Performance Prediction of Scheffler Solar Concentrator for Direct Steam Generation

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ABSTRACT

This study describes a method to predict the thermal efficiency of Scheffler concentrator for direct steam generation, which is a simple and cost-effective method for various process steam applications. The Scheffler concentrator with a surface area of 16 m^2 is utilized to concentrate solar radiation onto a fixed-point receiver. However, the high operating temperature of the Scheffler dish receiver leads to increased heat losses, which can significantly reduce its efficiency. A mathematical model was developed to predict the daily thermal efficiency of the system by predicting receiver heat losses. The theoretical predictions of the model are compared with the experimental results. The difference in output power between the theoretical predictions and the experimental results is only 4.84%. Furthermore, the thermal performance of the Scheffler concentrator is influenced by seasonal variation and geometrical parameters. Therefore, a mathematical model is proposed to determine the temperature at the receiver under local climatic conditions. Monthly and annual performance of the system is predicted from thermal balance, and the results show that the system produces 8.90 MWh annually and achieves a monthly average efficiency of 38.80%. The theoretical thermal efficiency estimated using the heat loss model agreed well with the experimental efficiency, with a deviation of 2.33%. In conclusion, this research proposes a comprehensive methodology for predicting the thermal efficiency of the Scheffler concentrator, which can be used to optimize its performance for direct steam generation applications. The proposed models can also be employed to predict the system's performance under different operating conditions, providing valuable insights for designing and implementing solar thermal power systems.

1. INTRODUCTION

The burning of fossil fuels is used to generate heat to meet the thermal energy requirements for various applications. However, the excessive use of fossil fuel resources and the resulting increase in energy demand for improved living standards have contributed to environmental pollution. Air pollution is caused by a variety of sources such as vehicle emissions, thermal power plants, burning of agricultural waste, and household biomass burning. Research conducted in India has found that prolonged exposure to polluted air has resulted in respiratory disorders in both children and adults [1]. Energy demand is always rising, yet conventional energy sources have certain limitations. The increasing worry for environmental deterioration and the adverse impact of air contaminants on well-being has emerged as a motivating factor for employing eco-friendly and dependable sources of energy in different industries. Solar energy presents a viable option for generating both heat and electricity [2,3]. Concentrated Solar Power (CSP) provides a financially feasible and efficient means of converting solar energy into heat [4]. The use of CSP for direct steam generation has been demonstrated to be a viable and widely available technology, with relatively straightforward construction and operation methods [5]. It is becoming popular for industrial process heating. Many industries have adopted CSP technology for applications that require low to medium temperatures. This is because CSP systems are capable of producing temperatures in the range of 100-500°C, which is suitable for a variety of industrial processes such as desalination, drying, and space heating. However, some industries are also exploring the use of CSP for higher temperature applications, such as power generation [4]. Reducing the demand for electricity for industrial process heating could help to alleviate the burden on energy security. Many research projects have explored the utilization of Compound Parabolic Concentrator (CPC) and parabolic dish systems for proposes such as heating water and producing steam. [7–10].

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A. Gudekar et al. [11] developed a cost-effective Compound Parabolic Collector (CPC) system has been developed for the intension of producing process steam. The experimental unit has a total aperture area of 30m^2, and research findings have shown that the system efficiency can reach up to 71% for steam generation at atmospheric pressure. J. Feldhoff et al. [12] has showcased the economic viability of implementing direct steam generation in a solar thermal system that employs artificial oil as a medium for heat transfer. It has been stated that direct steam generation holds great promise in enhancing the efficiency of a parabolic trough thermal power plant, leading to potential cost reductions of up to 11% in power generation. P. Kumar [13] reported the quantitative and practical analysis of Scheffler concentrator for producing steam. The concentrator effectiveness was found to be between 85% and 90% while the overall effectiveness ranged from 30% to 45%. A. Amine et al. [14] developed mathematical model for performance prediction of parabolic tough collector. Investigation of thermo-hydraulic behavior for direct steam generation was carried out under various operating conditions. Overall efficiency at the evaporation section was observed to be less than preheating efficiency. AnjumMuniret al. [15] developed a mathematical model to offer a complete design approach for a reflector parabola curve and an elliptical frame. Mathematical modeling proves concentrator can focus at fixed point throughout the year. M. Chandrashekara and A. Yadav [16] performed an experimental investigation on a 2.7 m^{2}Scheffler reflector for desalination. The receiver was coated with exfoliated graphite. With sensible and latent heat storage materials, maximum outputs of 4.67 and 6.67 litres of distillate were produced, respectively. Ayub et al. [17] used a Scheffler reflector with a size of 10 square meters for decentralized food baking. The reflector was able to achieve a temperature range between 300°C to 400°C at the receiver, which is the part of the reflector where the solar radiation is concentrated. In the baking chamber, which is the area where the food is placed, a temperature range of 200°C to 230°C was achieved. This result indicates that the Scheffler reflector is capable of producing high temperatures suitable for baking and cooking purposes, and can be used as an alternative to traditional cooking methods that rely on fossil fuels or electricity. Additionally, the use of decentralized solar energy systems like the Scheffler reflector can also reduce dependence on centralized power grids and help to promote sustainable development. Srivastava and Yadav [18] conducted experiments to extract water particles from the atmosphere using a Schaeffler reflector with a surface area of 1.54 m2. To extract water from air, the authors used silica gel molecular sieves and activated alumina. Different amounts of these materials were used in the experiment, with 1 kg of each material used individually. The results of the experiment showed that the production rate of drinkable water was 43 ml/day when 1 kg of molecular sieve was used, 38 ml/day when 1 kg of activated alumina was used, and 155 ml/day when 1 kg of silica gel was used. This experiment demonstrates the potential of using CSP technology for water extraction from the atmosphere, which could be a valuable solution in areas with water scarcity. V. Kamboj et. al. [19] experimentally investigated 1.54 m^2 Scheffler concentrator for steam generation with three different arrangements of the receiver. The system generated steam at 2.1 bar pressure. The findings demonstrate that the enhancement in efficiency was achieved up to 18.40% with black paint receiver. Scheffler concentrator has also been used for distillation, cremation, agricultural produce drying, coffee making, syrup production, oil extraction, food cooking and electricity generation [20,21]. S. Indora and T. Kandpal [22] presented financial attractiveness of Scheffler concentrator for institutional steam based cooking. It has been found that the payback period is 9, 7 and 6 years for 200, 500 and 1000-person kitchen respectively. Kumar et al. [23] have shown allurement of Scheffler reflector under various climatic conditions of India for different process heat applications. As reported by A. Amine et al. [14] direct steam generation reduces the cost of plant by about 15%, by eliminating the need of heat exchangers.

