ISSN (Print) : 0974-6846
Indian Journal of Science and Technology, Vol 9(48), DOI: 10.17485/ijst/2016/v9i48/105785, December 2016 ISSN (Online) : 0974-5645

Investigation on the Performance of a Cylindrical Parabolic Concentrating Solar Water Heater

Amit Kumar Bhakta*, Birendra Kumar and S. N. Singh

Department of Mechanical Engineering, Indian Institute of Technology (ISM), Dhanbad - 826004, Jharkhand, India; jgecbitsismd@gmail.com, bk.11pg010@gmail.com, snsingh.631@yahoo.com

Abstract

Background/Objectives: The objectives of the present work are focused to investigate the theoretical heat gain, heat loss and instantaneous collector efficiency of cylindrical parabolic concentrating solar water heater over a clear day. **Methods/Statistical Analysis:** The performances of a cylindrical parabolic concentrating solar water heater fitted with copper absorber tube, using water as working fluid are investigated theoretically. The theoretical investigations are studied for water flow rates 0.1 kg/s and 0.15 kg/s between 8:0 h and 16:0 h over a sunny day. **Findings:** The theoretical results are showed that intensity of solar beam radiation with respect to time much more at noon than that calculated at 8:0 and 16:0 hours. Theoretical solar beam radiation data obtained are compared and validated with that of experimental based published data. The instantaneous efficiency, useful heat gain, hourly energy collected and heat loss are influenced by water mass flow rate. **Application/Improvements:** The theoretical study consumes less time than analytical and experimental studies. The initial capital investment is must to procure the experimental setup, whereas for theoretical work not required neither capital investment nor procurement process.

Keywords: Absorber Tube temperature, Heat Loss, Rate of Heat Gain, Solar Beam Radiation

1. Introduction

Solar energy is one of the forms of renewable and eternal sources of energy. Using concentrating collector high temperature can be obtained as its thermal efficiency high than flat plate collector one. In[1] conducted theoretical and experimental studies on cylindrical parabolic trough fitted with transparent tube along the focal axis of the reflector. They found better thermal efficiency using black liquid as a working fluid. In[2] conducted the study on the heat gain of a cylindrical parabolic concentrating trough and their results demonstrated that the concentrator performance influences by water flow rate. In[3] showed the variation of heat loss factor. In[4] showed the distribution of solar radiation flux. In[5] showed the performance of the tracking solar collector is much better than stationary CPC solar collector. In[6] showed change of mass flow rate affects on energy efficiencies. In[7] determined the thermal performance of a newly designed model of parabolic trough solar collector. In[8] studied on solar parabolic trough concentrator with bending absorber tube and the results showed the circumferential temperature distribution. In[9] showed that efficiency increases with temperature. In[10] estimated the heat gain and heat loss. In[11] used Therminol 55 as working fluid and the results revealed that instantaneous efficiency and heat gain influenced by incident beam radiation. In[12] showed that the experimental results of thermal performances less than theoretical results. In this work, the performances of a sun tracking cylindrical parabolic concentrating solar water heater with copper absorber tube fitted along the focal axis of the concentrating reflector has been studied theoretically. The objectives of the present study have concentrated to investigate the theoretical heat gain and performance of cylindrical parabolic concentrating solar water heater over a sunny day.

To facilitate the present theoretical study, the following points are considered:

- The water flow is unidirectional and along the absorber tube axis.

**Author for correspondence*

- The heat condition along the axis of the absorber tube is negligible.
- The thermal and physical properties of water are constant.

2. Data Analysis

The cylindrical parabolic concentrating solar water heater made of a parabolic concentrating trough and copper absorber tube. Absorber tube is fitted along the focal axis of the concentrating reflector, in order to receive the radiations reflected from parabolic concentrating reflector. Black paint painted around the outer surface of the copper absorber tube to enhance the absorptance and reduce the reflectance. The reflector is covered by the thin SOLARFLEX foil of reflectivity 0.974. The schematic view is shown in Figure 1. The present theoretical study is worked out using the theoretically calculated data of beam radiation, inclination, zenith angle and hour angle, on 21st April of 2016, at IIT (ISM) Dhanbad, Jhankhand (longitude 86.444 E, latitude 23.875^o), India. On 21st April of 2016, the average wind velocity 0.5 m/s and ambient temperature varied from 27^{o}C to 32^{o}C as recorded. The theoretical study is worked out using the specifications of the experimental setup, which is under construction. The length and width of the parabolic concentrating reflector are 1.22 m and 1.69 m respectively. The length of Copper absorber tube is 1.22 m. Also the values of thermal properties are absorptivity 0.9, emissivity 0.9, and thermal conductivity (k) 386 W/m-K etc. The specifications of the cylindrical parabolic concentrating solar water heater are detailed in Table 1. The theoretical study worked out using water as working fluid. The thermo-physical properties of water at 20^{o}C are given in Table 2.

