



Comparison of performance analysis of Scheffler reflector and model formulation

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Abstract

The performance of Scheffler reflector has been studied. In this system, a single drum of 20 liter capacity was installed at focal point to serve the dual purpose as absorber tube and storage tank. The performance analysis tests have revealed that the average power and efficiency in terms of water boiling to be 1.30 kilowatts and 21.61 % respectively against an average value of beam radiations of 742[Wm⁻²]. The maximum water temperature in the storage tank to 98 °C was achieved on a clear day operation and ambient temperature between 28 °C to 31 °C. Using this experiment a generalized data based model is formulated.

Keywords: Scheffler Reflector, Heat, Solar energy, Thermal.

Nomenclature: Dish diameter: D [m²]

Introduction

German Scientist Wolfgang Scheffler has devised a parabolic reflector set up to harness solar energy using low cost set up which can be used in rural areas in India. A concentrating primary reflector tracks the movement of the sun, focusing sunlight on a fixed place. The focused light heat a very large pot, which can be used for heating, steam generation, cooking, baking breads, water heating and for incineration (Ulrich Oelher & Scheffler, 1994; Scheffler, 2006a,b). The Scheffler reflector can be used for the supply of hot water for domestic purposes. These systems can have one water storage tank which performs dual function of absorbing solar radiation and preserving heat of water.

Many methods are suggested to keep water temperature at a satisfactory level. Among them, the use of a selective absorber that reduces radiation thermal losses and double glazing, transparent insulation and inverted or evacuated absorber to suppress convection thermal losses are suggested to preserve water storage heat. In the literature, few works are referred to Scheffler Reflector with cylindrical water storage tanks mounted at focal point. The use of Scheffler reflectors can result in effective water heating by using the non-uniform distribution of solar radiation on the cylindrical absorber surface. In most of the above systems the part of the cylindrical absorber is thermally insulated in order to reduce storage tank thermal losses (Varghese, 2000). Considering that this reflector systems aims to cover domestic needs of about 100-200 liter per day, the aperture area of this can be up to about 2.0-2.5 m² which corresponds to use of cylindrical storage tank with diameter 0.2 m to about 0.4 m (Scheffler, 2006a).

In the present work, experimental study of Scheffler reflector water heater (SRWH) consisting single storage

tank as an absorber mounting in side curved reflector trough, has been used. The solar reflector for 20 liter per day capacity is designed. In this design, the thermal insulation on storage tank is not provided due to bring down the cost of water heater and for its wide applications in domestic sector. The paper is focused on the performance analysis of Scheffler Reflector water heater for average power and efficiency in terms of water boiling test at Bangalore in India (Munir & Hensel, 2009a,b).

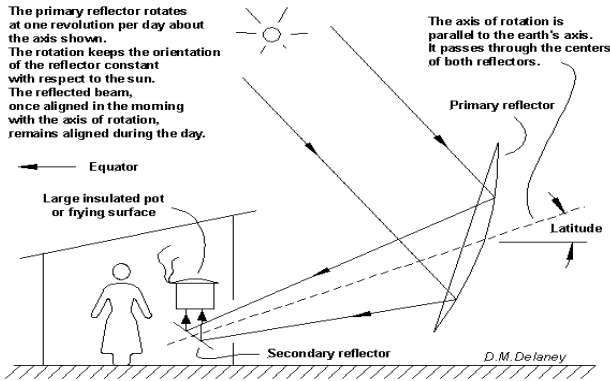
Design concepts of the SRWH

Solar water heating system of this type differ from flat plate solar collector in design and operation as the unit serves for dual operation, to absorb solar radiation as well as reservoir of heated fluid. The designed model for experimentation is shown in Fig.1. The solar reflector of 20 liter per day capacity is designed with dish diameter of 8 m².