The Scheffler reflector is a type of parabolic dish concentrator that has a polar-axis automatic tracking system to maintain a fixed focus and achieve high temperatures at the receiver. This promising CSP technology offers several advantages over other CSP technologies, such as requiring less land area per square meter of aperture area and reduced maintenance costs. In this study, a heat transfer model has been proposed to determine the daily performance of the Scheffler concentrator, and the results obtained with the proposed model have been compared with experimental results. Although direct steam generation (DSG) using Scheffler concentrator is an attractive technology for revolutionary steam applications, seasonal variation can significantly affect their performance. With large seasonal variations observed in India, the authors have proposed a mathematical model to predict the monthly and annual thermal performance of the Scheffler concentrator for direct steam generation.

2. EXPERIMENTAL SETUP

The system is comprised of a Scheffler concentrator, a receiver, and a steam separator. The experimental setup is situated in Nanded (MS), India, with a latitude of 19.1114 North and a longitude of 77.2945 East. Figure 1 illustrates a photograph of the experimental setup. Scheffler reflector is preferable among CSP technologies due to shadow less concentration [24]. Wolfgang Scheffler, a renowned German scientist, developed the Scheffler reflector, which is a paraboloid-based concentrator designed to focus solar radiation at a specific point. This reflector is a groundbreaking invention, consisting of a 16 square meter elliptical rim with flexible surface curvatures and 20 crossbars. Reflective solar-grade mirrors measuring 22 x 22 cm are mounted on aluminum strips, which are curved and held in place by supporting rods. The reflector includes both a manual seasonal tracking system and an automatic daily tracking system. The reflector can track the sun's movement throughout the day with the help of the daily tracking system, which employs a DC motor and an on/off relay to keep the receiver in focus. The ability to modify the telescopic clamps makes seasonal tracking easier. The reflector, on the other hand, rotates at an angle of half the declination angle of the sun and needs to be adjusted every 3 – 4 days for seasonal monitoring. For daily tracking, it rotates along an axis parallel to the polar axis. [25]. The Scheffler dish stands more upright in winter than in summer. The Scheffler reflector has a unique geometry that provides a shadow-free receiver, allowing for efficient and consistent concentration of solar radiation onto a single focal point. This makes it an attractive option for various solar thermal applications such as cooking, baking, and water heating. However, the reflector's design is complicated and requires careful assembly, which can be time-consuming and costly. Additionally, the reflector has a heavy structure that can be challenging to transport and install. These factors can make the Scheffler reflector less practical for certain applications, and alternative concentrator designs may be more suitable.

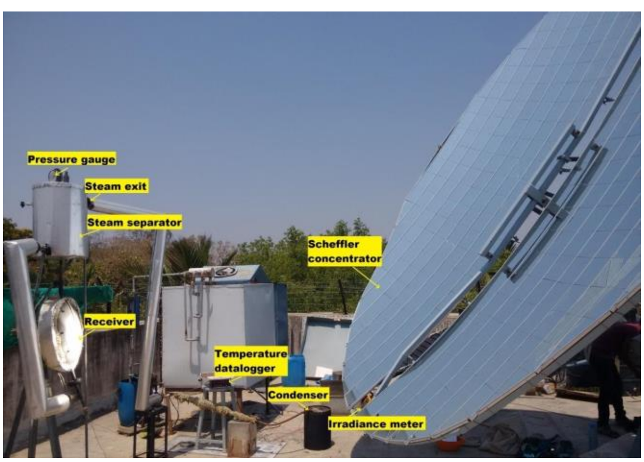
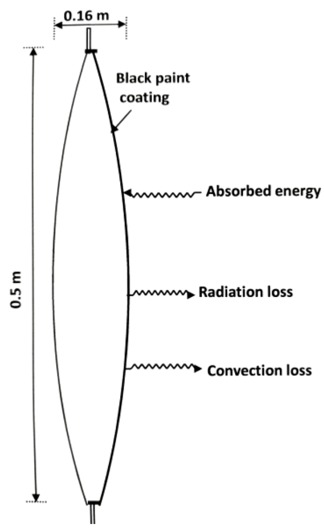


Fig. 1. Photograph of experimental setup.