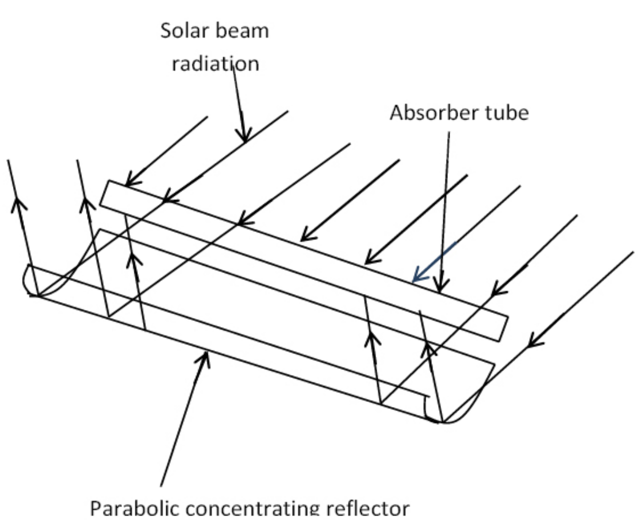

Figure 1. Schematic view of a parabolic concentrating reflector.

3. Theoretical Data Reduction

The declination has determined by Cooper[13] simple relation as follow:

$$\delta = 23.45 \sin[(360/365)(284+N)] \tag{1}$$

The expression of solar beam radiation over a clear day has formulated by ASHRAE[14] as follow:

$$I_b = I_{bn} \cos\theta_z \tag{2}$$

Table 1. Specification of the cylindrical parabolic concentrating solar water heater design specification

Reflector	aperture	area		(A_{ap})
2.07278 m^2				(L)
Reflector		length		
1.22 m				
Reflector		width		(W)
1.699 m				
Focal		distance		(f)
0.606 m				
Concentration		Ratio		(C)
3.630				
Absorber	Tube			Material
Copper				
Absorber	Tube	inner	dia.	(D_i)
0.037 m				
Absorber	Tube	outer	dia.	(D_o)
0.042 m				

Table 2. Thermo-physical properties of water at 20^{o}C

Property Value	
Density	998.2 kg/m^3
Kinetic viscosity	1.006 x 10^{-6} m^2/s
Thermal conductivity	0.599 W/m-^{o}C
Prandlt number	7.02
Specific heat, C_p	4.183 kJ/kg-^{o}C

Whereas, solar beam radiation in the direction of the sun rays has postulated from ASHRAE model such as

$$I_{bn} = A\exp\left(-B/\cos\theta_z\right) \quad (3)$$

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (4)$$

Where, A and B are constants whose values have been given by Threlkeld and Jordan[15].

Tilt factor for beam radiation can be derived as follow:

$$r_b = (1 - \cos^2\delta\sin^2\omega)^{1/2} / (\sin\varnothing\sin\delta + \cos\varnothing\cos\delta\cos\omega) \quad (5)$$

The expression of heat flux absorbed by the absorber tube can be derived as follow:

$$S = I_b r_b \rho\alpha\gamma \quad (6)$$

The rate of theoretical useful heat gain is the solar beam radiation absorbed by working fluid with time is given by[16] and determined using equation (7) as follow:

$$Q_{u,th} = L\left(W - D_o\right)F_R\left(S - U_l\left(T_{fi} - T_a\right)/C\right) \quad (7)$$

Where, F_R, F' and U_l are given by[16]. These are calculated using equations (8), (9) and (10) as follow:

$$F_R = \left(mC_p/\pi D_o L U_l\right)\left[1 - \exp\left\{-\left(F'\pi L D_o U_l\right)/mC_p\right\}\right] \quad (8)$$

$$F' = \left(1/U_l\right)/\left[\left(1/U_l\right) + \left(D_o/D_i h_f\right) + \left\{D_o \ln\left(D_o/D_i\right)/2k_p\right\}\right] \quad (9)$$

$$U_l = h_w + h_{p\text{-}a} \quad (10)$$

Where, $h_w = Nu_a k_a / D_o$

$$Nu_a = 0.3Re_a^{0.6} \text{ for } 1,000 < Re_a < 50,000$$

$$Re_a = \rho_a V_w D_o / \mu$$

The radiation heat transfer coefficient on outside of copper absorber tube (h_{p-a}) is given by[12]. It is evaluated using equation (11) as follow:

$$h_{p\text{-}a} = \varepsilon\sigma\left(T_p + T_a\right)\left(T_p^2 + T_a^2\right) \quad (11)$$

