loss from glass cover outer surface of solar still to atmosphere, W/m^2

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

q_{cwgi}: Convective heat transfer rate within solar still from water to glass cover inner surface, W/m^2

q_{ewgi}: Evaporative heat transfer rate within solar still from water to glass cover inner surface , W/m^2

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

q_{rwgi}: Radiative heat transfer rate within solar still from water to glass cover inner surface, W/m^2

Q_u: The useful energy output of an evacuated tube, W

Q_u: The useful energy output of an evacuated tube, W

T_a: Ambient temperature, K

T_a: Ambient temperature, K

T_a: Ambient temperature,˚C

T_b: Temperature of basin liner,˚C

T_{gi}: Temperature of glass cover inner surface,˚C

T_{go}: Initial temperature of glass cover, ˚C

T_{ig}: Temperature of the inner glass tube, K

T_{og}: Temperature of the outer glass tube, K

T_s: Equivalent sky temperature as a function of the ambient air temperature, K.

T_{sky}: Temperature of sky,˚C

T_w: Temperature of water,˚C

T_w: Temperature of water in basin,˚C

U_b: The overall bottom heat loss coefficient between water mass and atmosphere,W/m^2K

U_{bs}: Total bottom and side heat loss coefficient between water mass and ambient, W/m^2 K

U_L: Overall heat loss coefficient of the tube, W/m^2K

U_{LS}: Over all heat loss coefficient between water mass and atmosphere, W/m^2 K

U_t: Over all top heat loss coefficient between water mass and atmosphere, W/m^2K

V: The wind speed (m/s).

X_w: Mean character length of solar still between basin and water surface, m

GREEK SYMBOL

β: Latitude of place

ϵ_{eff}: Effective emissivity

ϵ_g: Emissivity of water

ϵ_{og}: Emissivity of the outer glass.

ϵ_w: Emissivity of glass

η_{opt}: Optical efficiency, %

σ : Stefan –Boltzmann Constant (5.6697×10^{-8}) W/m^2K^4

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