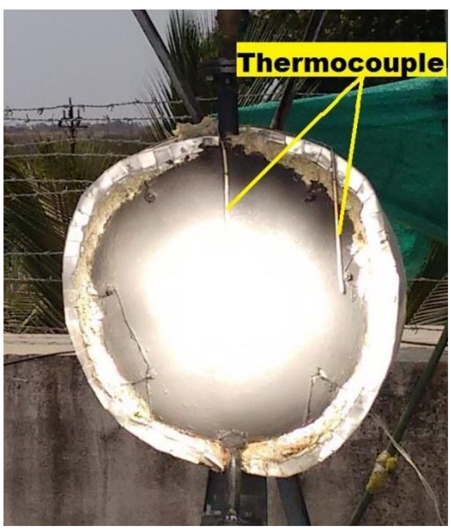
A Scheffler solar concentrator, which is the main component of this solar energy system, reflects sunlight onto a receiver set in front of it. The receiver, made of hollow cast iron, has a volumetric capacity of 18 liters and an aperture diameter of 0.5 meters, as determined by theoretical analysis of the focal image. Black Antireflection Paint is applied to the outside of the receiver to improve absorption. To minimize thermal losses, a 5 cm thick layer of rock wool insulation covers the other sides of the receiver. The heat transfer medium employed for direct steam generation is water, which absorbs the energy received from the reflector and undergoes a phase change to steam with the cavity. The overhead tank, which has a volumetric capacity of 30 liters and is thermally insulated, is used to store water and feed it into the receiver. The upper and lower part of the receiver is connected to the tank through pipes, so water can keep flowing through the vertical receiver because of the density difference [26]. The water enters the bottom of the hollow cast iron receiver where it absorbs heat from the concentrated solar radiation. The heated water then rises and is replaced by cooler water entering the receiver, creating a continuous flow of water through the receiver. As the water absorbs more heat, it eventually boils and produces steam. The steam rises to the top of the receiver and enters the insulated overhead tank, where it is separated from the water. The separated steam is collected for further use, while the water is recirculated back to the receiver. There are two thermocouples connected to the receiver to keep an eye on the inside and outside temperature of the focal point, providing important data for controlling and optimizing the system's performance. In order to measure the incidence of solar radiation on the inclined surface of Scheffler dishes, an irradiation meter is installed on the elliptic frame of the dish. This irradiation meter is Seaward solar survey 200R. The irradiance meter has a measuring range of 100-1250 W/m^2 with an accuracy of ±1 W/m^2. To measure diffuse radiations, a ring is provided on the Pyranometer (Model – DAM 8101). K-type thermocouple with a temperature measurement accuracy of ±0,2 ºC is used to measure the temperature at various points. An anemometer with a measurement range of 0.4 to 45 m/s and an accuracy of 0.1 m/s is used to measure the wind speed. The pressure gauge has an accuracy of ±1%. An exact calibrated glass tube water level indicator that is mounted to the outside of the tank is used to track water evaporation from the tank. The rate of steam flow is calculated by measuring the amount of water that has evaporated. It has been calculated that the solar beam's average uncertainty is 2.1%. Using a K-type thermocouple, the temperature measurement uncertainty is 1.4%. The measurement of wind speed has a 1.6% error. Condensate measurements have a 3.6% error margin. The mass flow rate of steam and the strength of the sun beam are also factors that affect uncertainty inefficiency. Correlations between the measured variables yield a cumulative efficiency uncertainty of 4.0%.

3. MATHEMATICAL MODELING

The thermal output variation concerning environmental conditions is determined using a thermodynamic model. Parameters recorded during experimentation are utilized to calculate the theoretical and experimental efficiency of the Scheffler concentrator for direct steam generation. A mathematical model is employed to calculate the receiver's temperature using geometrical and climate parameters. Based on the suggested mathematical model, the monthly and yearly performance of the examined system is forecasted. Please let me know if you would like any further assistance.



(a)



(b)

Fig. 2. (a) Energy balance for the receive (b) Photograph of receiver.

3.1 Thermal analysis

The efficiency and losses of the system are determined by taking into account various factors at each stage of operation. The receiver losses are an important consideration when evaluating the thermal performance of the system. The two main contributors to receiver losses are convection and radiation losses. In order to calculate the system's efficiency and losses, the assumption of steady-state conditions is made, where the average receiver temperature is assumed to have a uniform distribution of solar radiation. The law of energy conservation, which asserts that energy, cannot be generated or destroyed but only converted or moved from one form to another, is the foundation of the energy balance equation. The useful energy output of the concentrator is calculated in steady-state as the difference between the concentrated energy on the receiver and the radiant energy dispersed into the environment.

The amount of solar radiation that the concentrator concentrates and the receiver absorbs is equal to the system's total useful energy, less the energy lost due to radiation and convection. The concentrator concentrates the solar radiation on the receiver, which absorbs the energy and heats up the water to generate steam. The steam is then separated in the overhead tank, and the useful energy output is determined by subtracting the radiant energy losses from the concentrated energy on the receiver.

Therefore, it's important to minimize radiation and convection losses and maximize the receiver's ability to absorb solar radiation in order to increase the system's efficiency. This can be achieved through the use of proper insulation and reflective coatings, as well as by designing the concentrator and receiver to maximize the absorption of solar radiation.

$$Q_{u,th} = Q_r - Q_l \tag{1}$$

3.2 Calculation of concentrated energy on the receiver

Solar radiation is the main energy source for the functioning of a CSP system. However, not all radiation that falls on the reflector is concentrated at the receiver. In a CSP system, only the direct (beam) solar can be focused by the concentrator to generate high temperatures and produce steam. On the other hand, the indirect (diffuse) radiation is less intense and cannot be concentrated enough to generate the required temperatures. In fact, the diffuse radiation can actually reduce the overall efficiency of the system by increasing the thermal losses. [27]. the amount of solar radiation power that can be utilized by the Scheffler concentrator is expressed as

$$Q_c = A_c I_b \tag{2}$$

The equation for calculating the solar declination angle is used to determine the aperture area of the Scheffler concentrator [15].

$$A_c = A_s \cos\theta \tag{3}$$

The aperture area of the Scheffler concentrator is determined by the cosine of the solar declination angle. denoted as θ

where

$$\cos\theta = \cos(43.23 \pm \delta/2) \tag{4}$$

The Scheffler solar concentrator is designed to maintain its focus on the fixed point as the sun's position changes with the seasons. To achieve this, the major axis of the elliptical rim is tilted by half of the solar declination angle. The declination angle (δ) is calculated using the following equation [28].

$$\delta = 23.45\left[2\pi\left(\frac{284+n}{365}\right)\right] \tag{5}$$

where, n is the day of the year

It should be noted that the declination angle is positive (+) for locations in the southern hemisphere and negative (–) for locations in the northern hemisphere. This tilt helps in maintaining the concentration of solar radiation on the fixed point of the concentrator, despite the seasonal changes in the sun's position.

