Experimental performance analysis of an improved receiver for Scheffler solar concentrator

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Abstract

This study presents the experimental analysis of the convex receiver for a Scheffler solar concentrator. The solar receiver with three different arrangements was tested for steam generation. Thermal performance is determined by energy analysis. An analysis of the receiver with the first arrangement revealed approximately 42% heat losses from the bare receiver. Then a convective heat loss is mitigated by providing a cavity on the receiver. However, no significant improvement in thermal efficiency is observed. Further, the tube coil is fixed on the cavity's inner wall and water circulated through the coil to harvest the maximum energy. The average intensity of solar beam radiation was 638 W/m^2 during the experimentation time of 9:00 to 15:00 h. The stagnation test result estimated that $109 \text{ W/m}^2 \text{ K}$ overall heat loss coefficient of the receiver. The receiver's energy efficiency with the first, second, and third arrangements was obtained to be 57.71%, 60.93%, and 68.03%, respectively, under the same operating conditions. In all receiver arrangements, the third arrangement has been found attractive for enhancing the parabolic dish concentrator's efficiency.

Keywords Solar parabolic dish concentrator · Scheffler solar concentrator · Flat receiver · Cavity receiver · Energy efficiency · Overall heat loss coefficient

1 Introduction

Relentless use of fossil fuel for better living standard cause environmental degradation. Increasing electrical and heat energy demands constitutes a driving force for utilizing clean and reliable energy sources in all energy-consuming sectors. Solar energy is an attractive energy source that generates both electricity and heat. The use of concentrated solar power (CSP) is an efficient and financially affordable way to convert solar energy into heat [1]. Most industries are using CSP for low and medium temperature range applications [2]. The reduction in electricity demand for thermal processes might decrease the burden on energy security.

Parabolic concentrator concentrators are preferable among all CSP technologies [3, 4]. A parabolic dish

concentrator is a curved surface system with reflecting material that directs beam radiation onto a receiver. The high temperature is achieved at the receiver due to an increased concentration ratio. Many researchers have designed and developed parabolic dish concentrators. The type of parabolic dish solar concentrator developed and used in different regions in the world depends on solar irradiance and application.

The reflecting frame, receiver, and support structure are three major components of a parabolic dish concentrator. A receiver is a key component of the system in the conversion of solar energy into thermal energy. The thermal performance of the parabolic dish concentrator depends on the design of a receiver. The Smaller receiver cannot intercept all reflected radiation while the large size receiver increases heat losses to the atmosphere. The receiver's

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size and shape should be appropriate so that it can absorb maximum concentrated radiation and reduce heat losses. External receiver and cavity receiver are two main types of receiver. The external receiver is placed at the focal point of the concentrator and radiation absorbed by the receiver surface facing towards the concentrator. However, in the cavity receiver, concentrated radiation enters through the front opening and radiation absorbed by the internal surfaces of the cavity. This absorbed radiation is converted into thermal energy and transferred to the heat transfer medium in the receiver.