The storage tank painted black is so positioned that its periphery lies on the focus of the parabolic reflector. Non return valve was fitted at the inlet line and air vent, pressure relief valve at the outlet line. For analysis and testing purpose, Al-Cr thermocouples were located at different positions in the heater. This type of compact solar water heater is simple in design, low in cost, easy in operation and maintenance, easy to install and of high efficiency compared to flat plate collectors and tubular type integrated collector storage systems.

The storage tank has an entrance for the water at the top of one side and an exit at the bottom of the other side. The SRWH inlet is connected directly to the overhead or supply tank and its out let is regulated by the valve. It is naturally circulated type water heater. The storage tank is hydraulically tested for fluid pressure of 0.588 MPa.

Fig. 1. (a) A model of SRWH system, (b) Schematic of SRWH



How the Scheffler cooker keeps its area of focus on the cooking place as the sun moves.

Testing procedure and experimentation

The Scheffler reflector used here has an area of 8m². The sunlight that falls onto this reflector is reflected sideways to the focal point away from the reflector. The axis of daily rotation is located exactly in north-south-direction, parallel to earth axis and runs through the centre of gravity of the reflector. Thus the reflector always maintains its gravitational equilibrium and the mechanical tracking device (clockwork) can be moved easily in position with the sun. The focus is located on the axis of rotation to prevent it from moving when the reflector rotates. During the day, the concentrated light is rotated around its own centre but not in sideways. Thus the focus stays fixed. At the focus it has a container to hold 20 liter water. The parameters measured were: ambient temperature, water temperature, solar radiation and wind speed. K-types thermocouple is used to measure water temperature which has a range of -200 °C to 1250 °C. Wind speed is measured by battery operated digital Anemometer with a range 0.3 to 30 m/s and with a facility to show ambient temperature. A pyranometer is used to measure the radiation. The experimentation was carried in the month of June, September and December 2009 and January, February, March, April, May 2010. These months covers winter, summer and rainy season in India. The readings were taken at different time zones between 9 AM to 5 PM for various days. All readings were taken at the interval of 5 minutes. More than 600 observations

were recorded. The sample observations are shown in Table 1.

Performance evaluation

The efficiency was calculated with the following equations:

$$\eta = \frac{10^3 \times E_p}{\int_{t=0}^{t_p} [(G_{bave}) \times A_s \times dt]} \times 100 \tag{1}$$

Where E_p is the total heat energy, t is the time; G_{bave} is the beam radiation at time t , A_s is the aperture area of the Scheffler reflector which is also a variable function whose value can be determined for any day of the year by the following formula.

$$\text{Aperture area} = \text{Reflector Area} \times \cos (43.23^\circ - \text{seasonal angle deviation of the sun}/2) \tag{2}$$

Different equations were used to calculate solar declination for all the days of the year. The equation quoted by Duffie and Beckman (1991) with least error (< 0.035⁰) is used for calculation of solar declination:

$$\delta = (180/n) [(0.006918 - 0.399912) \cos (n-1) 2 \pi/365 + 0.070257 \sin (n-1) 2 \pi/365 - 0.006758 \cos 2(n-1) 2 \pi/365 + 0.000907 \sin (n-1) 2 \pi/365 - 0.002679 \cos 3(n-1) 2 \pi/365 + 0.00148 \sin 3(n-1) 2 \pi/365] \tag{3}$$

Where n is the day of the year.

Funk (2000) described the procedure for evaluating different types of solar cookers and his research was focused on the influence of test conditions on results minimization if uncontrolled variables are held to certain ranges. He has used water for the evaluation of the cookers in terms of power. For the performance test with water only, the following equation was used:

$$E_p = m_w C_w \Delta T / 3600. \tag{4}$$

Where m_w is the mass of water used. C_w is the specific

Table1. Readings of various parameters in solar water heater.