Concentrated energy on the receiver [29].

$$Q_r = \rho_m \alpha_{rec} \Gamma A_c I_b \quad (6)$$

where, ρ_m is the reflectivity of the mirror and Γ denotes intercept factor. Intercept factor is depending on geometric and optical parameters of the reflector and receiver [30]. Based on the size of the focal image at the receiver during different seasons receiver aperture diameter is designed to intercept all reflected radiations. However, an inaccuracy in the rim and crossbars of the Scheffler reflector limits the intercept factor. For the critical conditions of the reflector and receiver, intercept factor is assumed to be 0.98. α_{rec} represents the absorptivity of the black painted receiver front surface.

Solar radiations reflected from the Scheffler concentrator forms elliptical image at the focal point. Irradiance concentration area is obtained by knowing the dimensions of the elliptical image at receiver. Semi minor axis and semi major axis of the image formed by every point of the Scheffler concentrator on receiver is calculated with the help of guidelines given by [31]

$$a_n = 4 L_n tan\theta_s \quad (7)$$

$$b_n = 2 L_n sin\theta_s \left[\frac{1}{sin(\phi_n+\theta_s)} + \frac{1}{sin(\phi_n-\theta_s)}\right] \quad (8)$$

where, L_n represents the distance between the focal point and upper extreme point of reflector on nth day of the year, ϕ_n is angle between L_n and vertical axis passing through focal point of reflector and θ_s is half angle subtended by the sun on earth surface and approximately it is 0.27°.

$$L_n = \sqrt{(x_n)^2 + (y_n - f)^2} \quad (9)$$

$$\emptyset_n = \left(\frac{y_n - f}{L_n}\right) \quad (10)$$

The image area is calculated as

$$A_n = \pi\, a_n b_n \quad (11)$$

Due to seasonal variations in focal image size, irradiation concentration ratio is crucial. The ratio of the reflector aperture to the solar energy concentration area is known as the irradiation concentration ratio. [29].

$$C_{irr} = \frac{A_c}{A_n} \quad (12)$$

3.3 Calculation of heat losses of the receiver

The following equation can be used to determine the heat loss from the front surface of the unglazed receiver to the atmosphere.

$$Q_l = Q_{c,r-a} + Q_{r,r-a} \quad (13)$$

The following formula can be used to express the rate of heat transfer from the receiver and its surroundings due to convection.

$$Q_{c,r-a} = h_c A_r (T_r - T_a) \quad (14)$$

h_c is calculated using the relation given by [28]

$$h_c = 5.7 + 3.8V \quad (15)$$

The rate of heat loss from the receiver to the atmosphere caused by radiation is expressed by the following equation [30]:

$$Q_{r,r-a} = A_r\, h_r (T_r - T_a) \quad (16)$$

where,

$$h_r = \frac{\epsilon_r \sigma (T_r^4 - T_{sky}^4)}{(T_r - T_a)} \quad (17)$$

Overall heat loss coefficient is calculated as

$$\frac{1}{U_l} = \frac{1}{h_c + h_r} \quad (18)$$

3.4 Calculation of temperature of receiver

Theoretical temperature at the center of the receiver where thermocouple 1 is placed is calculate from the relation given by [34]

$$T_{r,cen} = \sqrt[4]{\frac{\alpha_r C_{irr} I_b}{\varepsilon_r \sigma}} . \xi_{att} \quad (19)$$

Above equation represents the temperature at the receiver within the focal image. Amount of radiations concentrated within the focal image and heat removal factor is considered to achieve accurate results with actual conditions. To achieve a temperature at the receiver that is close to the operating temperature, an attenuation constant ξ_{att} is used.

$$\xi_{att} = \eta_c F_R \quad (20)$$

3.5 Calculation of efficiency of steam generation

Before the water reaches the boiling point, the flow inside the DSG loop is single phase. Single-phase flow occurs from the overhead tank to the receiver when the water inside reaches the boiling point, and two-phase flow occurs from the receiver to the tank. Energy needed to bring the water's temperature up to the boiling point and then energy supplied to vaporize it are the two categories of useful energy produced by the system.

The system generates useful energy at a rate that is calculated as.

$$Q_{u,exp} = Q_{sen} + Q_{lat} \quad (21)$$

where, heat power required to bring water at boiling point is determined as

$$Q_{sen} = mC_p \frac{\Delta T}{\Delta t} \quad (22)$$

m is the mass of the water in the tank and receiver; C_p is the water's specific heat and $\frac{\Delta T}{\Delta t}$ is the rate of temperature rise over time. It is specified as the latent heat needed for vaporization

$$Q_{lat} = \dot{m} h_{fg} \quad (23)$$

$\dot{m}$ represents the mass flow rate of the steam and h_{fg} is latent heat of steam at atmospheric pressure.

Thermal efficiency of the system for direct steam generation is the ratio of energy utilized for vaporization of water to the solar energy received by concentrator.

$$\eta_s = \frac{Q_u}{Q_c} \quad (24)$$

4. RESULT AND DISCUSSION

A 16-m^2 Scheffler concentrator's performance was examined during several days of experimental testing in March. It is found that the average aperture area during this time was 11.77 m^2. The performance of the Scheffler concentrator for direct steam generation at atmospheric pressure was predicted using a mathematical model, which was then verified using experimental data. The model's outcomes and the experimental data had a good degree of agreement. Based on these findings, the work concluded that proposed model could be used for predicting the daily, monthly, and annual performance of the Scheffler concentrator. This information can be useful for designing and optimizing the concentrator for various applications.

4.1 Daily performance evaluation

Figure 3 depicts the changes in direct solar radiation and ambient temperature on a clear day (March 26, 2019). The graph shows that the strongest solar beam radiation occurred between 11:35 and 13:35 hours. The peak hours of solar radiation occur when the sun is at its highest point in the sky. The experiment's average measurement of solar beam radiation was 524 W/m^2, indicating the overall level of solar energy received that day. The graph shows a linear increase in ambient temperature from 9:00 to 13:50 hours. This indicates that the temperature gradually increased during this time period. The temperature ranged between 38 and 39.4°C after reaching its peak. During the experiment, the average ambient temperature was 37.2°C. These temperature variations shed light on the thermal conditions that prevailed on that clear-sky day. Variation in the wind speed is shown in Figure 4. During the experimentation, the wind speed was in the range of 0.5 to 4.6 m/s and the average value is 2.0 m/s.