While, heat transfer coefficient (h_f) based on inside diameter of the absorber tube is given by[12] and evaluated using Equation (12) as follow:

$$h_f = \left(k_w/D_o\right)\left[3.6 + \left\{0.0668\left(D_i/L\right)RePr\right\}/\left\{1 + 0.04\left(\left(D_i/L\right)RePr\right)^{2/3}\right\}\right] \quad (12)$$

Reynolds number for average water velocity is determined using equation (13) as follow:

$$Re = \rho_f V_m D_i / \mu_f \quad (13)$$

Where, $V_f = m/\rho_f A_0$

The water outlet temperature is determined using the Equation (14) as follow:

$$T_{fo} = T_{fi} + \left(Q_{u,th}/mC_p\right) \quad (14)$$

The average temperature of the absorber tube (T_p) is given by[12] and evaluated using Equation (15) as follow:

$$T_p = T_{fm} + \left(mC_p\left(T_{fo} - T_{fi}\right)/h_f \pi D_o L\right) \quad (15)$$

Where, water bulk mean temperature is the half ofsumof water temperatures at inlet and outlet and determined using Equation (16) as follow:

$$T_{fm} = \left(T_{fi} + T_{fo}\right)/2 \quad (16)$$

The instantaneous collector efficiency for solar beam radiation is evaluated using the Equation (17) as follow:

$$\eta_{th} = Q_{u,th}/I_b r_b WL \quad (17)$$

The energy quantity is determined to count the hourly collection of the useful heat gain by water. The hourly energy collected is the solar radiation absorbed by water during one hour interval as given by[11] and determined using Equation (18) as follow:

$$E_c = \frac{\left[mC_p\left(T_{fo} - T_{fi}\right)_{j+1} + mC_p\left(T_{fo} - T_{fi}\right)_j\right]}{2} \times 3600 \quad (18)$$

The rate of heat loss is the difference between the total solar energy incident on the aperture of the concentrating reflector and rate of solar energy absorbed by water and it is calculated using the Equation (19) as follow:

$$Q_l = \left(W - D_o\right)LS - Q_{u,th} \quad (19)$$

4. Results

Results obtained from the present theoretical investigation on the performance study of Cylindrical Parabolic Concentrating solar water heater with copper absorber tube are explained and discussed in detail.

4.1 Theoretical Heat Gain and Performance Analysis

Figure 2 presents the variation of theoretical intensity of solar beam radiation with time for water flow rates 0.10 kg/s and 0.15 kg/s. This is clear that the intensity of the solar beam radiation enhances with time till noon. The intensity of incident solar beam radiation enhances from 8:0 h and its value arrives 952.5744 W/m^2 at noon. After

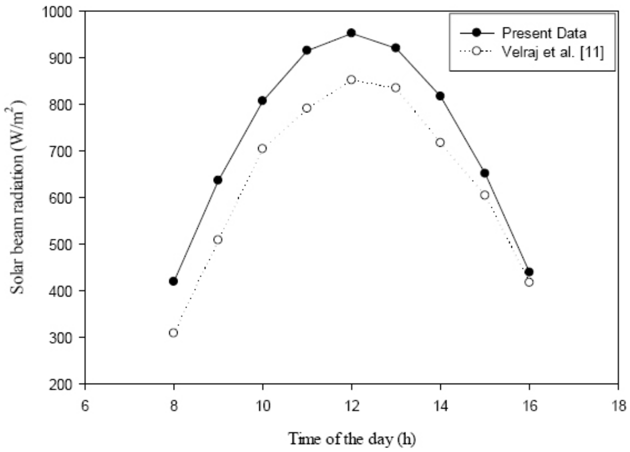

Figure 2. Variation of solar beam radiation with respect to time.