Extensive works on a solar receiver for medium and high-temperature applications have been done in the last few years. The Major challenge in receiver design is the trade-off between receiver temperature and thermal efficiency. Many researchers have investigated the thermal performance with the different arrangements of a cavity receiver. Zhu et al. [5] did an experimental study on the performance of the pressurized volumetric receiver for a parabolic dish concentrator. Energy and exergy analysis reported the highest energy efficiency of about 87% and the highest exergy efficiency, approximately 36%, with average beam radiation 600 W/m^2 . An experimental and numerical study was carried out by Jilte et al. [6] to investigate losses from the cylindrical cavity receiver used in the parabolic dish concentrator. Their receiver attained the inner wall temperature from 200 to 500°C for different cavity inclination. They reported that the convective loss significantly varies with change in cavity inclination. Zhang et al. [7] carried out a transient analysis molten salt cavity receiver. They conducted experiments and presented the effect of input power on a cavity receiver's temperature and energy efficiency. Pavlovic et al. [8] have carried out an experimental investigation on a corrugated spiral cavity receiver of a parabolic dish concentrator. The absorber was the stainless steel spiral tube without a selective surface. According to results, the collector showed a thermal efficiency of about 34% due to increased losses from the receiver. Thirunavukkarasu and Cheralathan [9] have presented the consequence of aspect, the ratio on energy efficiency, and overall heat loss of the conical frustum cavity receiver. They constructed and tested receivers of aspect ratio 0.8, 1.0, and 1.2 on a clear sky day. They have reported that receiver temperature and thermal performance decrease with an increase in aspect ratio. Kumar and Shukla [10] reported 21% improvement in the helical coil solar cavity receiver's thermal efficiency than the tube receiver. They also observed 4.35% increases in the temperature of the receiver. The experimental analysis of the copper coil wound cavity receiver of SK 14 parabolic concentrator was done by Mawire and Taole [11]. The receiver's thermal analysis revealed that the maximum energy and exergy efficiencies 45% and 10%, respectively.

The work in Ovidio Lopez et al. [12] shows a cavity receiver with glass cover is efficient than a flat receiver.

Some studies proposed a cavity receiver for a parabolic dish concentrator to achieve high temperatures by suppressing heat losses. Yang et al. [13] proposed a cavity receiver with an air curtain to reduce convective heat losses. Numerical analysis showed a decrease in convective heat losses. Further, they concluded that heat losses could be suppressed with forced air circulation. Bopche and Kumar examined [14] the effect of the aperture opening, glass cover thickness, and inclination angle of cavity receiver on thermal performance. They have reported the contribution of convective and radiative heat losses in each case of the receiver. A numerical analysis of the solar cavity receiver was carried out by Sinha and Gulhane [15] to determine the effect of cavity temperature and emissivity on radiation heat loss. Their analysis results show that radiation heat loss increases rapidly as the cavity temperature increases from 673 to 2273 K . The thermal performance of the receiver significantly depends on radiative heat loss from the receiver. Receiver efficiency can be improved by enhancing the absorptivity of the receiver surface [16]. A variable aperture mechanism was found attractive in improving the efficiency of the cavity-type receiver. Approximately 60% of radiation losses from the receiver were mitigated by adjusting the aperture of the cavity receiver [17]. Huang et al. [18] presented an analytical function to predict the performance of the sphere receiver in a parabolic dish concentrator. Their proposed optimization process showed enhanced efficiency with sphere receiver than solar tower because of higher cosine factor.

Few researchers have focused on the external receiver of the parabolic dish concentrator. Nene et al. [19] compared heat losses from a cylindrical and conical receiver of Scheffler solar concentrator. Numerical analysis carried for tilt condition. They have reported that the conical receiver is better than a cylindrical receiver to mitigate convective heat loss. Kamboj et al. [20] experimentally investigated the solar steam boiler's thermal performance. An external steam boiler (receiver) was placed at the focus of the Scheffler solar concentrator. They tested the receiver with three different arrangements viz. black paint Coating, black paint coating and glazing and black paint coating, glazing, and side reflector. They reported that the receiver with side reflector and glazing is better than the other two regarding dryness fraction and thermal efficiency. Thirunavukkarasu and Cheralathan [21] experimentally studied the thermal performance of a Scheffler concentrator having a spiral tube receiver. Energy analysis revealed an average thermal efficiency of 56.21% for water heating with average beam radiation 750 W/m^2 . Chandrashekara and Yadav [22, 23] have evaluated the thermal performance

of exfoliated graphite coated flat receivers. They have carried out experiments using 2.7 m² Scheffler reflector for water desalination. They obtained an efficiency of about 40% and 42% with sensible and latent heat storage materials respectively. Stefanovic [24] developed a thermal model to investigate the solar concentrator collector with a spiral tube absorber and validated with experimental results. According to their results, a mean deviation of about 3.22% was observed between experimental and model results. The work presented by the author is useful in analyzing the effect of environmental parameters on the thermal efficiency of the system.