Figure 5 depicts the variation in receiver temperature with solar beam radiation. The temperature at the receiver's center unexpectedly rises above 200°C, when the dish is rotated to focus solar radiation there. Temperature distribution at the receiver was non-uniform, temperature decreases in radial direction. The results of various ray-tracing techniques show that the receiver is not consistently concentrated with the reflected rays from the Scheffler concentrator over the course of the year. This is a result of the sun's position fluctuating throughout the year, which causes a change in the solar declination angle. [35]. The average temperature at the receiver reaches up to 346°C at 13:35 hrs whereas the temperature at the center remains above 500°C during 11:15 to 14:35 hrs. Fluctuations in the intensity of solar beam radiation and wind speed lead the small steps in the receiver temperature profile.

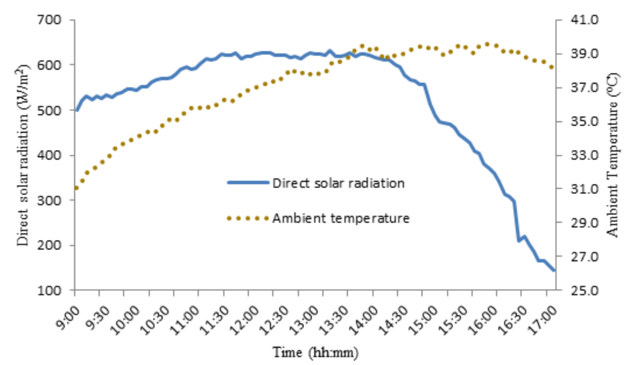


Fig. 3. Variation of direct solar radiation and ambient temperature with time.

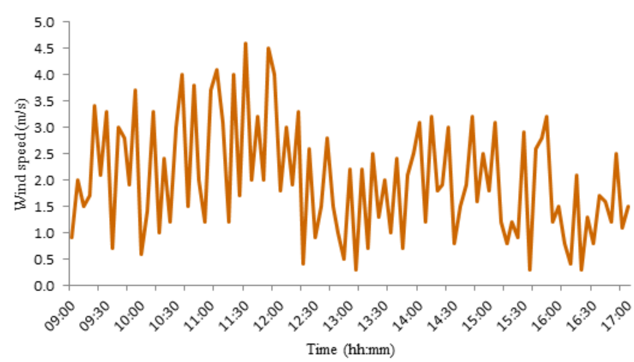


Fig. 4. Variation of direct solar radiation and ambient temperature with time.

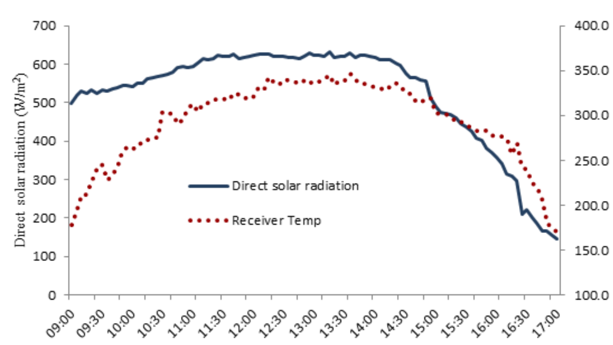


Fig. 5. Variation of direct solar radiation and receiver temperature with time.

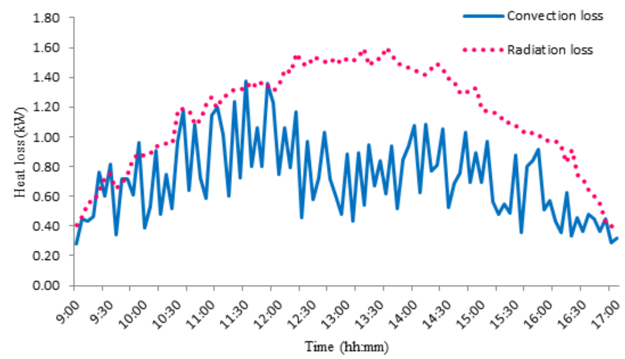


Fig. 6. Variation of conduction and convection losses of the receiver with time.

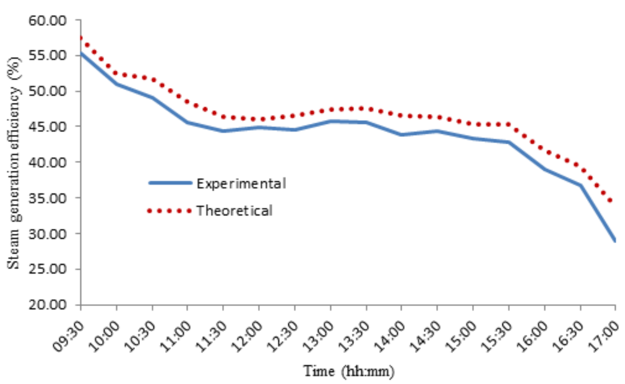


Fig. 7. Variation in efficiency of the Scheffler concentrator.

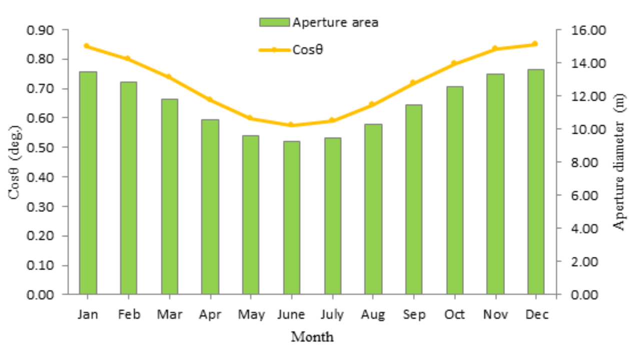


Fig. 8. Month wise variation of cosine factor and aperture area of Scheffler concentrator.