Date	S.No	Time [hour]	Generated water temp. [°C]	Wind speed [km/h]	Ambient temp. [°C]	Radiation falling in [W/m-2]
21 Feb 2010	1	9	25	16	28	700
	2	9.05	28	16	28	750
	3	9.1	34	16	28	750
	4	9.15	40	15	28.5	750
	5	9.2	45	16	28.5	750
	6	9.25	52	15	29	750
	7	9.3	58	15	29	750
	8	9.35	66	17	29	750
	9	9.4	73	17	30	750
	10	9.45	80	17	30	750
	11	9.5	86	17	30	750
	12	9.55	87	15	30	750
	13	10	90	15	31	775
	14	10.05	91	15	31	775
	15	10.1	93	14	31	775
	16	10.15	94	15	31	775
	17	10.2	96	15	31	775
	18	10.25	97	16	31	775
	19	10.3	98	16	31	775
	20	10.35	98	16	31	775

heat at constant pressure (for water $4.187 \text{ [kJ kg}^{-1} \text{ K}^{-1}]$) and $\Delta T \text{ [K]}$ is the change in temperature for a specific time.

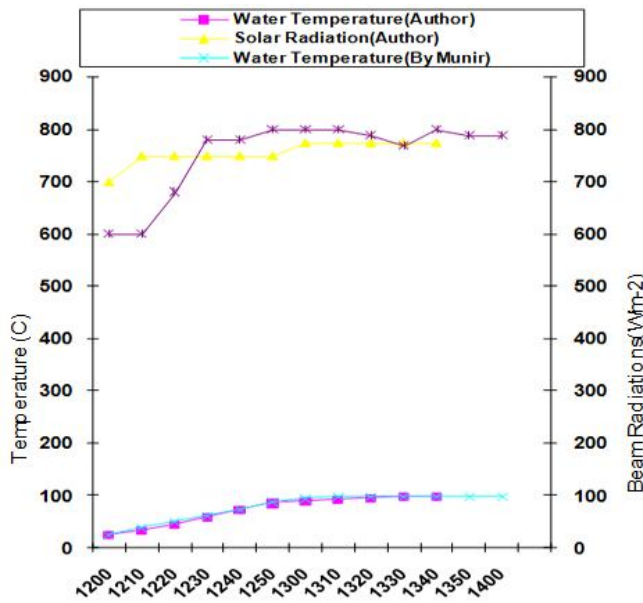
The average power available, P_{ave} , during the experiment is given as

$$P_{ave} = Ep/tp \tag{5}$$

Where t_p is the total process time.

In between the beam radiation range of 700 to $800 \text{ [Wm}^{-2}]$, Scheffler reflector showed that about half of the solar power collected by the reflector becomes finally available in the cooking vessel. The details of a performance evaluation of the solar system with 20 liter water on February 21, 2010 are shown in Table 1. Fig.2 illustrates the variation of water temperature, and solar radiation.

Fig. 2. Variation of solar radiations and water temperature



During the performance evaluation test with 20 liters of water, 2 liters of water was evaporated. The average power and efficiency in terms of water boiling test was calculated to be 1.30 kilowatts and 21.61 % respectively against an average value of beam radiations of $742 \text{ [Wm}^{-2}]$. This efficiency figure relates to the perfection of the reflector surface area, its reflectance, absorbance of the outer surface of the distillation tank exposed to radiations and insulation of the remaining surface.

Identification of variables

The term variables are used in a very general sense to apply any physical quantity that undergoes change. If a physical quantity can be changed independent of the other quantities, then it is an independent variable. If a physical quantity changes in response to the variation of one or more number of variables, then it is termed as dependent or response variable. If a physical quantity that affects our test is changing in random and

uncontrolled manner, then it is called an extraneous variable. The variables affecting the effectiveness of the phenomenon under consideration are Incident rays, Water Quantity, Operation time, Dish area, wind speed, ambient temperature, acceleration due to gravity, dish position wrt time. The dependent or the response variables in this case is Generated water temperature (Table.2)