In India, Scheffler concentrator has gained large popularity for community cooking and industrial heat application [25, 26]. Moreover, researchers have integrated the Scheffler concentrator to the backing unit and solar dryer [27, 28]. Dome type and flat surface external receiver are being used for Scheffler solar concentrator. These external receivers constitute the active and dead surfaces. The receiver's surface on which reflected radiations are concentrated is considered an active surface while others are treated as dead surfaces. However, the insulation is provided on the side and back surface; it contributes to thermal losses due to the high temperature of the receiver. In the receiver's modified design, the sidewall surface area is minimal, as two halves are welded to form the cavity, resulting in the lower ratio of dead surface to the active surface compared to the conventional designs of the receiver. The solar steam-based turmeric-cooking facility is established at SGGGS Institute of Engineering and Technology, Nanded, India. An external receiver having a convex front surface is developed by considering seasonal variation in the focal image. Receiver installed at the focal point of 16-m² Scheffler solar concentrator to generate steam for turmeric cooking. It has been observed that heat losses from the receiver significantly reduce the efficiency of the system during steam generation. It has also been found that the maximum energy utilization strategy is the better way to reduce heat losses and improve the thermal performance of the receiver. In the present work, the focus is given on harnessing the maximum solar energy received at the receiver for direct steam generation.

In previous studies, most researchers have used a cylindrical cavity receiver. They have considered the inner sidewall of a cavity as active surfaces and harvested solar radiation incident on it. The configuration they have used is not suitable for Scheffler's solar concentrator. In the case of the Scheffler solar concentrator, the shape and size of the focal image formed at the receiver vary with the declination angle. The nature of flux distribution at the receiver is different from other parabolic dish concentrators. The surface at the back of the cavity plays an important role in designing of receiver for the Scheffler concentrator. Some studies

showed the effectiveness of the external receiver, but they have not focused on the dead surface at the center of the coil and suppresses heat losses to ambient. This study aims to experimentally test the performance of the modified receiver for 16 m² Scheffler solar concentrators. Thermal efficiency was analyzed with three different arrangements of receiver for direct steam generation.

2 Experimental setup and procedure

2.1 System description

The schematic diagram of the experimental setup is shown in Fig. 1. This setup is located at Nanded (MS), India (latitude 19.1114 North, longitude 77.2945 East). The system consists of Scheffler solar concentrator, receiver, and steam condenser. The A Scheffler reflector is a parabolic concentrator type concentrator with polar axis automatic tracking, which maintains a fixed focus at the receiver. Scheffler reflector consists of flexible surface curvatures with an elliptical rim and 20 crossbars. In the present work, the total surface area of the reflecting frame is 16 m². Solar grade mirrors of size 22 × 22 cm are used as reflecting material and are placed over aluminum strips. The reflector has a two-axis tracking system. Relay controlled motor rotates dish automatically to track sun position. Telescopic clamps have facilitated seasonal tracking. The reflector has a shadow-free receiver however, complicated design and heavy structure are the main drawbacks of the Scheffler reflector. The photographic view experimental setup is shown in Fig. 2.

2.2 Solar receiver description

Convex shape receiver is constructed and installed at the focal point facing towards concentrator. The convex shape allows maximizing cavity volume by reducing the sidewall surface area. The receiver is made of cast iron having a volume 18 l. The focal image size is measured by placing a flat black color metallic plate at the focal point of the concentrator. The diameter of the focal image is measured to be 0.47 ± 0.02 m. In addition, from the design chart given by Reddy et al. [29] maximum diameter of the focal image formed on a flat receiver is calculated to be 0.42 m. Hence, in the present study, a 50-m² aperture area of the receiver is selected in order to intercept all reflected radiations.