Variation of conduction and convection losses with daytime is shown in Figure 6. Loss due to radiation heat transfer was dominant than the convection heat transfer loss from the receiver. Conduction heat loss was very less as compared with convection and radiation heat losses. With an increase in receiver temperature, there was an increase in radiation heat loss. Wind speed affects the coefficient of convective heat transfer, which results large fluctuations in convection heat loss. While the radiation heat transfer is directly proportional to the fourth power of temperature, convection heat transfer is directly proportional to wind speed. Radiation heat loss from the receiver to the ambient gradually increases from 0.49 kW to 1.60 kW especially during the 9.00 to 13:35 hrs. Average values of radiation and convection heat losses are 1.14 and 0.73 kW respectively.

The comparison of experimental and theoretical thermal efficiency is depicted in Figure 8. The comparison efficiencies have some differences due to some uncertainty in the experimental results, and the assumptions made in the theoretical method. As shown in Figure 7, thermal efficiency of system was more during the preheating of water in the receiver, and then decreased rapidly as the temperature of the water reaches to the boiling point. Average efficiency achieved before the commencement of steam generation was 51.75%. After that, noticeable drop in the efficiency was observed due to the lower value of heat transfer coefficient. Fewer fluctuations in the efficiencies were observed from 11:30 to 14:30 hrs. Decreased solar beam intensity after 14:30 hrs causes reduced rate of heat transfer to boiling water, which eventually decrease the thermal output from the system. Experimental efficiency values are lower than theoretical efficiency values. An average difference between theoretical and experimental efficiency is found to be 2.77%.

4.2 Monthly performance evaluation

Figure 8 illustrates how the aperture area and cos θ of the Scheffler concentrator change throughout the year. The relationship between the declination angle and aperture area in the northern hemisphere is inverse. The effective concentration ratio for a concentrator with variable aperture area requires intricate calculations. The non-uniform concentration of reflected rays at the receiver over the course of the year has been demonstrated by various ray tracing methods. The maximum aperture area is available in December whereas, minimum in June due to cosine factor. The amount of power available at concentrator is directly depends upon aperture area. Aperture area changes between 9.19 m^2 at summer solstice and 13.64 m^2 at winter solstice. In India, sky is clear from November to April and the average aperture area available is 12.59 m^2.

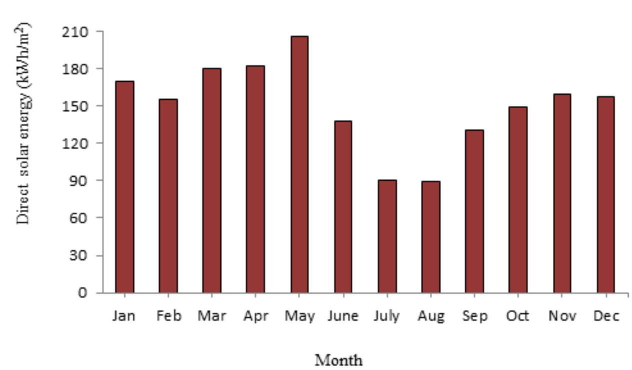


Fig. 9. Monthly average solar beam radiation energy in Nanded.

Figure 9 depicts the variation of monthly average solar beam radiation of Nanded (MS), India. It clearly shows that energy received from solar beam radiation can reach 1806 kWh/m^2/year. June to September is monsoon season in India due to this the monthly average solar beam energy is reduced during these months. From the climate data, annual average ambient temperature and wind speed of Nanded were 38°C and 3.5 m/s, respectively. Ambient temperature increases linearly from January to May, whereas wind speed increases from February to June.

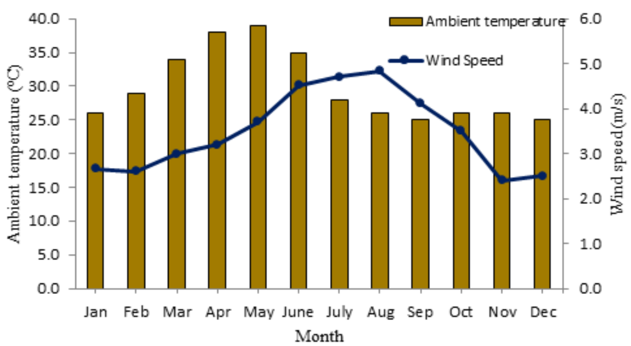


Fig. 10. Monthly average ambient temperature and wind speed.

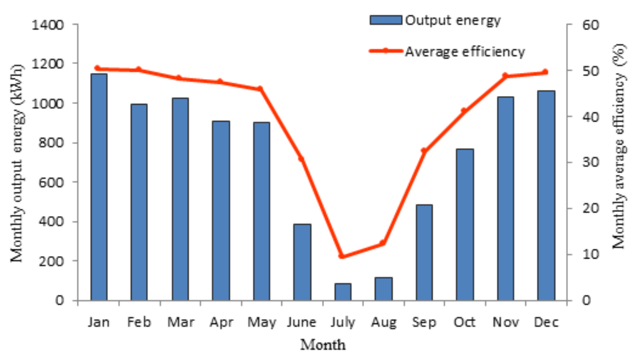


Fig. 11. Monthly average thermal output energy and efficiency.

Energy output and thermal efficiency of Scheffler concentrator is predicted from the proposed mathematical model. Temperature of the receiver within the focal image was calculated from equation (19) and heat losses from the receiver are determined. Thermal output from the system is determined by considering amount of energy received at the receiver and losses from the receiver. Estimated average energy output and monthly average efficiency of Scheffler concentrator are plotted in Figure 11. Predicted results show that higher energy output and efficiency values are obtained between January to May and then November to December.

Reduction in the output power from concentrator and receiver relative to the total available amount of solar energy at dish is presented in Figure 12. First bar shows the power available at Scheffler concentrator and second bar presents power received by the receiver. Amount of energy received at concentrator is depends on aperture area, while energy received at receiver is depends on reflectivity of mirrors, intercept factor and absorption of receiver. Third bar shows thermal output from the system. Energy balance presented in Figure 12 allows identifying the losses from the each component of the system. The annual average efficiency for direct steam generation at atmospheric pressure is found to be 42.48%.