Reduction of independent variables/dimensional analysis

There are several quite simple ways in which a given test can be made compact in operating plan without loss in generality or control. The best known and the most powerful of these is dimensional analysis. In the past, dimensional analysis was primarily used as an experimental tool whereby several experimental variables could be combined to form one. The field of fluid mechanics and heat transfer were greatly benefited from the application of this tool. Almost every major experiment in this area was planned with its help. Using this principle, modern experiments can substantially improve their working techniques and be made shorter requiring less time without loss of control. Deducing the dimensional equation for a phenomenon reduces the number of independent variables in the experiments. The exact mathematical form of this dimensional equation is the targeted model. This is achieved by applying Buckingham's n theorem (Hibert, 1961). When we apply this theorem to a system involving n independent variables, (n minus number of primary dimensions viz. L, M, T, Π) i.e.(n-4) numbers of n terms are formed. When n is large, even by applying this theorem number of n terms will not be reduced significantly than number of all independent variables. Thus much reduction in number of variables is not achieved. It is evident that, if we take the product of the terms it will also be dimensionless number and hence a n term. This property is used to achieve further reduction of the number of variables. Dimensional analysis is used to reduce the variables and following Pi terms were evolved out of it (Modak & Bapat, 1994).

Buckingham theorem in brief.

Generated Water Temperature $[\theta]$,
 $\theta_1 = f (Ib, VT, \text{Time}, D, W, \theta_2, g, Tr)$
 $\therefore f (\theta_1, Ib, VT, \text{Time}, D, W, \theta_2, g, Tr) = 0$
 $\therefore \Phi (\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5) = 0$
 $\therefore N = 9, m = 4$

\therefore No of Π terms $(n - m) = 9 - 4 = 5$

Repeating variables are
 $D [L], W [LT^{-1}], Ib [MT^{-3}], \theta_2$

As Repeating variables are
 $D [L^2], W [LT^{-1}], Ib [MT^{-3}], \theta_2$
 $\therefore \Pi_1 = D^{a1} W^{b1} Ib^{c1} \theta_1^{d1} \theta_2$
 $[M^0 L^0 T^0] = [L^2]^{a1} [LT^{-1}]^{b1} [MT^{-3}]^{c1} [\theta]$

Equating power of MLT on both sides we get,

Power of M, $0 = C1$

∴ C1 = 0
 Power of L, 0=2a1+b1
 ∴ 2a1 = -b1
 ∴ 2a1 = 0 (as b1 = 0)
 Power of T, 0= -b1-3C1
 ∴ b1 = 0 (as C1 = 0)

Power of θ2 0=d1+1 d1= -1
 $\Pi_1 = \theta_1 / \theta_2$

Similarly other Pi terms are calculated and shown in Table 3

Table 3. n -Terms used in mathematical modeling

Independent Pi Terms	
Description of Pi Terms	Equation of Pi terms
Pi-Term for water quantity and dish diameter	$\Pi_2 = V_T / D^{1.5}$
Pi-Term relating to wind speed	$\Pi_3 = W * \text{Time} / D^{0.5}$
Pi-Term relating to g and wind speed	$\Pi_4 = g * D^{0.5} / W^2$
Pi-Term relating to Dish osition	$\Pi_5 = Tr * D^{0.5} / W$
Dependent Pi terms	
Pi-Term relating to temperature	$\Pi_1 = \theta_1 / \theta_2$

Model formulation

The data of the independent and dependent parameters of the system has been gathered during experimentation. In this case there are one dependent and five independent pi terms involved in the experimentation. It is necessary to correlate various independent and dependent pi terms involved in this system quantitatively. This correlation is nothing but a mathematical model as design tool for such workstation. Based on the experimentation work performed on the experimental setup, using classical plan of experimentation, Deduction of generalized Experimental Models for the dependent n terms is discussed.

Formulation of experimental data based model

Four independent pi terms ($\pi_2, \pi_3, \pi_4, \pi_5$) and one dependent pi terms π_1 have been considered in the design of experimentation and are available for the model formulation.