Three types of arrangements of the receiver have been used during the experimentation as shown in Fig. 3. The front surface of the receiver is coated with black antireflecting paint to increase absorptance. Whereas back and side surfaces are thermally insulated with 40 mm thick rock wool covering. Insulation

Fig. 1 Schematic diagram of the experimental setup

Fig. 2 A photographic view of the experimental setup

is supported by adding aluminum cladding over it for proper fitting. The schematic diagram and photographic view of the receiver having a convex front surface are shown in Figs. 3a and 4a, respectively. In the second

arrangement, an insulated cylindrical cavity is added over the convex surface receiver shown in Figs. 3b and 4b. The cavity is made of joining the two concentric open cylinders. Space between two cylinders is filled with a

Fig. 3 Schematic of receiver with (a) first arrangement (b) second arrangement (c) third arrangement

Fig. 4 Photograph of receiver with (a) first arrangement (b) second arrangement (c) third arrangement

30 mm thick layer of rock wool. Figures 3c and 4c show the schematic and photographic view, respectively, of the receiver with a spiral coil on the cavity's inner wall. This is the third arrangement of the receiver. The coil is made of aluminum tube, and it has a diameter the same as the aperture area of the receiver. The tube has an inner diameter of 8 mm. Coil was packed with 15 turns of the tube to absorb maximum radiation. Water-emerged electric DC motor is used to circulate water through the coil from an insulated 25-l capacity reservoir.

2.3 Measuring instruments and method

Global solar radiation is measured using a pyranometer (Make: Dynalab, Model: RN 2104) of measuring range and accuracy $0\text{--}1500\text{ W/m}^2$ and $\pm 3\%$ respectively. The shading ring is employed for measuring diffuse radiation. K-type thermocouple is integrated with a temperature data logger. The least count of temperature measurement is $0.1\text{ }^\circ\text{C}$. Receiver temperature, water temperature, steam temperature, and ambient temperature were measure

during experimentation. Wind speed is measured with an anemometer having an accuracy 0.1 m/s and measuring range 0.4–45 m/s. The water flow rate through a spiral tube is measured using a laboratory rotameter with an accuracy $\pm 2\%$. A condensation apparatus is used to determine the steam flow rate. The condensed water is collected from the pipe provided at the bottom of the apparatus and the volume of the condensate is measured using a beaker with 10% accuracy.

2.4 System operation

The insulated tank of 30 l capacity provided over the receiver acts as a water storage tank cum steam separator. The heat transfer fluid used in this study is water. The storage tank is filled up with water using an electric motor. For the production of steam, water is circulated from the storage tank to the receiver through interconnected piping. Water circulation takes place due to the relative density difference (Thermosyphon principle). The generated steam is collected from the exit pipe provided at the top of the tank. The steam outlet pipe is connected to the condensation apparatus.

Initially, the effectiveness of the receiver is identified by performing a stagnation test. At stagnation condition, no heat is transfer to the heat transfer fluid inside the receiver. This test is conducted to determine the maximum overall heat loss coefficient of the receiver because of receiver attains maximum temperature at a stagnation condition. The experiment for the stagnation test was conducted on 8 March 2019. Later experiments are conducted for analysis of the receiver with three different arrangements. Experiment with the first, second, and third arrangements was conducted on 11 March 2019, 23 March 2019 and 30 March 2019 respectively. All experiments were conducted from 9:00 to 15:00 h.

3 Data analysis

The aperture area of Scheffler solar concentrator varies with solar declination angle, which can be calculated from the following equation [30].

$$A_{ap} = A_s \cos (43.23 \pm \delta/2) \quad (1)$$

where A_s is the surface area of the concentrator.

The aperture area of the concentrator is characterized by the $\cos\theta$. Declination angle δ can be found from the expression [31]

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

where n is the day of the year. The declination angle is positive (+) for the southern hemisphere and negative (–) for the northern hemisphere.