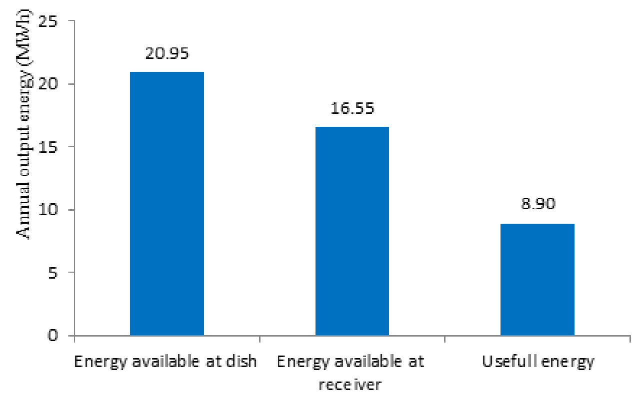


Fig. 12. Annual energy balance.

5. CONCLUSIONS

Scheffler concentration has proven its technical feasibility for seasonal changes in India during the year. In the present study mathematical model was developed to determine heat losses from the receiver and predict the monthly and annual thermal performance of the of the Scheffler concentrator. Heat transfer model was validated by using experimental data collected under the same operating conditions. Theoretical results obtained are presented to demonstrate the effectiveness of the Scheffler concentrator for desalination and steam based applications.

The experimental and theoretical investigations led to the following conclusions:

1. The aperture area and thermal performance of the Scheffler concentrator are significantly affected by the declination angle.

2. The convective and radiative heat losses contribute 12.06% and 19.05% respectively to the overall heat loss.

3. The theoretical thermal efficiency, calculated using the heat loss model, showed good agreement with the experimental efficiency, with a deviation of only 2.33%.

4. The Scheffler concentrator system has an annual net efficiency of 42.48%, producing 8.90 MWh of energy per year. The system has a maximum power output of 1.15 MWh with a monthly average efficiency of 38.80% in January and the lowest thermal output of 0.08 MWh in July.

5. The study provides guidelines for predicting the annual thermal performance of the Scheffler concentrator.

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NOMENCLATURE

A_c	aperture area of concentrator, m^2
As	surface area of concentrator, m2
A_r	surface area of receiver, m^2
An	solar image area on nth day, m2
an	semi minor axis of focal image on nth day, m
bn	semi major axis of focal image on nth day, m
Cirr	irradiance concentration ratio
FR	heat removal factor
f	focal length of paraboloid, m
hc	convection heat transfer coefficient, W/m2K
hr	radiative heat transfer coefficient, W/m2K
Ib	solar beam radiation, W/m2
Qc,r-a	convection power loss from receiver to ambient, W
Qr,r-a	radiation power loss from receiver to ambient, W
Qu,th	theoretical useful power, W
Qu,exp	useful heat experimentally, W
Qr	power received at receiver, W
Ql	power loss from receiver, W
Tr	receiver temperature, K
Ta	ambient temperature, K
Tsky	temperature of sky, K
Tr,cen	temperature at center of the receiver, oC
V	wind speed, m/s
xn	x-coordinate of points of intersection of section line and parabola, m
yn	y-coordinate of points of intersection of section line and parabola, m
δ	solar declination angle, degree
∈r	emissivity of receiver,
σ	Stefan Boltzmann constant,W m-2K-4
αr	absorptivity of receiver
ηc	optical efficiency of concentrator

REFERENCES

[1] Gordon, T., Balakrishnan, K., Dey, S., Rajagopalan, S., Thornburg, J., Thurston, G., Agrawal, A., Collman, G., Guleria, R., Limaye, S., Salvi, S., Kilaru, V., and Nadadur, S., 2018, “Air Pollution Health Research Priorities for India: Perspectives of the Indo-U.S. Communities of Researchers,” Environ. Int., 119(March), pp. 100–108

[2] Vardhan, A. S. S., & Saxena, R. 2023, MPPT of Solar Energy Conversion System with Modified Perturb and Observe Algorithm Using Bisection Method, GMSARN International Journal 17: 24-32

[3] Pannucharoenwong, N., Rattanadecho, P., Echaroj, S., Hemathulin, S., & Nabudda, K., 2020. The experiment of heat absorber from black gasket on the efficiency of double slope solar still, GMSARN International Journal, 14(1): 1-10.

[4] Kumar, A., Prakash, O., and Dube, A., 2017, A Review on Progress of Concentrated Solar Power in India, Renewable Sustainable Energy Reviews, 79:304–307.

[5] Guo, S., Chu, Y., Liu, D., Chen, X., Xu, C., Coimbra, C. F. M., Zhou, L., and Liu, Q., 2017, The Dynamic Behavior of Once-Through Direct Steam Generation Parabolic Trough Solar Collector Row under Moving Shadow Conditions, Journal of Solar Energy Engineering. Trans. ASME, 139(4).

[6] Farjana, S. H., Huda, N., Mahmud, M. A. P., and Saidur, R., 2018, Solar Process Heat in Industrial Systems – A Global Review, Renewable and Sustainable Energy Reviews, 82: 2270–2286.

[7] Hafez, A. Z., Attia, A. M., Eltwab, H. S., ElKousy, A. O., Afifi, A. A., AbdElhamid, A. G., AbdElqader, A. N., Fateen, S. E. K., El-Metwally, K. A., Soliman, A., and Ismail, I. M., 2018, Design Analysis of Solar Parabolic Trough Thermal Collectors, Renewable and Sustainable Energy Reviews, 82: 1215–1260.

[8] Naik, H., Baredar, P., and Kumar, A., 2017, Medium Temperature Application of Concentrated Solar Thermal Technology: Indian Perspective, Renewable and Sustainable Energy Reviews 76: 369–378.

[9] Tian, M., Su, Y., Zheng, H., Pei, G., Li, G., and Riffat, S., 2018, A Review on the Recent Research Progress in the Compound Parabolic Concentrator (CPC) for Solar Energy Applications, Renewable and Sustainable Energy Reviews, 82:1272–1296.