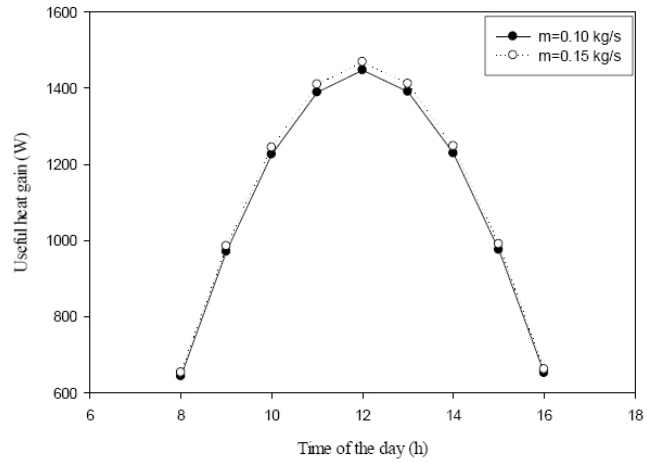

Figure 3. Variation of useful heat gain with respect to time.

noon, again starts to reduce. Also, this Figure shows that there is a good similarity between the present theoretical result and the experimental result[11].

Figure 3 indicates the change of the useful heat gain by water with time for water flow rates 0.10 kg/s and 0.15 kg/s. It is clear from the figure that the useful heat gain is affected by water mass flow rate. The useful heat gain by water changes with water mass flow rate. Also, it is concluded that the useful heat gain increases with time till noon and after that, it reduces gradually with time till 16:0 h. It is owing to the matter that energy gain by water is extremely affected by incident solar beam radiation on the concentrating reflector and temperature of absorber tube surface. Therefore, rate of useful heat gain follows their variations.

The change of average temperature of absorber tube surface with time is presented in figure 4. It is clear from this figure that the temperature of absorber tube surface is affected by flow rate of water and its value increases with decreasing water mass flow rate. The average temperature of absorber tube increases with a faster rate until noon, as the increase in solar radiation. After 12:0 h, the average temperature of absorber tube starts to reduce. However, average temperature of absorber tube changes with incident solar beam radiation rate.

Instantaneous collector efficiency against time is presented in Figure 5. It is clear from the figure that the theoretical result of instantaneous efficiency is extremely affected by the water mass flow. The theoretical value of instantaneous collector efficiency increases gradually with a very slower rate from 8:0 h to noon and at noon

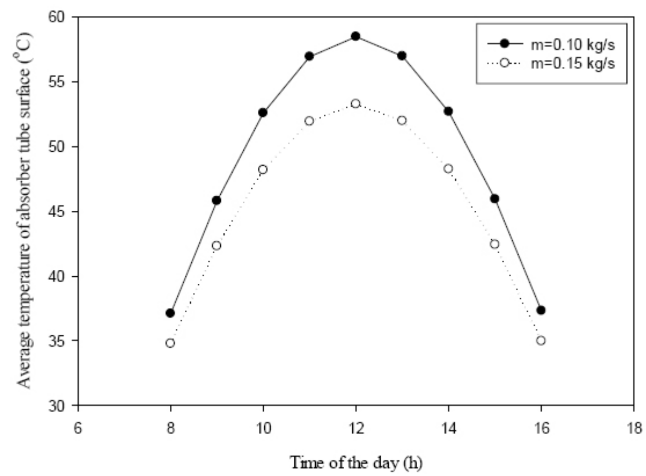

Figure 4. Variation of average temperature of absorber tube surface with respect to time.

its value arrives to a maximum. After this time, its value starts to reduce till 16:0 h. It is owing to the reason that instantaneous collector efficiency extremely affected by the incident radiation and rate of heat gain, so it follows their variations. This theoretical result was compared and validated with the experimental result[12]. Also, the figure shows a good agreement in the results between the present theoretical collector efficiency and the experimental result[12,17,18].

Figure 6 presents the variation of hourly energy collected during the time period between 8:0 h and 11:0 h. It has been found from the figure that hourly energy collected enhances with time during the time period between 8:0 h and 11:0 h. It is due to the reason that the water

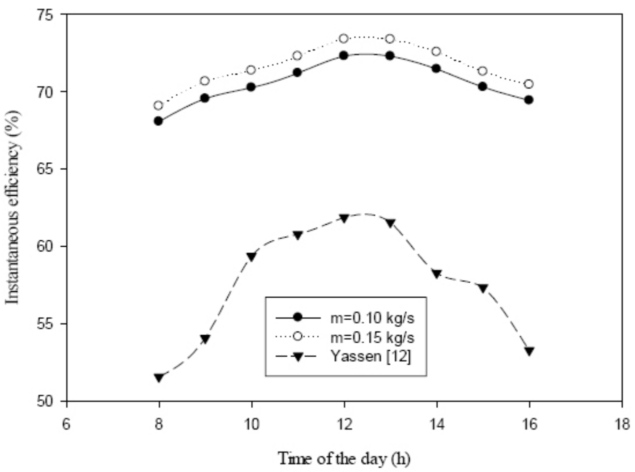

Figure 5. Variation of instantaneous collector efficiency with respect to time.