For the seasonal change in position of the sun, the major axis of the elliptical rim tilted by half solar declination angle to maintain focus at the fixed point. This adjustment is done in the position of the concentrator in North–South direction for changes in the size and shape of a focal image formed at the receiver.

The solar radiation power received by Scheffler solar concentrator determined from the relation

$$Q_s = A_{ap} I_b \quad (3)$$

where A_{ap} is the aperture area of the concentrator on n th day.

Useful power transferred from Scheffler concentrator is given by:

$$Q_d = \eta_{opt} Q_s \quad (4)$$

where η_{opt} is the optical efficiency of the concentrator. Optical efficiency is estimated to be 75% from mirror reflectivity and absorptivity of the receiver.

Useful energy obtained from the system is the energy required to raise the temperature of the water and energy supplied to vaporize it. The rate of useful energy obtained from the system is determined by

$$Q_{use} = Q_{sen} + Q_{lat} \quad (5)$$

where sensible heating power is given as:

$$Q_{sen} = m C_p \frac{\Delta T}{\Delta t} \quad (6)$$

m is the mass of the water in receiver and tank; C_p is the specific heat of water and $\frac{\Delta T}{\Delta t}$ is the rate of temperature rise with time.

Latent heat required for vaporization is given as:

$$Q_{lat} = \dot{m} h_{fg} \quad (7)$$

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

Useful thermal energy from the receiver is the receiver power.

$$Q_r = Q_{use} \quad (8)$$

The energy efficiency of the receiver is the ratio of useful energy obtained to the solar energy received by the receiver.

$$\eta_{th} = \frac{Q_{use}}{Q_d} \quad (9)$$

From the energy conversion law, heat loss from the receiver is expressed as:

$$Q_l = Q_d - Q_r \quad (10)$$

Q_l represents combined heat loss from the receiver due to conduction, convection, and radiation.

A stagnation test is conducted to determine the overall heat loss coefficient of the cast iron convex receiver. At stagnation condition, no useful energy obtained from the receiver. Therefore $Q_{use} = 0$.

From Eqs. (10) and (11)

$$Q_l = Q_d \quad (11)$$

Q_l can be written as

$$Q_l = U_l A_r (T_r - T_a) \quad (12)$$

From Eqs. (6), (7), (13) and (14)

$$U_l = \left(\frac{\eta_{opt} A_{ap} I_b}{A_r (T_r - T_a)} \right) \quad (13)$$

4 Uncertainty analysis

The uncertainty associated with solar beam radiation, temperature, and steam flow measurement is considered independent and random. Uncertainty in the measurement of solar beam radiation is 3% as obtained from the accuracy of the Pyranometer. Combined uncertainty in temperature measurement due to error in K-type thermocouple and data logger is $\pm 0.7^\circ\text{C}$. The steam flow rate has an uncertainty of 1.81% estimated from the repeated measurement. Uncertainty in concentrator power, receiver power, thermal efficiency and overall heat loss coefficient is calculated from the propagation of error method described by [32].

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x} \delta x \right)^2 + \dots + \left(\frac{\partial q}{\partial z} \delta z \right)^2} \quad (14)$$

Uncertainty in the function $q = (x, \dots, z)$ calculated from independent uncertainties $\delta x, \dots, \delta z$ in $x, \dots, z$ variables.

Uncertainty values of concentrator power, receiver power, overall heat loss coefficient, and thermal efficiency are presented in Table 1.

5 Result and discussion

Several experiments were conducted in March 2019. Experimental data obtained on a clear sky day with less difference in average solar beam radiation is analyzed. The

Table 1 Uncertainties of the obtained parameters

Parameter	Uncertainty value	Uncertainty %
Concentrator power	177 W	3.00
Receiver power	77.02 W	2.07
Overall heat loss coefficient	63.53 W	3.61
Thermal efficiency	2.48%	3.64

aperture area of Scheffler concentrator varies with the declination angle. At the experimental location, aperture area decreases from the month of December to June and again increases from June to December. Variation in an aperture of 16 m^2 Scheffler concentrator is shown in Fig. 5. The average aperture area available in December is 13.62 m^2 and in June 9.22 m^2 , such a large monthly variation in aperture area is observed. The average aperture area available in the month of March is close to the yearly aperture area of the Scheffler solar concentrator.