[10] Kessentini, H., 2018, Numerical Simulation, Design, and Construction of a Double Glazed Compound Parabolic Concentrators-Type Integrated Collector Storage Water Heater, Journal of Solar Energy Engineering, 138: 1–7.

[11] Gudekar, A. S., Jadhav, A. S., Panse, S. V, Joshi, J. B., and Pandit, A. B., 2013, Cost Effective Design of Compound Parabolic Collector for Steam Generation,” Solar Energy, 90: 43–50.

[12] Feldhoff, J. F., Benitez, D., Eck, M., and Riffelmann, K. J., 2010, Economic Potential of Solar Thermal Power Plants with Direct Steam Generation Compared with HTF Plants, Journal of Solar Energy Engineering Trans. ASME, 132(4).

[13] Kumar, P., Kumar, S., Kumar, R., and Mandal, S., 2018, Numerical and Experimental Analysis of Scheffler Concentrator Receiver for Steam Generation Using Phase Change Material, International Journal of Renewable Energy Research, 8(3).

[14] Amine, A., Rodríguez, I., and Ghenai, C., 2018, Thermo-

Hydraulic Analysis and Numerical Simulation of a Parabolic Trough Solar Collector for Direct Steam Generation, Applied Energy, 214: 152–165.

[15] Munir, A., Hensel, O., and Scheffler, W., 2010, Design Principle and Calculations of a Scheffler Fixed Focus Concentrator for Medium Temperature Applications, Solar Energy, 84(8): 1490–1502.

[16] Chandrashekara, M., and Yadav, A., 2017, Experimental Study of Exfoliated Graphite Solar Thermal Coating on a Receiver with a Scheffler Dish and Latent Heat Storage for Desalination, Solar Energy, 151: 129–145.

[17] Ayub, I., Munir, A., Ghafoor, A., Amjad, W., and Nasir, M. S., 2018, Solar Thermal Application for Decentralized Food Baking Using Scheffler Reflector Technology, Journal of Solar Energy Engineering, 140(6): 61005-61014

[18] Srivastava, S., and Yadav, A., 2018, Extraction of Water Particles from Atmospheric Air through a Scheffler Reflector Using Different Solid Desiccants, International Journal of Ambient Energy, 41(12): 1357-1369

[19] Kamboj, V., Agrawal, H., Malan, A., and Yadav, A., 2019, Thermal Performance of the Steam Boiler Based on Scheffler Solar Concentrator for Domestic Application: Experimental Investigation, Australian Journal of Mechanical Engineering, 19(5): 521-531

[20] Panchal, H., Patel, J., Parmar, K., and Patel, M., 2018, Different Applications of Scheffler Reflector for Renewable Energy: A Comprehensive Review, International Journal of Ambient Energy, 41(6): 716-728

[21] Nukulwar, M. R., and Tungikar, V. B., 2018, Thin Layer Mathematical Modelling of Turmeric in Indirect Natural Conventional Solar Dryer, Journal of Solar Energy Engineering Trans. ASME, 142(4): 041001-041007

[22] Indora, S., and Kandpal, T. C., 2019, Financial Appraisal of Using Scheffler Dish for Steam Based Institutional Solar Cooking in India, Renewable Energy, 135: 1400–1411.

[23] Kumar, S., Yadav, V., Sahoo, U., and Singh, S. K., 2019, Experimental Investigation of 16 Square Meter Scheffler Concentrator System and Its Performance Assessments for Various Regions of India, Thermal Science and Engineering Progress, 10: 103–111.

[24] Kumar, A., Prakash, O., and Kaviti, A. K., 2017, A Comprehensive Review of Scheffler Solar Collector, Renewable and Sustainable Energy Reviews, 77: 890–898.

[25] MNRE, 2014, Scheffler Dish Based Solar System: Operations and Maintenance Manual.

[26] Michaelides, I. M., Lee, W. C., Wilson, D. R., and Votsis, P. P., 1992, Computer Simulation of the Performance of a Thermosyphon Solar Water-Heater, Applied Energy, 41(2), 149–163.

[27] Cheralathan, M., Sornanathan, M., and Thirunavukkarasu, V., 2017, An Experimental Study on Energy and Exergy Performance of a Cavity Receiver for Solar Parabolic Dish Concentrator, International Journal of Exergy, 23(2): 129.

[28] Duffie, J. A., and Beckman, W. A., 2013, Solar Engineering of Thermal Processes, John Wiley & Sons, Hoboken, New Jersey.

[29] Ruelas, J., Velázquez, N., and Cerezo, J., 2013, A Mathematical Model to Develop a Scheffler-Type Solar Concentrator Coupled with a Stirling Engine, Applied Energy, 101: 253–260.

[30] Reddy, D. S., Khan, M. K., Alam, M. Z., and Rashid, H., 2018, Design Charts for Scheffler Reflector, Solar Energy, 163: 104–112.

[31] Uzair, M., Rehman, N., Siddiqui, M., & Kazmi, S. U. H. 2022, Improved methodology for determining seasonal and fixed optimum tilt angles for solar collectors, GMSARN International Journal, 16: 325-330.

[32] Karimi, R., Gheinani, T. T., and MadadiAvargani, V., 2018, A Detailed Mathematical Model for Thermal Performance Analysis of a Cylindrical Cavity Receiver in a Solar Parabolic Dish Collector System, Renewable Energy, 125: 768–782.

[33] Frank P. Incropera, David P. Dewitt, Theodore L. Bergman, A. S. L., 2007, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, Inc.

[34] Mendoza Castellanos, L. S., Carrillo Caballero, G. E., Melian Cobas, V. R., Silva Lora, E. E., and Martinez Reyes, A. M., 2017, Mathematical Modeling of the Geometrical Sizing and Thermal Performance of a Dish/Stirling System for Power Generation, Renewable Energy, 107: 23–35.

[35] Ruelas, J., Palomares, J., and Pando, G., 2015, Absorber Design for a Scheffler-Type Solar Concentrator, Applied Energy, 154: 35–39.