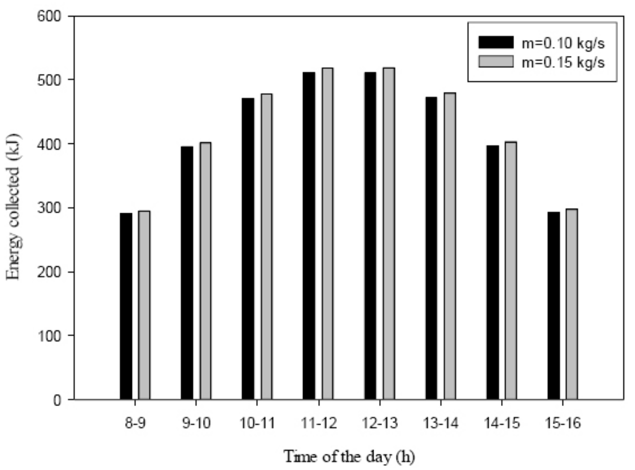

Figure 6. Variation of energy collected vs time.

temperature increases with a higher rate during this time period as the change in temperature is extremely affected by incident solar beam radiations. After 11: 0 h, heat loss about nearly energy collected and after 13:0 h, heat loss increases than energy collected until 16:0 h.

4.2 Heat Loss from of the Cylindrical Parabolic Concentrating Solar Water Heater

Figure 7 presents the effects of water mass flow rates on heat loss with time. Heat loss depends on temperature difference between absorber tube and ambient air. From the figure it is seen that the theoretical heat loss depends on the water mass flow rate. Therefore, heat loss enhances with surface temperature of absorber tube. Also figure

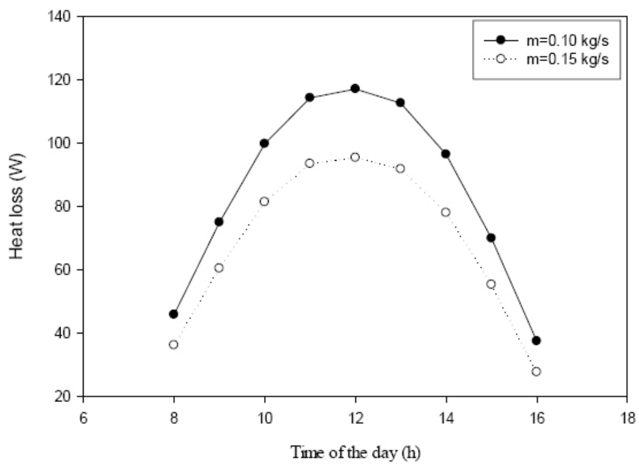

Figure 7. Variation heat loss with respect to time.

shows that heat loss with time increases until 12:0 h and after that it begins to decrease until 16:0 h.

5. Conclusions

The theoretical investigation was conducted to determine the performance of a cylindrical parabolic concentrating solar water heater fitted with copper absorber tube for water flow rates 0.10 kg/s and 0.15 kg/s during the time period between 8:0 h and 16:0 h of a sunny day.

- The average temperature of absorber tube surface and heat loss decrease with increasing water flow rate.
- The useful heat gain rate and hourly energy collected by the cylindrical parabolic concentrating solar water depend on incident solar beam radiation. Both the value increases with a faster rate between 8:0 h and 11:0 h. After 12:0 h, these start to decrease and reach to minimum values at 16:0 h.
- The instantaneous collector efficiency extremely depends on both the solar beam radiation and the heat gain. The peak value of instantaneous collector efficiency reached at 12.0 h.
- After13:0 h, the rate of heat gain is less than the rate heat loss, and this decreases the temperature of absorber tube and useful heat gain rate.

6. References

1. Huang BJ, Wung TY, Nieh S. Thermal analysis of black liquid cylindrical parabolic collector. Solar Energy. 1979; 22(3):221–4.