Figure 6 shows the variation in receiver temperature and overall heat transfer coefficient during the stagnation test. The intensity of solar beam radiation increases linearly from 9:00 to 10:10 h and then after small fluctuations are observed. At the beginning of the test lower receiver temperature is observed and higher overall heat loss coefficient this is due to the heat is being utilized for preheating of the receiver. Then after fluctuation in receiver temperature and overall heat loss coefficient are observed till the end of the test. The maximum receiver temperature recorded during the test is 371°C at 12:40 h. The overall heat loss coefficient dropped to $82\text{ W/m}^2\text{ K}$ from its maximum value of $300\text{ W/m}^2\text{ K}$. The average value of the receiver temperature and overall heat loss coefficient is obtained to be 314°C and $107\text{ W/m}^2\text{ K}$ respectively at average solar beam radiation 668 W/m^2 . The ambient temperature increased from 27 to 36°C during the test period. Ambient temperature has no significant effect on the overall heat loss coefficient as a receiver is at higher temperatures.

The variation of beam radiation, ambient temperature, and receiver temperature is shown in Fig. 7a–c. During the test of the receiver without any cover on it, the intensity of solar beam radiation increased from 492 W/m^2 reached a maximum value of 698 W/m^2 at 13:00 h. As presented in Fig. 7a, during the first 30 min of the test receiver temperature is below 200°C and then after it reaches to a maximum value of 285°C at 13:00 h. The large fluctuation in receiver temperature is observed due to variation in wind speed. The variation in the wind speed is observed between 0.4 to 4.6 m/s during the experimentation. Convection losses from the receiver are more dependent upon wind speed rather than the intensity of solar beam radiation. The average values of receiver temperature and ambient

Fig. 5 Daily variation in declination angle and aperture area of Scheffler solar concentrator

Fig. 6 Variation of receiver temperature and overall heat loss coefficient during stagnation test

temperature obtained during the performance test of the receiver with the first arrangement are 241 °C and 33 °C respectively. Figure 7b depicts the variation in parameters recorded during the test of the second arrangement of the receiver. Solar beam intensity increased gradually from the start of the second test but at 12:20 h small decrease is observed. After that, it suddenly increased and observed a value of 708 W/m² at 12:30 h. The average temperature recorded with the second arrangement is 266 °C which is about 25 °C more than the receiver with the first arrangement. An additional parameter, water temperature in the reservoir is presented in Fig. 7c. Water from the reservoir was continuously circulated through the coiled tube fixed on the inner wall of the cavity. Very low flow rate about 0.5 lpm was maintained. Water temperature in the reservoir increased slowly from the beginning to the end of the test. About 18 °C hourly rise in circulated water temperature was observed during the peak solar intensity period. The third arrangement of the receiver was made to show that effective and low-cost methods to harvest the wasted energy from receiver. The average solar beam intensity during this test was observed to be 645 W/m². The receiver temperature was recorded a lower value of 76 °C at the start of the test and after it increased rapidly to 221 °C within the 20 min. The maximum value of receiver

temperature was observed at 13:20 h and it is 302 W/m². With the second and third receiver arrangements, fewer fluctuations are observed in receiver temperature because of the minor effect of wind speed variation. The average ambient temperature during the first, second and third arrangement tests was 34, 36 and 39 °C.