Independent π terms = ($\pi_2, \pi_3, \pi_4, \pi_5$), Dependent π terms = π_1

Each dependent π is assumed to be function of the available independent π terms,

$\theta = f(\pi_2, \pi_3, \pi_4, \pi_5)$

Where, $\theta = \pi_1$, Dependent pi term "f (π_1) = function of ($\pi_2, \pi_3, \pi_4, \pi_5$)"

A probable exact mathematical form for this phenomenon could be the empirical relationships in between dependent dimensionless ratio and independent dimensionless ratio and are assumed to be exponential.

Following four mathematical relationships are

formed for three seasons in a year (winter, rainy, summer).

$\pi_1 = k_1 \times (\pi_2)^{a1} \times (\pi_3)^{b1} \times (\pi_4)^{c1} \times (\pi_5)^{d1}$ (1)

Considering Equation 1 to simplify

$\pi_1 = k_1 \times (\pi_2)^{a1} \times (\pi_3)^{b1} \times (\pi_4)^{c1} \times (\pi_5)^{d1}$ (2)

Taking log of both the sides

$\text{Log} [\pi_1] = \text{Log} [k_1 \times (\pi_2)^{a1} \times (\pi_3)^{b1} \times (\pi_4)^{c1} \times (\pi_5)^{d1}]$

Using logarithmic rule,

$\text{Log} [A \times B] = \text{Log} A + \text{Log} B$

$\text{Log} [\pi_1] = \text{Log} [k_1] + \text{Log} [(\pi_2)^{a1}] + \text{Log} [(\pi_3)^{b1}] + \text{Log} [(\pi_4)^{c1}] + \text{Log} [(\pi_5)^{d1}]$

Using logarithmic rule,

$\text{Log} [A^B] = B \times \text{Log} A$

$\text{Log} (\pi_1) = \text{Log} (k_1) + a_1 \times \text{Log} (\pi_2) + b_1 \times \text{Log} (\pi_3) + c_1 \times \text{Log} (\pi_4) + d_1 \times \text{Log} (\pi_5)$

Following are the abbreviations used for mathematical modeling:

$\text{Log} (\pi_1) = Z; \text{Log} (k_1) = K; \text{Log} (\pi_2) = A; \text{Log} (\pi_3) = B; \text{Log} (\pi_4) = C; \text{Log} (\pi_5) = D$

$Z = K + [a1 A] + [b1 B] + [c1 C] + [d1 D]$

In above equation, a_1, b_1, c_1, d_1, e_1 are unknowns whose value are to be find out, while A,B,C,D are set of values obtained during experimentation.

To solve the above equation, multiply coefficient of a_1, b_1, c_1, d_1 individually.

Multiplying by A,
 $AZ = AK + [a_1 A^2] + [b_1 AB] + [c_1 AC] + [d_1 AD]$

Multiplying by B,
 $BZ = BK + [a_1 AB] + [b_1 B^2] + [c_1 BC] + [d_1 BD]$

Multiplying by C,
 $CZ = CK + [a_1 AC] + [b_1 BC] + [c_1 C^2] + [d_1 CD]$

Multiplying by D,
 $DZ = DK + [a_1 AD] + [b_1 BD] + [c_1 CD] + [d_1 D^2]$

Above Set of equations are valid for the number of reading taken during experimentation, therefore taking summation of these for n values,

The equations become,

$\Sigma(Z) = n * K + [a_1 \Sigma(A)] + [b_1 \Sigma(B)] + [c_1 \Sigma(C)] + [d_1 \Sigma(D)]$

$\Sigma(AZ) = K * \Sigma A + [a_1 \Sigma(A^2)] + [b_1 \Sigma(AB)] + [c_1 \Sigma(AC)] + [d_1 \Sigma(AD)]$

$\Sigma(BZ) = K * \Sigma B + [a_1 \Sigma(AB)] + [b_1 \Sigma(B^2)] + [c_1 \Sigma(BC)] + [d_1 \Sigma(BD)]$