2. Hamad FAW. The performance of a cylindrical parabolic solar concentrator. Energy Conversion and Management. 1988; 28(3):251–6.
3. Mullick SC, Nanda SK. An improved technique for computing the heat loss factor of a tubular absorber. Solar Energy. 1989; 42(1):1–7.
4. Cheng ZD, He YL, Xiao J, Tao YB, Xu RJ. Three-dimensional numerical study of heat transfer characteristics in the receiver tube of parabolic trough solar collector. International Communications in Heat and Mass Transfer. 2010; 37(7):782–7.
5. Kim Y, Han G, Seo T. An evaluation on thermal performance of CPC solar collector. International Communication in Heat and Mass Transfer. 2008; 35(4):446–57.
6. Eskin N. Transient performance analysis of cylindrical parabolic concentrating collectors comparison with experimental results. Energy Conversion and Management. 1999; 40(2):175–91.
7. Arasu AV, Sornakumar T. Design, manufacturing and testing of fiberglass reinforced parabola trough for parabolic trough solar collectors. Solar Energy. 2007; 81(10):1273–9.
8. Khanna S, Sharma V, Kadare SB, Singh S. Experimental investigation of the bending of absorber tube of solar parabolic trough concentrator and comparison with analytical results. Solar Energy. 2016; 125:1–11.
9. Ceylan I, Ergun A. Thermodynamic analysis of a new design of temperature controlled parabolic trough collector. Energy Conversion and Management. 2013; 74:505–10.
10. Ouagued M, Khellaf A, Loukarfi L. Estimations of the temperature, heat gain and heat loss by solar parabolic trough collector under Algerian climate using different thermal oils. Energy Conversion and Management. 2013; 75:191–201.
11. Kumaresa G, Sridhar R, Velraj R. Performance studies of a solar parabolic trough collector with a thermal energy storage system. Energy. 2012; 47:395–402.
12. Yassen TA. Experimental and theoretical study of a parabolic trough collector. Anbar Journal for Engineering Sciences. 2012; 5:109–24.
13. Cooper IP. The absorption of solar radiation in solar stills. Solar Energy. 1969; 12:3–10.
14. ASHRAE, Hand book of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers; 1972. p. 385–443.
15. Threlkeld JL, Jordan RC. Direct solar radiation available on clear days. ASHRAE Transactions. 1983; 64:45–51.
16. Garg HP, Prakash J. Solar energy fundamentals and applications. 1st ed. New Delhi: Tata McGraw-Hill Publishing Company Limited; 2000.
17. Shanmugan S, et al. Honeycomb encapsulated atmospheric solar collector along with single basin solar still in highly energy absorbing weather condition. Indian Journal of Science and Technology. 2016; 9–5.
18. Naderi M. Nano fluid in water as base fluid in flat-plate solar collectors with an emphasis on heat transfer. Indian Journal of Science and Technology. 2016; 9-31.

Nomenclature

A_0 absorber tube cross-sectional area, m^2
A_{ap} reflector Aperture, m^2
C Concentration ratio
C_p specific heat at const. pressure, kJ/kg-°C
D_i absorber tube inner diameter, m
D_o absorber tube outer diameter, m
E_c energy collected, J
f focal length, m
F_R heat removal factor
F' collector efficiency factor
h_f inside heat transfer coefficient, W/m^2-°C
h_w outside heat transfer coefficient, W/m^2-°C
I_b intensity of beam radiation, W/m^2
I_{dn} intensity of beam radiation in the direction of sun rays, W/m^2
k_a thermal conductivity of air, W/m-°C
k_p thermal conductivity of absorber tube material, W/m-°C
k_w thermal conductivity of water, W/m-°C
L length, m
m water mass flow rate, kg/s
Nu Nusselt number
Pr Prandtl number
Q_l heat loss, J/s
Q_u useful heat gain, W
Re Reynolds number
r_b tilt factor
S heat flux, W/m^2
T_a ambient temperature, °C
T_{fi} inlet temperature, °C
T_{fo} outlet temperature, °C
T_p average temperature of absorber tube, °C
U_l heat loss factor, W/m^2-°C
V_m mean water velocity, m/s
V_w wind velocity, m/s
W reflector width, m

Greek symbols

α absorptivity of tube
γ intercept factor
δ declination
η instantaneous collector efficiency, (%)
ρ reflectivity of reflector
ρ_a density of air, m^3
ρ_f density of water, m^3
μ dynamic viscosity, N/m^2-s
ø latitude, (degree)
σ Stefan Boltzmann constant
θ_z angle of incident, (degree)
ω hour angle, (degree)

Subscripts

a air
th theoretical
f fluid
j at any time instant
j+1 one hour time interval from j th time
m average

Acronyms

ASHRAE American society of heating, refrigerating and air-conditioning engineers.