Variation in concentrator power, receiver power, and overall heat loss coefficient are presented in Fig. 8a–c. Concentrator power depends on the intensity of solar beam radiation and aperture area available during the experimentation. Maximum concentrator power 6.32 kW, 6.17 kW and 5.92 kW was obtained during the first, second and third arrangement test respectively. At the start of the test very low receiver power was observed but later it increased suddenly and varied in much the same way to thermal output from the system. Moreover, receiver power shows the same trend in the second and third arrangements of the receiver. The overall heat loss coefficient was observed to vary in an exactly inverse way to receiver power. The difference in average solar beam radiation during these three tests was a less but notable rise in receiver power was observed. This is because of augmented energy utilization in a modified receiver. The maximum and average values of concentrator power, receiver power and overall heat loss coefficient are presented in Table 2.

Fig. 7 Variation of solar beam radiation and receiver temperature with day time (a) first arrangement (b) second arrangement (c) third arrangement

The steam flow rate and time average energy efficiency of the receiver with three different arrangements are shown in Fig. 9a–c. Results of the first performance test with a bare receiver are illustrated in Fig. 9a. The test was started at 9:00 h and steam generation was

observed to be initiated after 10:10 h. The efficiency of the system at the beginning of the test was found to be less because of portion the energy concentrated on the receiver was stored as sensible heat in receiver material. The efficiency of the system dropped abruptly when

Fig. 8 Power variation with day time (a) first arrangement (b) second arrangement (c) third arrangement

steam generation started this indicated the increase in the overall heat loss coefficient of the receiver. Steam generation started with a flow rate of 4.80 kg/h and later maximum flow rate observed to be 5.88 kg/h at

13:10 h. Steam condensed using specially designed apparatus and condensate measure after every 10 min of interval. Before steam generation efficiency was calculated by considering the sensible heat required to reach

Table 2 Performance parameters

Parameter	Receiver arrangement		
	First	Second	Third
Maximum concentrator power (kW)	6.32	6.17	5.92
Average concentrator power (kW)	5.70	5.60	5.49
Maximum receiver power (kW)	3.69	3.77	4.23
Average receiver power (kW)	3.30	3.43	3.75
Maximum overall heat loss (kW)	2.75	2.63	2.43
Average overall heat loss (kW)	2.44	2.20	1.76
Maximum thermal energy efficiency (%)	73.51	74.21	74.07
Average thermal energy efficiency (%)	57.71	60.93	68.03

the water to boiling point. After the steam generation started, the latent heat of vaporization was considered for efficiency calculation. Figure 9b depicts the variation of steam flow rate and efficiency of the receiver for the second arrangement. The average efficiency of heating the water to the boiling point was observed to be 66.63%. After the water temperature reaches the boiling point evaporation of water started and evaporation efficiency is lowered than water heating efficiency. Less variation in steam flow rate was observed from 10:40 to 13:00 h but a sudden decrease was found after 14:30 h. Cavity provided on the receiver suppressed convective heat losses making steam flow rate independent of wind speed. Spike in solar beam intensity at 12:30 h suddenly dropped the efficiency of the system this can be caused by increased re-radiation losses from the receiver. In the third arrangement of the receiver, the percentage of energy harvested through sensible heating is more as compared to the first and second arrangements. Figure 9c shows the variation in steam flow rate and efficiency in the case of the third arrangement of the receiver. Compared with the first and second arrangements, the enhancement in efficiency was observed during solar beam radiation's peak intensity. Thus, the addition of a coiled tube on the cavity's inner surface suppressed heat losses by capturing the maximum energy at the receiver. No significant effect on the steam flow rate was observed in this arrangement. The average steam flow rate was found to be 5.32, 5.50, and 5.64 kg/h with the first, second, and third arrangement of the receiver. This shows that the receiver's arrangement does not vary the overall steam flow rate under identical atmospheric conditions. However, variation in the overall efficiency was observed because of utilizing the rejected heat form receiver. The thermal efficiencies achieved with the receiver's third arrangement are 10.32% and 7.10% higher than the first and second arrangements, respectively, under the same operating conditions. The

maximum and average values of the steam flow rate and efficiency are given in Table 2.