$\Sigma(CZ) = K * \Sigma C + [a_1 \Sigma(AC)] + [b_1 \Sigma(BC)] + [c_1 \Sigma(C^2)] + [d_1 \Sigma(CD)]$

$\Sigma(DZ) = K * \Sigma D + [a_1 \Sigma(AD)] + [b_1 \Sigma(BD)] + [c_1 \Sigma(CD)] + [d_1 \Sigma(D^2)]$ (3)

To solve these equations, reducing it to matrix form

$$\begin{bmatrix} \Sigma(Z) \\ \Sigma(AZ) \\ \Sigma(BZ) \\ \Sigma(CZ) \\ \Sigma(DZ) \end{bmatrix} = \begin{bmatrix} N & \Sigma(A) & \Sigma(B) & \Sigma(C) & \Sigma(D) \\ \Sigma A & \Sigma(A^2) & \Sigma(AB) & \Sigma(AC) & \Sigma(AD) \\ \Sigma B & \Sigma(AB) & \Sigma(B^2) & \Sigma(BC) & \Sigma(BD) \\ \Sigma C & \Sigma(AC) & \Sigma(BC) & \Sigma(C^2) & \Sigma(CD) \\ \Sigma D & \Sigma(AD) & \Sigma(BD) & \Sigma(CD) & \Sigma(D^2) \end{bmatrix} \times \begin{bmatrix} K \\ a_1 \\ b_1 \\ c_1 \\ d_1 \end{bmatrix}$$



By putting the values for various parameters in the matrices shown above the following matrices are obtained.

For summer

$$\begin{matrix}
 119.37 \\
 364.51 \\
 239.25 \\
 3.48 \\
 312.63
 \end{matrix}
 =
 \begin{matrix}
 360.00 & -1099.32 & 629.56 & 20.14 & -885.85 \\
 -1099.32 & 3356.930 & -1922.45 & -61.51 & 2705.09 \\
 629.56 & -1922.44 & 1254.44 & -75.28 & -1687.15 \\
 20.14 & -61.51 & -75.28 & 228.96 & 59.69 \\
 -885.85 & 2705.09 & -1687.15 & 59.69 & 2350.31
 \end{matrix}
 \times
 \begin{matrix}
 K \\
 a_1 \\
 b_1 \\
 c_1 \\
 d_1
 \end{matrix}$$

Using MATLAB7.0, the values obtained are provided in Table 4.

Table 4. Various values of indices obtained for mathematical models

Pi terms	Generated water temperature		
	Summer	Winter	Rainy
K (constant)	0.44	0.87	0.93
A	-0.11	-0.0007	-0.01
B	0.42	0.45	0.33
C	0.12	0.16	0.14
D	0.16	0.12	0.07

The various mathematical models for different seasons are stated below:

$$\begin{aligned}
 \Pi_1 &= 0.44 \cdot (n_2)^{-0.11} (n_3)^{0.42} (n_4)^{0.12} (n_5)^0 & - (4) \\
 \Pi_1 &= 0.87 \cdot (n_2)^{-0.0007} (n_3)^{0.45} (n_4)^{0.16} (n_5)^{0.12} & - (5) \\
 \Pi_1 &= 0.93 \cdot (n_2)^{-0.01} (n_3)^{0.33} (n_4)^{0.14} (n_5)^0 & - (6)
 \end{aligned}$$

Conclusion

The present study was conducted with one of most temperature sensitive process industry using solar energy. This study also concludes that these types of innovative solar concentrators can open new landmarks in decentralized solar based systems. In addition, other benefits like reduction of fossil fuels consumption and global warming cannot be ignored. The study also suggests that such types of systems must be equipped with necessary mountings and instrumentations to monitor and control the desired thermal parameters during temperature sensitive industrial processing. The mathematical model is formulated which can be used to analyze the data and to establish relationship between different variables of Scheffler reflector. This type of model is not prepared before by researchers in this area and thus the model will be useful to find and optimize the parameters affecting output of the phenomena.

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