The thermal efficiency of the receiver achieved in the present work and in the similar type of previous studies is presented in Table 3. Scheffler solar concentrators and other parabolic dish concentrators are considered for comparison. Mawire and Taole [11] have reported 86.53% efficiency of cylindrical cavity receiver of SK-14 parabolic dish at constant solar radiation 900 W/m². Scheffler solar concentrator has gained popularity for water distillation and steam based applications. A study carried out by Chandrashekara and Yadav [23] showed a 9% improvement in desalination efficiency with graphite coating on the receiver. The authors claimed that they have achieved 40.00% efficiency for water desalination. A conical cavity receiver developed by Cheralathan et al. [33] shows similar efficiency that of the first arrangement in the current study. Although they have used a cavity receiver, not packed the coils close and also not effectively utilized the radiations concentrated at the focus of the concentrator. In experimentation conducted by Nene et al. [34] reported an average thermal efficiency of 58.00% for conical shape external receiver with a tilt arrangement for steam generation. Agrawal and Yadav [35] achieved 51.69% efficiency of the hollow cubical mild steel receiver for ice melting. Lopez et al. [12] achieved 60% and 64% thermal efficiency respectively for the flat and cavity receiver of commercial parabolic dish concentrator.

6 Conclusions

This experimental work presents the thermal performance analysis of the receiver for Scheffler solar concentrator. In these experiments, a receiver with three different types of arrangement was tested under identical solar radiation condition and the following conclusions are drawn:

The maximum temperature of the receiver reached during the stagnation test is 371 °C. This shows the receiver can be used for pressurized steam generation. The overall heat loss coefficient from the stagnation test is estimated to be 109 W/m² K.

In this experiment, under average beam radiation 640 W/m² receiver temperature of 241 °C, 266 °C, 253 °C was achieved with first, second and third arrangement.

The average thermal efficiency of the receiver for first, second and third arrangements has been calculated 57.71%, 60.93% and 68.03%, receiver cover with tube coil increases the overall efficiency of the system.

Overall heat loss coefficient has an inverse effect on receiver power. However, the overall heat loss coefficient can be suppressed by increasing the energy utilization rate at the receiver.

Fig. 9 Steam flow rate and efficiency variation with day time **(a)** first arrangement **(b)** second arrangement **(c)** third arrangement

In this study, the receiver with the third arrangement is found efficient. This receiver was tested to demonstrate the easy way to capture the maximum energy concentrated

at the focus of the concentrator. In the future, air can be blown through a coil provided on the inner wall of the receiver cavity to supply the hot air to the indirect dryer.

Table 3 Comparison of thermal efficiencies of present work with previous studies

Researcher	Concentrator type and surface area	Receiver	Thermal output	Receiver efficiency
Mawire and Taole [11]	SK-14 parabolic dish 4 m ²	Spiral coiled external receiver	Hot water	86.53%
Chandrashekara and Yadav [23]	Scheffler 2.7 m ²	Square box receiver with front surface coated with exfoliated graphite	Distilled water	60.73%
Cheralathan et al. [33]	Scheffler 16 m ²	Conical cavity receiver	Hot water	57.39%
Nene et al. [34]	Scheffler 2.7 m ²	Conical external receiver with tilt	Steam	58.00%
Agrawal and Yadav [35]	Scheffler 1 m ²	Cubical receiver	Molten ice (water)	51.69%
López et al. [12]	Parabolic dish (Commercial) 16.9 m ²	Flat and cavity receiver	Hot thermal fluid	Flat: 60% Cavity: 64%
Present work Third arrangement	Scheffler 16 m ²	Convex receiver with coiled cavity	Steam (atmospheric pressure) and Hot water	68.03%

Compliance with ethical standards

Conflicts of interest No conflicts of interest.

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